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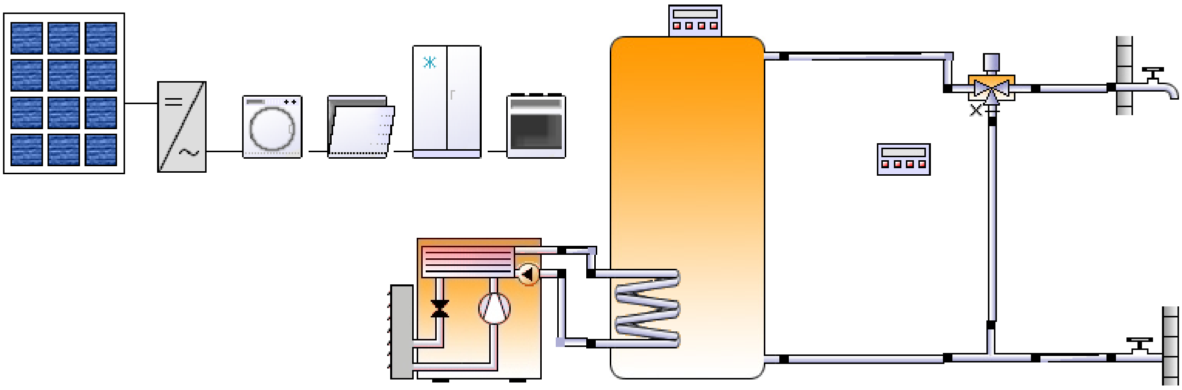

Self-production systems for household electricity and hot water consumptions

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Resumo

Esta tese analisa a utilização integrada de sistemas fotovoltaicos para autoconsumo com bombas de calor para águas quentes sanitárias de forma a diminuir a quantidade de energia adquirida à rede, com base na comparação técnico-económica com outras soluções de geração de electricidade e geração de águas quentes sanitárias mais tradicionais.

A análise é baseada na utilização da ferramenta computacional PolySun para a simulação dos diferentes sistemas e para a análise do seu comportamento com diferentes parâmetros.

Os resultados demostram que o período de retorno é de 8,2 anos quando comparado com um sistema tradicional de termoacumulador elétrico sem autoconsumo. Em particular, há uma redução líquida do consumo de 827kWh. Contudo, a solução depende do tipo de perfil de utilização de electricidade e assim é possível em algumas condições reduzir o período de retorno com base na utilização de um sistema de autoconsumo de 1 a 1,5 kW (4 a 6 painéis).

Palavras-chave - Autoconsumo, bomba de calor, fotovoltaico, Polysun, auto produção.

Abstract

Solar self-production systems with a heat pump (HP) for household electricity and hot water consumptions are used to decrease the amount of energy purchase from the electric grid. This system is compared with other systems that also produce electricity and domestic hot water (DHW).

Software Polysun is used to simulate and study the different systems. Several simulations are accomplished with software Polysun to study the different systems of production of electricity and DHW. Also other simulations are implemented to study how to improve the parameters of the system that affect the self-production.

Results show a payback period of 8.2 years for the system of study compared with other a system without photovoltaic (PV) panels and an electric resistance to produce DHW. For some consumption profiles an optimum solution for the number of PV panels can be found to decrease the payback period, the results are always between 4 and 6 panels. Also the study show that for the same profiles of consumption, the system of study needs 827kWh less energy from the grid compared with the next system.

Keywords - self-consumption, heat pump water heaters, rooftop photovoltaic, Polysun, self-production.

Table of Contents

List of figures

List of tables

List of abbreviations

AC - Alternative current
BOS - Balance-of-system
CAGR - Compound annual growth rate
COP - Coefficient of performance
C-SI - Cristal silicon
DC - Direct current
mc-Si - Mono-crystalline
NPV - Net present value
PR - Performance ratio
PV - Photovoltaic
pc-Si - Polycrystalline Silicon
STC - Standard Tests Conditions

1 Introduction

Self-consumption is a new concept in energy markets. Self-consumption implies the use of energy sources in the house to decrease the purchase of energy from the electrical grid. It can be done from different energy sources but the concern with the climatic change has increased the interest in the self-production of energy from renewable sources. Many forms of renewable energies are available nowadays. The need to implement the installations in a domestic environment implied the use of a static low maintenance system. PV systems are a good solution for this purpose.

PV self-consumption optimization recently received a lot of attention. In many cases demand side management is more effective and cheaper than the usage of battery systems or is used in combination with electrical storage. In particular, the combination of heat pump heating systems with PV rooftop installations is promising and potentially offering a relatively high self-sufficiency quota. It is important to recognize that the coupling between electrical and thermal systems has the advantage to utilizing already existing thermal storage elements (hot water storage tank or thermal inertia of buildings), which typically have a time constant of about one day and experiencing no deterioration also with high number of charging.(Solaris, Sma, & Technology, 2014)

The cost of PV modules have decreased around 1600% since 1980 (Fraunhofer ISE, 2015). Prices in the past made the introduction of PV systems to reduce the cost of electricity bills unprofitable. The reduction costs have increased the use of photovoltaic systems for self-consumption.

The international energy agency (IEA) has estimated an increase in the market of photovoltaic energies for 2050 (Hoeven, 2014). (Fraunhofer ISE, 2015) study the future decrease in the cost of all the devices of a PV installation. Also (Glunz, Nozik, Conibeer, & Beard, 2014; Richter, Hermle, & Glunz, 2013; Shockley & Queisser, 1961; Würfel, 2005) study the theoretical cell efficiency limits of the different module materials. Cell efficiencies have not been found this limits yet, so cell efficiencies will grow in the future (Fraunhofer ISE, 2015). The photovoltaic market will improve in the future making the investment of this system more profitable.

Also laws for self-consumption have helped to increase the self-production system though still they have much to improve. This study is made for the Iberian Peninsula countries, Portugal and Spain. Spain and Portugal regulations for self-consumption are similar. These countries share the same market which makes them to have similar market prices. However, the consumer prices are not similar due to differences in how the tariff is defined, including taxes.

This study aims to analyze and improve a domestic PV system with a HP for the production of electricity and DHW. Also the comparison of this system with other solutions to get all the electricity and DHW for a house is made. The software Polysun is used for the comparison of the different systems as well as to study the different parameters that affect the self-production and the auxiliary energy needs from the grid of the installation.

For the assessment of the system of study, a comparison of it with other systems available in the market is done. The results assessed from the simulations are: the self-consumptions, the auxiliary energy needs from the grid to cover the consumption profiles of the house and payback period of each system.

Parameters that affect the self-production and the performance of the installation studied are: the location of the installation in the Iberian Peninsula, the stratification in the DHW tank and the different consumption profiles.

Simulations of the system in different locations in the Iberian Peninsula disclose the differences in self-consumed energy and payback periods for the same consumption profiles. Stratification improvements in the HP tank are reviewed from past studies and also a simulation to check the auxiliary energy need for DHW production with different heat exchanger positions in the tank is carried out. Some consumption profiles are also studied with simulations to see how they can affect the self-consumption in the same installation.

Finally the new concept of this system is the storage of thermal energy in the tank of the HP. The electricity that is not consumed in the home appliances from the PV panels is used to feed the HP to produce DHW. This increases the self-consumption of the installation reducing the payback period.

2 Methods

2.1 Iberian Framework legislation for self-consumption

Spain and Portugal have a regulation frame work for self-consumption. Although, their self-consumption legislations are different. These countries share the same market which makes them to have similar market prices. However, the consumer prices are not similar due to differences in how the tariff is defined, including taxes.

2.1.1 Portuguese legislation of self-consumption to installations of less than 1,5kW.

The Decree-Law n.º 153/2014 defines the legal regime applied to the electricity production for self-consumption and to sell to the public electric grid from renewable sources, through small production units.(MINISTÉRIO DO AMBIENTE, 2014)

This section analyses only the case of installations with less than 1.5kW without selling the electricity injected in the public electricity grid. For installations with less than 1.5kW that are connected to the grid it is necessary to add a meter to count the electricity produced in the installation and the price of this meter makes the investment less profitable. Also installations of less than 1.5kW have easier authorisation procedures.

The features that Portuguese installations must have are: the power of the installation has to be less than two times of the contracted power, the electricity produce is instantly injected in the installation of consumption, the installation is set up in the same place as where consumption is going to be, the annual production should be less than the annual consumption, the installation of a meter is not needed, the authorisation procedures are carry out through an electronic platform and simple prior notification.

2.1.2 Spanish Legislation of self-consumption to installations of less than 10kW without electricity injection in the public electric grid.

The Royal Decree 900/2015, of 9th of October regulates the administrative, technical and economic conditions, for the modalities of electricity supply with self-consumption and production with self-consumption.

For this study a type 1 of self-consumption installation of the Royal Decree 900/2015, in which the only user of the installation is the owner, with a power of less than 10kW without electricity injection in the public grid would be chose to make profitable the investment.

The features that Spanish installations must have are: the electricity produced is instantly injected in the installation of consumption, the installation is set up in the same place as where consumption is going to be, installations of less than 10kW without batteries have no additional charges to pay, it is compulsory a meter to count the net energy generated and it is optional a meter to count the self-consumed electricity , it is necessary a contract with the distributor company of at least 1 year, the power of the connexion to the grid of the installation has to be lower than the contracted power and less than 10kW.

2.2. Present and future market of photovoltaics

2.2.1 Current solar photovoltaic panels for domestic self-consumption.

Presently, various types of solar cells are industrially available, however, the strive for research and development is continuing to expand and improve this technology.

In terms of technology, crystal silicon (c-Si) is the main material used in the PV industry. Presently, over 80% of the world PV industry is based on c-Si wafer technologies (see figure 1). Other module technologies are available in the market but they are less used, therefore they are not going to be discussed. These technologies are: Cadmium Telluride solar cell (CdTe), Copper Indium Gallium Selenide solar cells (CIGS), amorphous Silicon solar cells (a-Si) and Multijunction cells.

Although single crystalline cells account for the majority of PV panels, there are a few types of silicon PV technologies on the market today: mono-crystalline (mc-Si), poly-crystalline (pc-Si) and silicon hetero-structures.

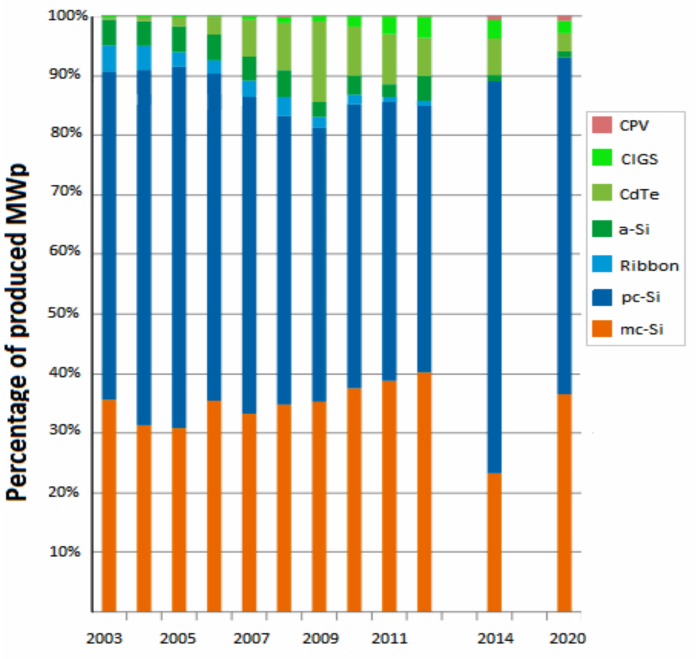


Figure 1 PV module technology overview.

The mc-Si efficiencies are about 15% to 18%.(iea, 2014) The maximum efficiency in the lab of mc-Si solar cell reached is 25.6% and in the module 22.9%. The manufacturer Sunpower has a panel model X21-345 for residential purposes made of mc-Si with an efficiency of 22.5%. Furthermore, a panel from the same company part of a shipment for a residential installation was verified by the National energy renewable laboratory(NREL, 2016) to have an efficiency of 22.8 percent, setting a new world record. (Sunpower company, 2016)

The pc-Si cell is made in much the same way as the mc-Si PV cell. They are slightly less efficient and slightly cheaper to buy than mc-Si, however, its temperature coefficient is better than that of the mc-Si. The cell efficiency for the best laboratory cells is 21.3% and for the best module is 19.2%.

2.2.2 The future of photovoltaics

Solar photovoltaic is already today a low-cost renewable energy technology. Cost of power production from large scale photovoltaic installations in Germany fell from over 40 ct/kWh in 2005 to 9ct/kWh in 2014 and even lower prices have been reported in sunnier regions of the world, since a major share of cost components is traded on global markets.(Fraunhofer ISE, 2015)

Solar power is expected to be the cheapest form of electricity in many regions of the world.(Fraunhofer ISE, 2015) Even in conservative scenarios the price of solar technologies will not increase in worst cases. Depending on annual sunshine, power cost of 4-6 ct/kWh are expected by 2025, reaching 2-4 ct/kWh by 2050 (conservative estimate).(Fraunhofer ISE, 2015)

Financial and regulatory environments will be key to reducing cost in the future. Cost of hardware sourced from global markets will decrease irrespective of local conditions. However, inadequate regulatory regimes may increase cost of power by up to 50 percent through higher cost of finance. This may even overcompensate the effect of better local solar resources.

2.2.2.1 Market

The sun could be the world’s largest source of electricity by 2050, ahead of fossil fuels, wind, hydro and nuclear, according to reports issued by the IEA (figure 2). The two IEA technology roadmaps show how solar PV systems could generate up to 16% of the world’s electricity by 2050 while solar thermal electricity (STE) from concentrating solar power (CSP) plants could provide an additional 11%.

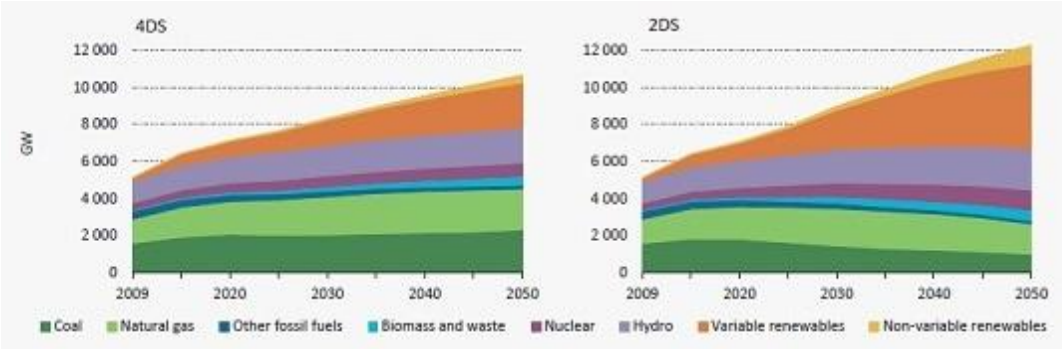


Figure 2 Generation capacity by technology in scenarios 2DS and 4DS of the IEA.

Figure 2 shows the different scenarios of the IEA. The IEA developed a series of energy technology roadmaps for solar energy. The vision for each of the IEA's roadmaps is based on the energy technology perspectives. The scenario 2DS is calculated based on an average global temperature increase to 2°C, scenario 4DS is calculated based on an average global temperature increase to 4°C. As PV technology will cover a different amount of the total energy production. In all scenarios the energy production by PV increase each year till 2050, so clearly the PV market is going to rise to an installed capacity between 3000 and 70000 GW.

2.2.2.2 Cost

The cost and price dynamics of technologies are often quantified following the experience curve approach, which relates the cumulative produced quantities of a product and the sinking unit costs (production costs). The concept is based on learning effects, which were first described by Wright as early as 1936 in a mathematical model for production costs of airplanes (Wright, 1936)

Following the study of (Fraunhofer ISE, 2015), the price experience curves for the different devices of the system and for different scenarios are going to be shown in the next paragraphs.

The first three scenarios assume a conservative approach where there are not technology breakthroughs and build only on technology developments within crystalline silicon technology. The most pessimistic scenario (scenario 1) considered, is based on a 5 percent compound annual growth rate (CAGR) of the global PV market after 2015. More pessimistic scenarios, e.g. assuming no further market growth or even a reduction in market volumes in the long term, were widely dismissed as not realistic. An intermediate scenario (scenario 2) builds on a 7.5 percent CAGR and an optimistic scenario (scenario 3) on a 10 percent CAGR between 2015 and 2050. An additional PV breakthrough scenario (scenario 4) was developed to assess the impact of an "extreme" market scenario. This scenario is not based on a bottom-up assumption on market growth but rather takes as a starting point a largely PV-based energy system in 2050, in which PV provides 40 percent of global electricity demand in a "high electrification" scenario.

Modules

The price dynamics of PV modules have followed a price experience curve since 1980 (see figure 3). Several oscillations below and above the trend line are observable. Such price behaviour is not uncommon, oscillations above the learning curve were for example caused by material scarcity and scarcity in production facilities along different parts of the module production value chain. An extensive discussion of the experience curve for PV can be found in (Nemet, Husmann, Willeke, & Weber, 2012).

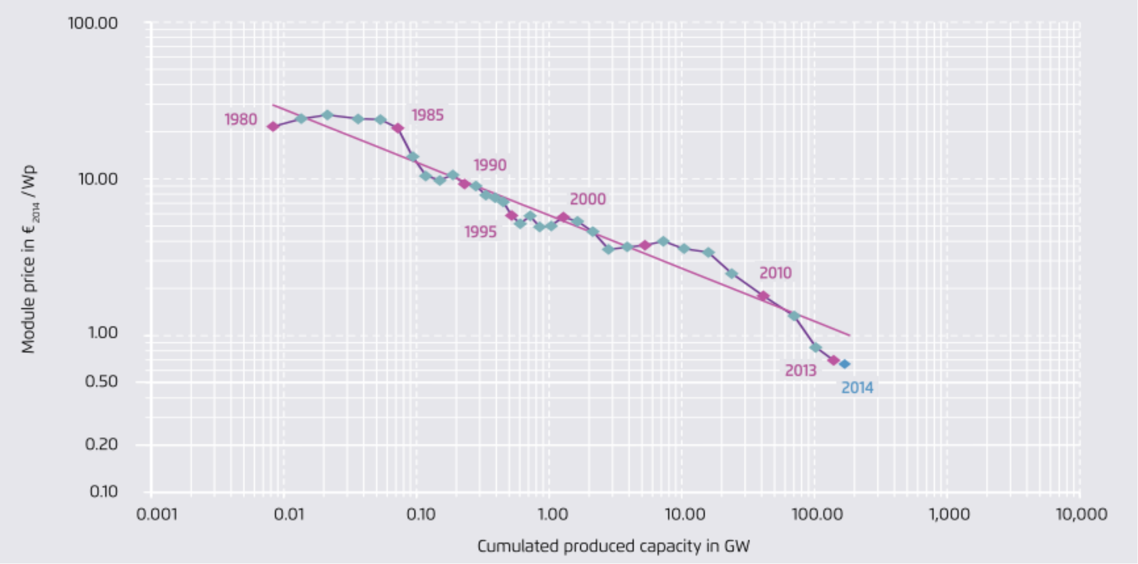


Figure 3 Historical price experience curve of PV modules since 1980.(Fraunhofer ISE, 2015).

It is important to note that the learning rate depends on the time period, which is used for fitting the trend line. The starting year for PV module experience curves is 1980 in the analysis. The learning rates depend on the date until which the data is fitted. The values vary from 19.8 to 22.6 percent, leading to an average learning rate of 20.9 percent.

Combining the assumptions on the future development of the price experience curve with the scenarios of market development described above leads to future prices of modules between 14 and 35.7 ct eur/Wp in 2050 (see table 1)

Learning rate	Scenario 1 [ct eur/Wp]	Scenario 2 [ct eur/Wp]	Scenario 3 [ct eur/Wp]	Scenario 4 [ct eur/Wp]
19%	35.7	30.4	25.7	20.9
20,90%	31.5	26.4	21.9	17.5
23%	27.3	22.3	18.1	14

Table 1 Cost of PV modules in 2050 for different scenarios

Finally the cost of the PV modules in 2014 is about 65 ct €/Wp and in a pessimistic scenario this price will reduce in 2050 to 35.7 ct €/Wp , so almost half of the price of nowadays. The costs for the modules in 2050 depending on the learning rate and scenarios can be seen in table 1.

Inverters

Notable progress has been achieved during the last decades not only at the module/cell level of photovoltaics, but also in the inverter technology. Costs came down from over 1 EUR/Wp in 1990 to almost 10 ct EUR/Wp 2014. Main drivers for this development were improved power semiconductors and new circuit topologies.

At the same time inverters became “smarter” by offering advanced monitoring and communication interfaces that help to improve the availability and performance of PV installations.

Figure 4 shows how size and weight of inverters have improved over the last decades. New power semiconductors based on silicon carbide technology, higher switching frequencies and higher voltage levels in utility scale inverters are promising approaches for further improvements in PV inverters.

Figure 4 Illustration of the progress in PV inverter technology

Like for the PV modules, an approach for the learning curve is chosen to estimate the future cost reduction of PV inverters. Table 2 shows the extrapolation of the historical learning curve that is based on data provided by SMA, with a learning rate of 18.9 percent. The minimum and maximum prices possible for each scenario are shown.

	Scenario 1 [ct$_{eur}$/Wp]	Scenario 2 [ct$_{eur}$/Wp]	Scenario 3 [ct$_{eur}$/Wp]	Scenario 4 [ct$_{eur}$/Wp]
Minimum	3.5	3.0	2.6	2.1
Maximum	4.2	3.6	3.1	2.5

Table 2 Minimum and maximum prices of the inverters for different scenarios

In 2013 the price of the inverters of less than 20kW was 15 ct eur /Wp and in the worst case for 2050 this price will be reduced in more than one third, 4.2 ct eur /Wp.

Balance of system

Balance-of-system (BOS) encompasses all components of a photovoltaic system other than the photovoltaic panels. (Fraunhofer ISE, 2015) shows that mounting of the installation, direct current (DC) cabling, grid connection and infrastructure are nearly 80% of the BOS cost. The study of each of these criterions will show how the tendency of the BOS price is for the future.

Starting from typical BOS costs today, an upper and lower estimation of long term cost reduction in each component of BOS costs is required, assuming that the module efficiency would remain unchanged. In the case of installation cost the expert discussions resulted in an estimation of approx. 0.5ct/Wp today and a cost reduction potential of only 10 percent until 2050 in the worst case and 40 percent in the best case.

In the table 3 the BOS cost in 2014, the future cost (2050) assuming the module efficiency remain unchanged(~15%) and the future cost (2050) with doubling the efficiency(~30%) are shown for each component of the BOS.

	Present cost [ct/Wp]	Future cost without eff. [ct/Wp]	Future cost with eff. [ct/kWp]
Mounting structure	7.5	3.8-6.0	1.6-3.8
Installation	5.0	3.0-4.5	1.3-2.8
DC cabling	5.0	3.0-4.5	2.0-3.2
Grid connection	6.0	2.4-3.6	2.4-3.6

Table 3 Future BOS prices

Summarizing the BOS cost, combining all assumptions to get an overall result, in average BOS costs in 2014 were 34 ct/Wp and will decline by 39 percent to 21 ct/Wp when combining all worst-case assumptions and to 12 ct/Wp when combining the best-case assumptions, representing a 65 percent cost reduction.

2.2.2.3 Efficiencies

The key for high efficiency is that a photovoltaic device transforms as much energy of the photons in the solar spectrum as possible into electrical energy. The part of the spectrum that could be used by a conventional single-junction solar cell is determined by the bandgap of its semiconductor material. Photons with energies below the bandgap are not absorbed and therefore always lost. Photons with energy higher than the bandgap are typically well absorbed but the excess energy beyond the bandgap is lost by thermal processes. These limitations determine a maximum theoretical efficiency for single-junction solar cells under the standard AM1.5g spectrum with no light concentration of 33 percent (Würfel, 2005). AM1.5g spectrum defines the direct optical path length through the Earth's atmosphere for a zenith angle of 48.2°.

The underlying detailed balance approach, which was developed by (Shockley & Queisser, 1961), assumes an idealised solar cell composed of perfect and in particular direct semiconductor material with the optimal bandgap (1.34eV). Semiconductors like silicon and Gallium Arsenide are close to this optimal bandgap.

However, as silicon is an indirect semiconductor, the theoretical efficiency limit is significantly lower due to inevitable recombination losses. This leads to a theoretical cell limit for crystalline silicon solar cells of 29.4 percent under AM1.5g (Richter et al., 2013)(Glunz et al., 2014). For crystalline silicon solar cells in the laboratory it is assumed that 28 percent could be reached. The industrial cell limit is seen by 26 percent (Swanson, 2005). Inevitable losses in the module cause a further reduction leading to an industrial module limit of 25 percent. It could be assumed that such high-end modules will be available in 2050. However, an industry standard of 24 percent is assumed for 2050.

2.3 Simulation programs

Simulation is the representation of a real world process or system through use of another system, for example a computer program designed for that purpose. It is a technique for modelling and investigating systems or processes performance. Simulation has many applications across the engineering fields i.e. computer and communication system, manufacturing and material handling, automobile industry, transportation, health care and many more fields.

Recent advancements and technical development in the field of simulation modelling made it popular and today is the most widely used and accepted tool in the system analysis, research and development. Today's market is continuously increasing in the number of simulation softwares available and the use of these simulation softwares is easier due to their availability in many platforms, this is the reason why the market has specific simulation software for each specific task.(Sharma, Verma, & Sing, 2014)

A commercial demand of analysis and planning softwares for the calculation of small installations such as installations for private owners and small businesses, investing on small to medium grid-connected or building integrated systems, has led into the development of many PV analysis and planning software packages, mainly designed to be used for the design of technical and economical projects by the PV installers and architects, especially during the initial design phases of a project.

In the field of study of this thesis there are around fifty small or large simulation softwares, which basically are categorized in simulation tool, economic evaluation tools, photovoltaic industry related tools, analysis and planning tools, monitoring and control tools, solar radiation maps and some other online softwares. (Sharma et al., 2014) The software required for this study is an analysis and planning tool to help to analyze where the installation can be improved and to study which is the best configuration of components.

There are several programs that could be used to solve our problem: PVSYST ("PVsyst program," 2016), PV F-CHART ("PV F-chart program," 2016), Solar Pro ("Solar pro program," 2015), PV*SOL expert ("PV SOL PREMIUM," 2015), Polysun ("polysun," 2016), pvPlanner ("PVplanner program," 2016), Archelios ("archelios pro program," 2016), BlueSol ("bluesol," 2013), DDS- CAD PV ("DDS-CAD PV," 2016), Solarius-PV ("Solarius-PV program," 2016) and also TRNSYS despite it is not and analysis and planning tool , it belongs to the simulation tools and is very used worldwide.

2.3.1 Polysun

The simulation program that is going to be used is Polysun, it is a well established standard software for a wide range of decentralized power generation components used by planners and engineers. Polysun offers a user-friendly but accurate prediction of the technical, economical and ecological performance of such systems. (Lacoste, Wolf, Witzig, & Mär, 2010)

The software offers catalogues with component data enabling to access the relevant physical parameters without the need to deal with various data sheets from the manufacturers. The graphical user interface as well as the internal software structure is based on a modular system approach. Polysun offers reliable yield-forecasts and, in particular, allows comparing different solar systems with one another.(Lacoste et al., 2010) Based on statistical weather data, the software is able to predict the solar energy production as well as the heating demand of the building and the sanitary hot water. The weather data generator, Meteonorm (The International Energy Agency (IEA), 2013)(Meteonorm, 2016) is included as an integral part of Polysun. Meteonorm produces a typical weather profile for a user-defined location interpolating between weather stations and satellite weather data. The software gives appropriate advice in designing renewable energy systems with the powerful wizard and a large database of examples for this means. In the wizard, the user can select the optimization target and Polysun gives a recommendation for the dimensioning of the relevant components.

One of the strengths of Polysun is that in addition to the energy calculations, it analyses the hydraulic topology on the thermal system and calculates the fluid flow in all pipes. It can be used to design applications for modern energy efficient buildings and combined photovoltaic and thermal systems. The simulation model therefore also includes pumps, three-way valves, heat exchangers and thermal storage tanks with stratification as well as the detailed control algorithms in the system. (Solaris et al., 2014).

2.3.2 Studies

Polysun has been used in many studies, "Fast simulation algorithm for PV self-consumption with heat pump systems: calibration methodology with comprehensive dynamic simulation model as reference" (Solaris et al., 2014), "Teaching Solar Thermal system design by use of simulation software" (Witzig, Geisshüsler, Lacoste, Kohli, & Wolf, 2009), "Comparison of Polysun simulation with direct measurements of solar thermal system in rapotice" (Jelínek, Sedlák, & Lišková, 2014), "Dynamic simulation of a PV-diesel-battery hybrid plant for off grid electricity supply" (Yilmaz, Ozcalik, Aksu, & Karapinar, 2015), "The analysis on the impact of the roof angle on electricity energy generation of photovoltaic panels in Kahramanmaras, Turkey—A case study for all seasons" (Yilmaz, Ozcalik, & Dincer, 2015).

Also other softwares of its category, analysis and planning tools, have been used in different studies, "Accuracy analysis of software for the estimation and planning of photovoltaic installations" (Hasimah, Khalid, & Mohammad, 2009), "Operational Performance of Grid-connected PV Systems on Buildings in Germany" (Jahn & Nasse, 2004) but their accuracy as a complete software package against real-world data has not been assessed.

(Axaopoulos, Fylladitakis, & Gkarakis, 2014) examined the accuracy of TRNSYS, Archelios, Polysun, PVSyst, PV*SOL and PVGIS(online tool that it is not at the same level of calculations as the rest of softwares) in comparison to the real electrical energy generated by a grid-connected 19.8kWp photovoltaic installation in Greece. In their study, the software packages are being assessed only for their calculative accuracy, other criteria, such as the user interface, features and support, are beyond the scope of their study.

The climatic data for the area of their study was extracted from the PV park log files they had in the field, which contained the global irradiation received on horizontal surface, the irradiation on the inclined surface at 30°, the ambient temperature, the module temperature and the wind speed all in hourly values for a full calendar year.

Two parameters have been the criterion for comparison of the different softwares of the study: the accuracy of the calculated energy generation and the calculated received global irradiation. For the calculation of the energy generation, the log file data has been included in each of the programs, to focus just in test the accuracy of the energy generation. One disadvantage of (Axaopoulos et al., 2014) study was that, at that time in which the study was carried out Polysun just allowed the entry of the monthly global irradiation on the horizontal plane, ambient temperature and wind speed. Now it would be possible to introduce the hourly data of the log files, so the results of nowadays should be more accurate.

Figure 5 shows the monthly deviation of the calculated global irradiation of each program compared with the calculated in the field on the 30° plane. Figure 6 shows the monthly deviation in the energy generation calculated by each program compared with the calculated from the measurements in the PV park.

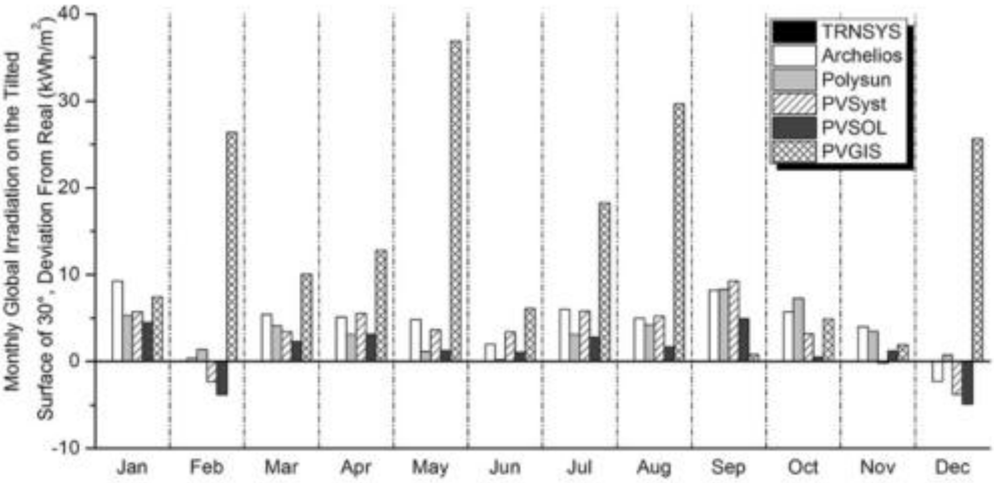
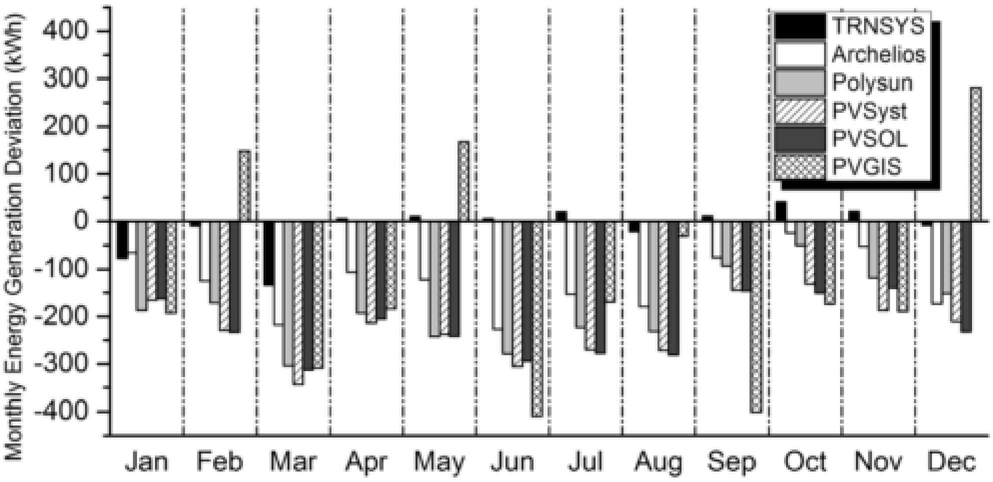


Figure 5 Monthly deviation of the calculated global irradiation on the 30° plane from the measured in the field.



(Axaopoulos et al., 2014)

Figure 6 Monthly deviation of the calculated energy generation from the measured in the PV park (Axaopoulos et al., 2014)

Their study concluded that combining both the accuracy of the calculated energy generation and the calculated received global irradiation, Polysun appears to be the most accurate software amongst the PV analysis and planning applications. Polysun displayed the second most accurate energy generation results and, at the same time, the second most accurate received global irradiation results as well. On the other hand, Archelios displayed the most accurate energy generation results but had the least accurate received global irradiation calculation, significantly over estimating the irradiation received by the system, while PV*SOL displayed the most accurate calculation of the global irradiation received by the system but the accuracy of the energy generation results was the second worst, excluding PVGIS.

Following (Axaopoulos et al., 2014) results, Polysun is the most accurate program tool of analysis and planning applications and because this reason is going to be the program used for simulations in this thesis.

3 System description

3.1 System of study

The system of study is a product of a Portuguese company named CRITICAL KINETICS. They call the system HOT PV 1500 and it is adapted to the Portuguese legislation of self-consumption.

The system seeks to increase the self-consumption rates compared with the production rates of the PV panels for self-consumption. This is achieved using the self-produced electricity to feed the heat pump which produces the Domestic Hot Water (DHW). As it will be shown, the installation does not have batteries so there is no way to store electrical energy itself. Because of the heat pump, only sensible thermal energy can be stored. This backup makes possible the store of energy when the production of electricity of the PV panels is higher than the consumption of the home appliances, in this case the excess of electricity produced goes to the heat pump avoiding the waste and reducing the purchase of electricity from the grid.

A key device in this system is Solar LogTM, it is a yield monitoring system that reads the production and consumption of the system. This device make possible to manage the energy flows to improve the self-consumption making the return period smaller and increasing the amount of energy self-consumed. Figure 7 shows an scheme of how the system works

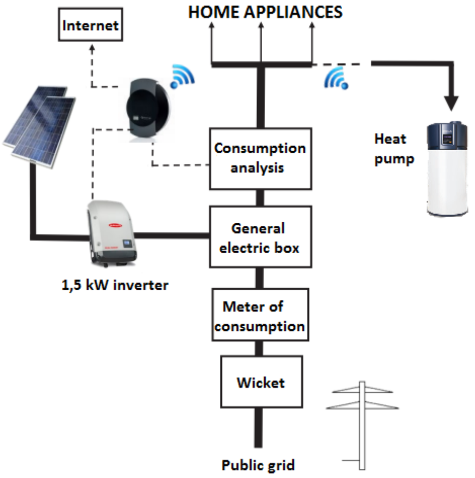


Figure 7 Scheme of the system of study.

Devices of the system of study

The product of SOLAR KINETICS includes.

1) PV panels with a power of 1500Wp
2) Inverter of 1500W
3) Electric box and DC cables
4) Aluminium mounting structure of the PV panels
5) Solar-Log 300 Meter^{TM}
6) Heat pump

PV panels

The panels of the installation go to a maximum of 1.5 kWp. The features of PV panels that are used in the system are shown in annex A.

Inverter

The inverter converts the DC current in alternate current (AC) current as the PV panels produce DC current and all home appliances use AC current. For this system just one inverter or a group of microinverters are used.
Microinverters have higher lifetimes because they do not reach high temperatures having better efficiencies than normal inverters. Nevertheless, they have higher prices.
The normal inverter datasheet of SMA and the microinvertes datasheet of INVOLAR used in the installation are shown in annex A.

Solar-Log 300 MeterTM

Self-consumption can be measured and displayed as a graph with an energy meter. Smart energy logics activate and deactivate individual appliances depending on the amount available energy. The Solar-Log 300 can be installed in plants with a maximum total power of 15 kWp regardless of the number of inverters. A Solar-Log scheme of work with a heat pump is shown in the figure 8.

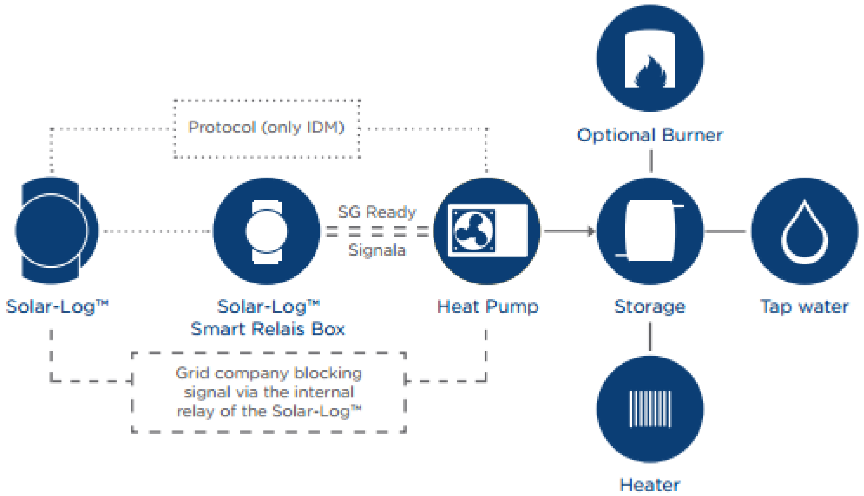


Figure 8 Solar-Log scheme of work with a heat pump.

The protocol connection to the IDM heat pumps additionally includes transferring the weather forecast data for the next 12 hours. This allows for foresighted planning for the efficient operation of the heat pumps.

Heat pump

The system uses an air-to-water heat pump, which means that the heat pump uses the warm from the air to transfer it to the water in the tank. The advantage of the heat pump to produce DHW is the coefficient of performance (COP), deeper information can be obtained (Tobergte & Curtis, 2013). The nominal COP of this machine is 3.6. Thus, the electric bills for the DHW get reduced by more than two thirds when compared to a regular electric water heater. The datasheet of the heat pump used for the system is shown in annex A.

3.2 System configurations

The demand of all the electricity needs of a house can be supplied in many different ways. In this section some configurations are explained. Five systems have been considered to study the impact of different variations of the devices of the system. Figure 9 shows systems A, B and C in Polysun. The five systems are:

A. The one in which this thesis is focused (see section 2.4).
B. A house with 2 solar thermal panels and a tank to accumulate the DHW with an electric boiler to produce DHW when the solar panels cannot.
C. A house with photovoltaic panels which feed first the home appliances and use the excess of production to feed an electric boiler. This system has also the solar-log to control the production and consumption. Normally this system would not have the solar-log but it is good to see how much savings there are in the first system because of the heat pump alone.
D. This system has not self-production, which means that all electricity is been taking from the electric grid. To produce the DHW an electric boiler is used. This system is used to compare how much savings the other systems have in comparison with a system without self-consumption. This system is similar to system C but without self-production.
E. The system is similar to system A but there is not self-production. It is also similar to system D as all the electricity need is purchased from the grid but the DHW is produced with a heat pump.

Simulations are carried out with the same consumption profiles for DHW and electricity for other appliances. The DHW profile is the H45 of Polysun which describes a family with working parents and two children in a residential building. The yearly consumption of the electric profile is 2000 kWh and for the DHW profile, the needs in hot water are 2000kWh (200l/day at 40˚C). The location for all simulations is Alameda neighbourhood in Lisbon where Instituto Superior Técnico (IST) is located. Panels are tilt 33˚ facing south. The number of panels for both PV and thermal are 6 PV panels (9.9 m^2) and 2 thermal panels (4m^2) respectively. This assumption is used trying to fit the self-production for a house of 4 people.

The payback periods of each of the installations are studied. An inflation rate of 2% and the prices of EDP for a contracted power of 3.45 kVA are used to calculate the savings in the future electric bills. The net present value (NPV) of each of the future savings is calculated to get the return period.

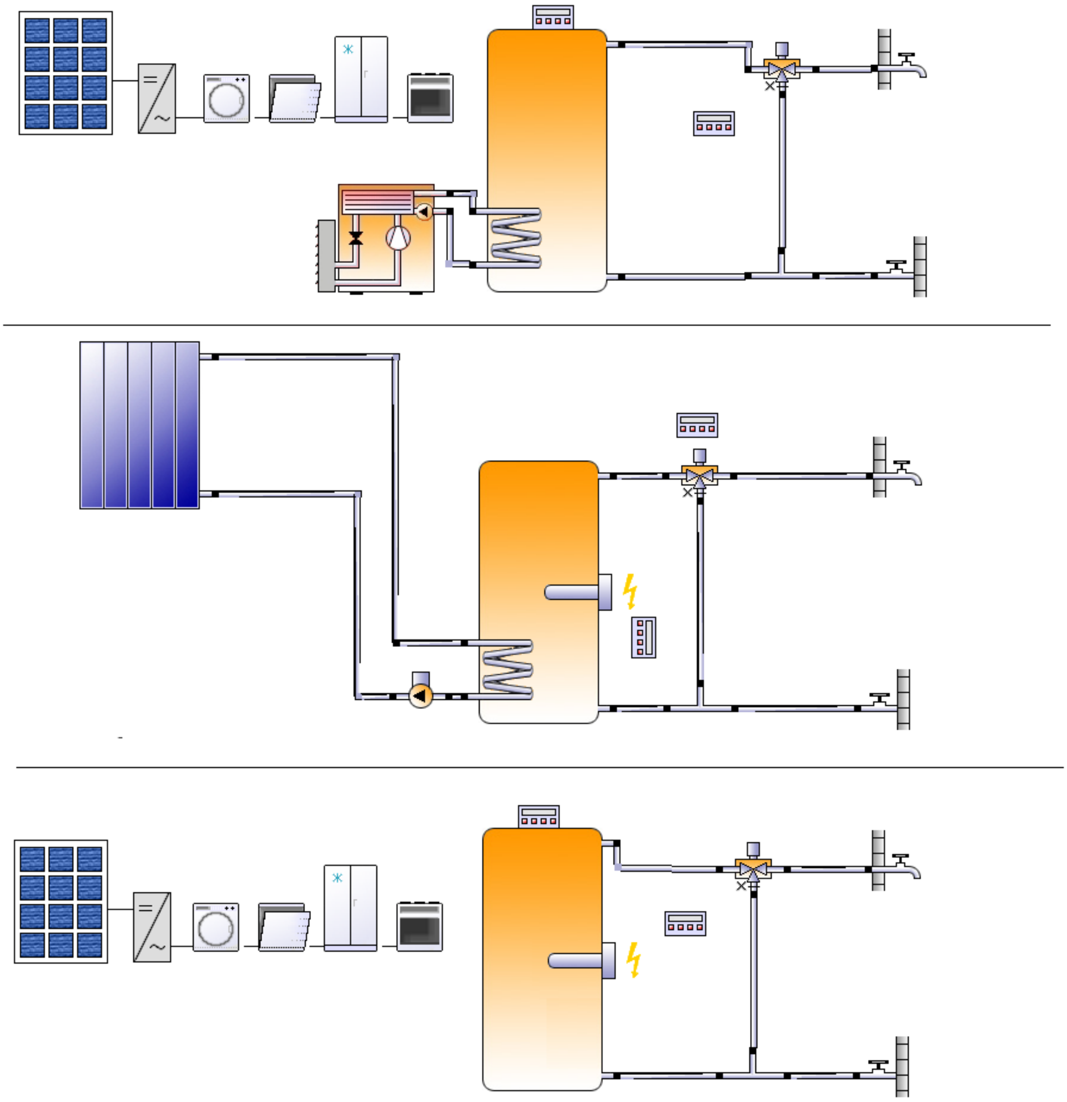


Figure 9 Configuration of each of the systems A, B and C, respectively.

3.3 Parameters that influence the energy production of the system.

3.3.1 Location of the system in the Iberian Peninsula

Weather conditions are the most important determining factor for electricity production of an installation, so the study of these factors is crucial to establish the behaviour of the system. Variations of the output voltage and current of the modules occur with different weather conditions.

This study is focus in the Iberian Peninsula which includes Portugal and Spain. There are some similarities in temperatures and irradiance values of Spain and Portugal. However, Spain has some areas where extreme temperatures and irradiance values are reached both the lowest and the highest of the Peninsula. Wind values are in general similar in Spain and Portugal

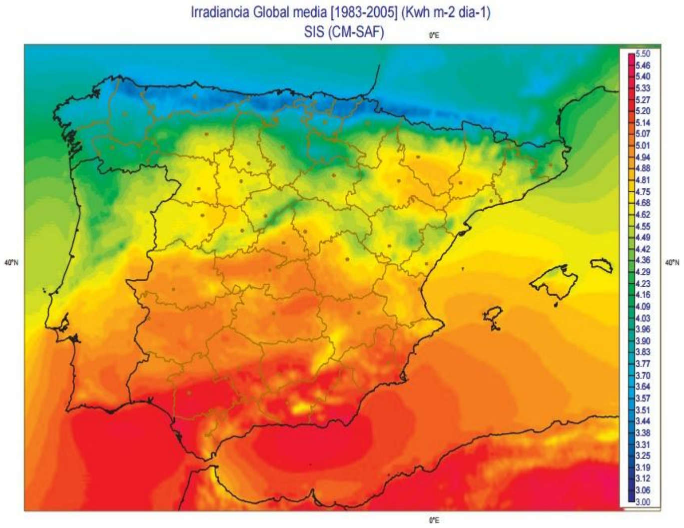


Figure 10 The average global irradiance from 1983-2005.(Im & AEmet, 2011)(Sancho et al., 2012)

Differences in global irradiances and direct irradiances depending on the latitude in the Iberian Peninsula are found as can be seen in figure 10, where highest values are in Andalusia and Murcia, the lowest values are in the north shore of Galicia, north of the Cantabric mountain range, Vasc Country and the Rioja and intermediate values are in the center of the Peninsula. (Sancho, Riesco, & Jiménez, 2012)

Module temperature depends on irradiance, ambient temperature and ventilation.(Mayfield, 2012) Figure 11 shows the average temperatures in the Iberian Peninsula. Annual average values for mean air temperature in the Iberian Peninsula vary between values below 2.5 °C in areas of high altitude in Spain (Pyrenees) and values higher than 17 °C, seen in the Spanish provinces of Huelva, Seville, Cadiz, and part of the coastline between Malaga and Alicante. In the simulations the dissipation value can be chosen in Polysun. It can be set in three different positions, poor, medium and good. For these different positions the increase of the module temperature from the ambient temperature is 20, 30 and 40 degrees Celsius respectively. In all simulations the heat dissipation parameter is set as medium.

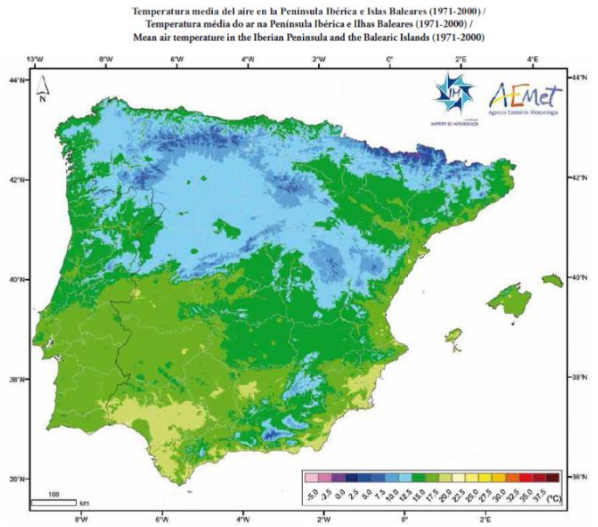


Figure 11 Average temperatures in the Iberian Peninsula from 1971-2000. (Im & AEmet, 2011)

The module voltage is affected by the module temperature. The change in voltage of the module determines the system voltage and therefore the design of the entire PV system. In particular, the increase in voltage at low temperatures should be taken into account. When several modules are connected in series, this amount can increase enough to exceed the voltage resistance of downstream devices. The current hardly changes with changes in module temperature. It increases slightly with increasing temperature.

The yield of a solar system can be calculated by means of the H.G. Beyer model.(Beyer et al., 2004) This model relies on the following inputs: 3 efficiency readings for the module at different irradiance conditions, 3 efficiency readings for the inverter with different loads, the installed power and the module's temperature coefficient.

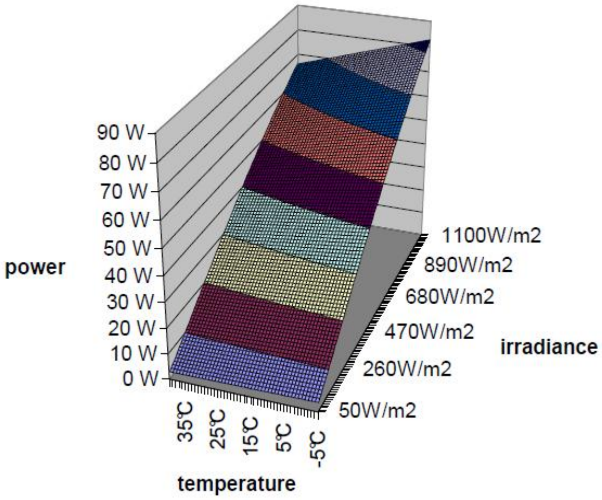


Figure 12 Influence of irradiance and temperature on a crystalline module.

Energy production increases approximately linearly with irradiance. Influence of temperature affect less the production and is dependent on the type of cell technology. A temperature increase of 10°C will cause, for example, the energy production of crystalline cells to be cut back by about 4 to 5%. (Velasolaris, 2015) Figure 12 shows a graphic that illustrates the variation of power in function of irradiance and temperature for a crystalline module.

In relation with the irradiance, five locations with different values of irradiances have been chosen in the Iberian Peninsula in order to see their performance in the simulations. Table 4 shows the coordinates of each place, their average, maximum and minimum temperature and the average radiation they have.

	Radiation	Temperature			Coordinates		
Place	Averg. [W/m2]	Averg.	Max.	Min.	Latitude	Longitude	Altitude
Berasategui, Spain	251	13	33	-4	36.419	-6.149	4
Salomonde, Portugal	314	13	33	-3	37.011	-8.940	1
Sintra, Portugal	340	17	36	5	38.803	-9.382	193
Chiclana de la frontera, Spain	363	18	37	4	41.682	-8.092	607
Sagres, Portugal	384	18	36	6	43.124	-1.979	491

Table 4 Latitude, longitude and altitude of the places of study.

In the simulations the same parameters are used in all the cases in order to make the results comparison reliable for every place of study. The installation has 6 photovoltaic panels facing south and tilted 33°. The profiles of consumption are H45 for electricity of the home appliances which is the profile of a family with two children and working parents. For the DHW a residential profile of consumption where 200 litres of water at 40°C are daily needed is chose. The electricity needs to produce all DHW will increase in places where the temperatures are lower because the water from the network would have lower temperatures.

The payback periods of the installation in the different locations are calculated. The price of the whole installation, including BOS, with six PV panels is considered 4840€.

In the results, monthly values are calculated taking in to consideration the hourly results of Polysun. In the case of the values which are just interesting during the hours of sun as module efficiency, inverter efficiency and radiation and arithmetic mean of all monthly values is calculated for day light hours.

3.3.2 Stratification in the DHW tank

Stratification is a physical phenomenon which consists in the layering of bodies of water based on their temperature. Stratification in hot water tanks separates lower density hot water that floats to the top of the tank from higher density cold water that sinks to the bottom with a mixing layer in between.

An important phenomenon to be explained is why the stratification affects positively the behaviour of the water tank and the installation. (Laine, 2015) shows how the stratification enhances the use and production of hot water of the installation in solar thermal hot water systems.

The first advantage of the use of stratified tanks is that it is easier to get more often the set point temperature. Domestic hot water is obtained by mixing hot water from the top of a tank, and cold water from the water supplier. If the temperature at the top of the tank is not high enough to provide the needed temperature, the auxiliary heat has to turn on and supply heat to the top part of the tank. The average temperature at the top of a stratified tank is generally higher than in a comparable mixed tank. Thus, the set point temperature is more often available in a stratified tank. Therefore, the use and cost of auxiliary heat will be less for a stratified tank, when compared to a mixed tank.

The second advantage of use stratified tanks is the presence of less lime scaling. In the lifetime of a hot water tank, the water consumption and following the volume of circulated through a thermally stratified tank is less compared to a mixed tank. The reason is that the temperature in the top part of a stratified tank as well as the outlet from the tank is higher, and therefore less volume of hot water is needed in order to supply a certain temperature. The additional consumption of water from a mixed domestic hot water tank, and following the additional refilling of lime containing fresh water, will increase the lime scaling in the tank. Scientific studies indicates that the lime scaling in a low flow system can be 2.5 times less, than in a comparable mixed tank.(Furbo, 2004)

The third advantage is the need of smaller tanks. As argued above, the higher the temperature is in the top part of the tank, the less volume of hot water is needed in order to supply a certain temperature. Therefore, smaller (cheaper) tanks can be applied to a certain system offering the same DHW, when the tank is thermally stratified, compared to a mixed. Furthermore, the reduced volume of circulated water in a thermally stratified tank, will cause fewer disturbances of the thermal layers, and therefore further enhance the stratification of the tank.

The most recent assessment of performance improvements indicates a potential of up to 10 – 25 %(Laine, 2015). A 10 – 25 % performance therefore appears to be a reliable interval when discussing the possible performance improvements associated with establishing thermal stratification. The large potential does indeed justify the application of stratification enhancers in commercial hot water storage tanks.

(Altuntop, Arslan, Ozceyhan, & Kanoglu, 2005) analyze in a experimental and numerical model study the effect of using different obstacles on thermal stratification in a cylindrical hot water tank. The temperature distributions within the tank for 12 different obstacles inside the tank, like the ones can be seen in figure 13, and for no obstacle are obtained and compared to find the configuration that most improve the stratification. As a result, higher thermal stratification is achieved with obstacles close to the cold water inlet of the bottom. The obstacle types having a gap in the centre appear to have better thermal stratification than those having gap near the tank wall. Figure 13 shows three different types of obstacles.

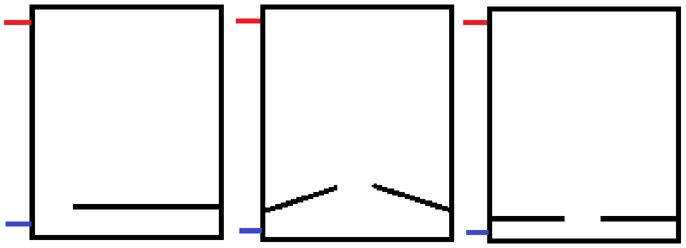


Figure 13 Hot water tanks one with a gap in the tank wall and two with the gap in the center

A comparisons of the two tanks with better performance, middle and right tank of figure 13, in terms of the temperatures of hot water supply indicate that the right tank obstacle provides the best thermal stratification among all the considered cases.

(Fernandez-Seara, Uha, & Sieres, 2007) studied the dynamic operation of a full-scale domestic hot water storage tank with a capacity of 150 l equipped with three different inlet and two outlet ports for draw-off flow rates of 5, 10 and 15 l/min. In the figure 14 can be seen a section of the tank.

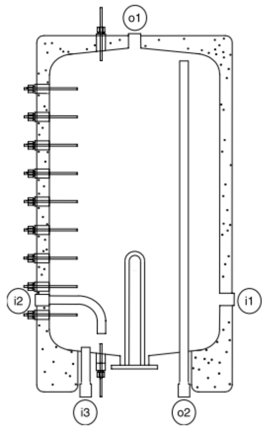


Figure 14 Tank of the study of the study (Fernandez-Seara et al., 2007)

The conclusions of this study are, firstly, the outlet o1 performs better than outlet o2 regardless of the inlet used since it avoids the heat exchange of the exiting water with the remaining water in the tank. Secondly, inlet i2 performs better than inlets i1 and i3 since it provides the highest thermal energy and exergy efficiencies and the best thermal stratification of the water in the tank. Therefore, i2–o1 inlet–outlet port configuration provides the best performance among the different ports arrangements tested.

(Hariharan, Badrinarayana, Srinivasa Murthy, & Krishna Murthy, 1991) have carried out experiments on a scale model of stratified hot-water tanks. The storage tanks are cylindrical vessels made of stainless steel, each having 6 Litres capacity but with different geometries (L/D) values of 1.56, 2.06, 3.54 and 4.00. Two pipes located at the top and bottom allow simultaneous charging and discharging experiments. The D/d ratios for all of the tanks are maintained constant, being “D” the inside tank diameter and “d” the inside diameter of the distributor pipe. In the experiments L/D ratios are studied (1.56, 2.06, 3.54 and 4.0).

The results of this experiments show that stratification improves with increasing L/D ratios, but deteriorates at the greatest L/D of 4.0. The lack of stratification becomes more apparent for high L/D values when the flow rates are higher. Under the experimental conditions of this study, L/D values between 3 and 4 seem to be optimal.

(Spur, Fiala, Nevrala, & Probert, 2006a) studied and validated the enhancement of a TRNSYS simulation model of the behaviour of a domestic hot-water store, with an immersed heat-exchanger. This model simulates the dynamic heat-depletion and recovery processes in the immersed heat-exchanger and predicts the transient temperature-patterns for various domestic hot water draw-off versus time profiles. For the comparison of the different profiles they used a methodology based on different parameters such as unsupplied volume or energy.

The differences of efficiency between studied profiles were significant, and a variance of 13.3 % was found between two different profiles.

Also (Spur et al., 2006a) concluded that the immersed heat-exchanger coil should be located in the upper region of the hot-water tank to achieve high heat-extraction rates from the tank water. This assertion was also found in (Laine, 2015) where they said that locating the heat-exchanger in the bottom of the tank will disturb the thermal stratification.

The studies that checked the performance of the heat exchangers inside the water tank do not have the same system configuration as this study. For example in (Spur, Fiala, Nevrala, & Probert, 2006a) they keep the hot water inside the tank and the DHW flows through the heat exchanger. To check the results for the system of study, a simulation in Polysun was carried out for three different heat exchanger positions in a tank of 300 litre. The location of all simulations is Lisbon, Alameda neighbourhood (Portugal) where the IST is located. The number of PV panels is 6 with 250 Wp each. They are facing south and tilt 33 degrees. All these values are equal for each of the different heat exchanger positions. Figure 15 shows the configuration of the systems to simulate with different heat exchanger.

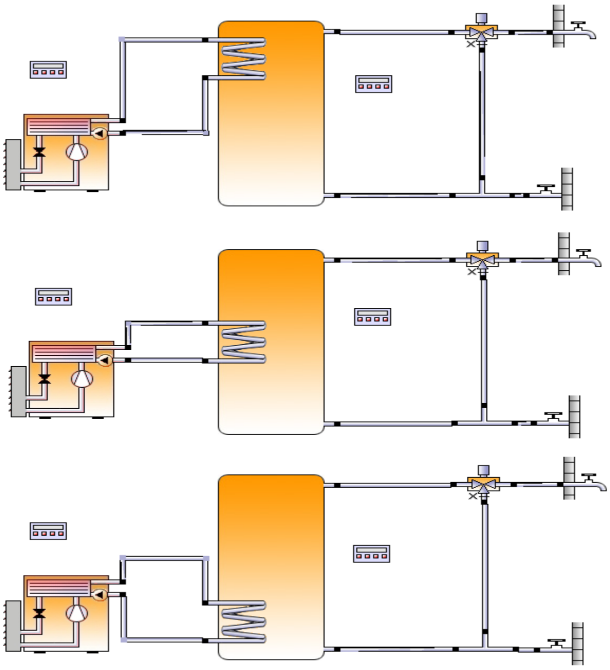


Figure 15 System configuration of the stratification simulation with different heat exchanger position in Polysun.

For the domestic hot water profile consumption was chose the profile of the EU reference(EU M324EN) tapping cycle number 3, featuring 24 draw-offs with the energy output of 11.7 kWh equivalent to a total volume of 200L at 60˚C daily. (Health, 2004) This DHW profile is used for the labelling and to make the technical datasheets of the DHW tanks, this is the reason of why this profile is chosen in this case to study the performance of the heat exchangers in the tank.

3.3.3 Consumption profiles.

Different consumption profiles can affect the self-consumption of electricity, the electric profile of consumption of the home appliances (electric profile) and the profile of the DHW consumption (DHW profile).

Polysun has a large data base of profiles of consumption for both, the electricity profile and the DHW profile. These profiles of consumption are given in Polysun hourly in Watts for all year.

In the study, we assume that the electricity produced by the PV panels cannot be stored in batteries. Nevertheless, it can be stored as heat in the tank of the heat pump. This characteristic of the system gives preference to the electricity consumption to the home appliances and then, just if the electricity production is higher than the electricity consumption of the home appliances, it is used to feed the heat pump.

In order to compare how the electricity profile of consumption can affect the self-consumption, three different simulations with different electric profiles but with the same DHW profiles are carried out in Polysun. The three different profiles were chose from Polysun data base and they are the H45 which is the profile of a family with two children and working parents , the profile G0 which is for an average commercial activity and the profile H11 that is for a student house. For the DHW profile a residential profile is chose. Join the electric profile of an average commercial activity with a DHW profile of a residential building is made to show how this particular electric consumption profile affect the self-consumption of the system.

The location of all simulations is Lisbon, Alameda neighbourhood (Portugal) where the IST is located. The PV panels have 250 Wp, they are facing south and tilt 33 degrees. The number of panels in all simulations varies from 3 to 8 to see how increasing the number of PV panels increases the self-consumption and also the impact in the payback period.

The DHW profile of consumption requires less energy than the home appliances due to the HP. Also thermal capacity of storage makes the DHW production more flexible. These two facts make the variation of the self-consumption of the DHW profile difficult.

For the test case of a house of 4 people, the electricity needs to cover all the consumption of the home appliances is 2000 kWh/year and the electricity needs to produce all the DHW is 860 kWh/year including energy losses. As the DHW is stored in the tank, the self-consumption of the DHW profile is adapted to the self-consumption of the home appliances. So the DHW is produced when there is electricity production from the PV panels and not consumption in the house. Therefore, DHW is very flexible to be produced and it has high rates of self-consumption making its improvement difficult.

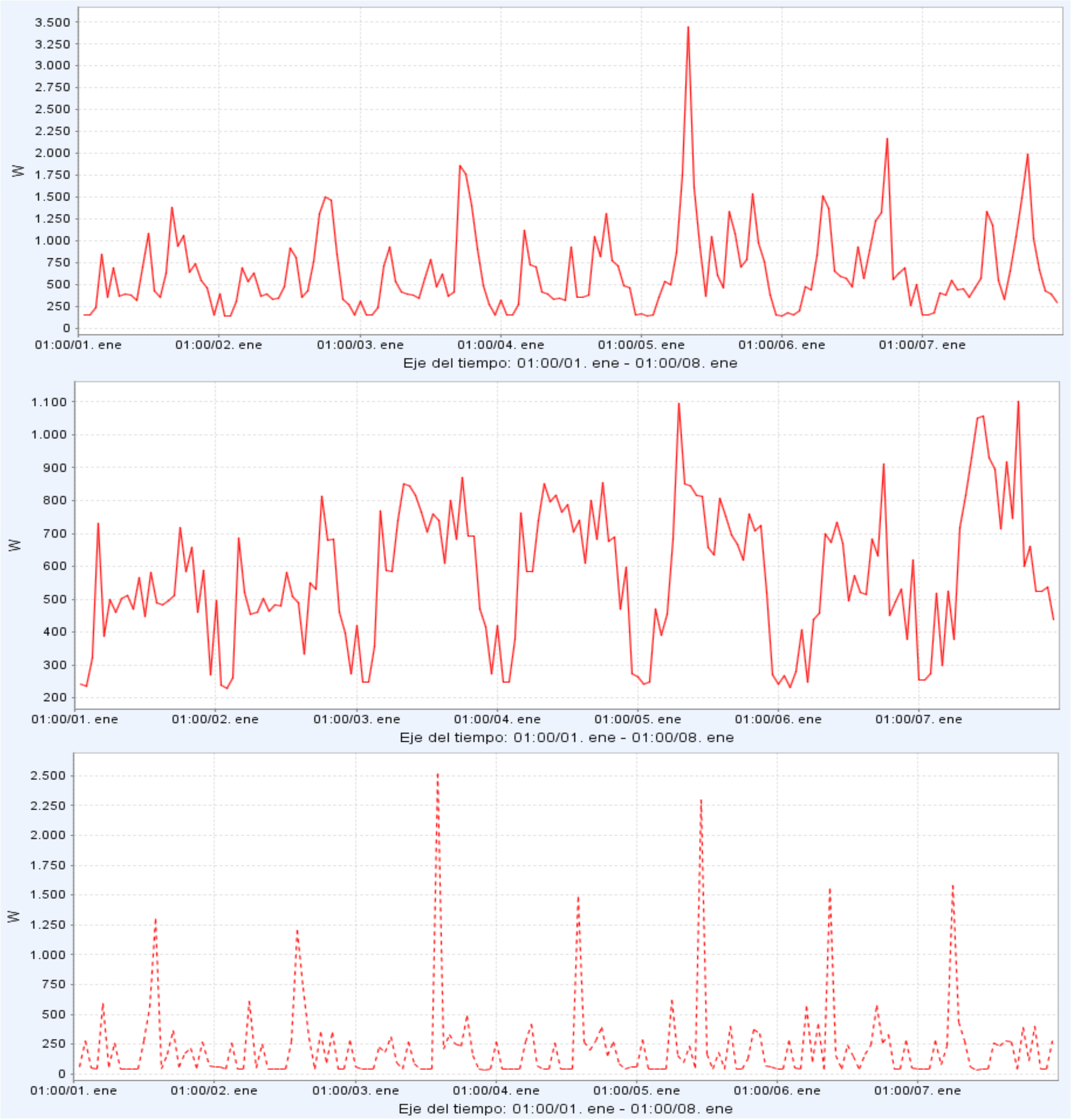


Figure 16 From top to bottom Polysun H45, G0 and H11 electricity consumption profiles for the first week of the year. (Polysun graphics).

Figure 16 shows the three consumption profiles for the first week of the year as consumption profile needs vary each of the 365 days of the year. It can be seen that in the profile H45 the consumption peaks reach higher values than G0 and G0 profile has normally higher values than H11. H11 profile has smaller peaks of consumption more spread during the day also having these small peaks during the night. Daylight consumption of G0 is normally around 600 W, for H45 is normally under 500W, and for H11 small peaks go till 250 W. Profile H11 has one time per day higher peaks that can go till 2500 W. G0 has higher daylight consumption than any other profile.

4 Results

In section 3.1 simulations are carried out to show the different systems needs of electricity from the grid and the self-consumed energy. Also an economical assessment of the payback period of each system is done.

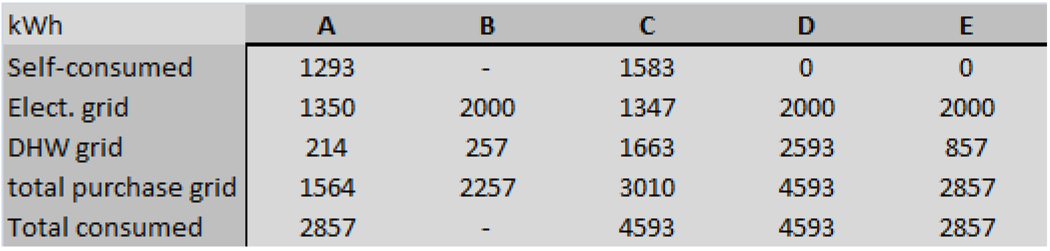
In section 3.2.1, monthly radiation and autoconsumption for each place of study are discussed. Also, for each location, how the temperature of the panel affect the efficiency is reviewed. The comparison of the self-production and self-production is exposed in a table. Lastly payback periods depending on the location are also shown.

A study of the auxiliary energy need to cover certain profile of consumption with three different heat exchangers is done in section 3.2.2.

Section 3.2.3 shows the domestic self-consumptions for the different electric profile of consumption for different number of PV panels. An economical assessment is done to study if optimum payback periods can be found. The future savings in the electric bills are also reviewed and exposed graphically.

4.1 System configuration

Systems with the heat pump, A (PV+HP) and E (HP), have a reduction in the yearly electric consumption to produce DHW of 1736kWh. This can be seen in the values of “total consumed” in table 5. “Total consumed” make reference to the total electricity in kWh that the system need to cover the profiles of consumption. In the case of system B there is not number because the thermal panels. “self-consumed” is the total electricity in kWh self-consumed from the PV panels. Finally “Total purchase grid” values are the addition of “Elect. Grid” and “DHW grid” that are the energy purchase from the grid to cover the electricity profile and the DHW profile respectively.



kWh	A	B	C	D	E
Self-consumed	1293	-	1583	0	0
Elect. grid	1350	2000	1347	2000	2000
DHW grid	214	257	1663	2593	857
total purchase grid	1564	2257	3010	4593	2857
Total consumed	2857	-	4593	4593	2857

Table 5 Overview of consumptions for all systems.

System A has the smallest purchase of electricity to cover the same electric and DHW profiles, follow it by system B (thermal), E, C (PV+ elect. resist.) and D (elect. resist.), respectively.

Figure 17 shows the annual electricity self-consumption of each of the five systems as well as the annual purchase from the electric grid. System B does not use electricity to produce DHW. This makes its self-consumption zero as it is just producing DHW from the thermal panels.

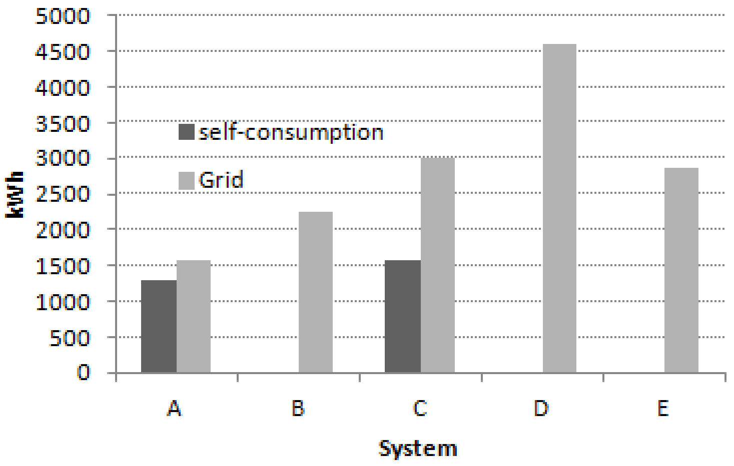


Figure 17 Self-consumption and grid purchase of electricity for systems A, B, C, D and E.

The decrease in the electricity needs for DHW due to the use of the heat pump reduces the self-consumption in the case of the system A but also the electricity purchase from the grid. Also a huge reduction of electricity purchased from the grid for production of DHW occurs in the system B where just 257 kWh are purchased from the grid. But also in system B, the lack of electric production make the system purchase all the electricity need for the home appliances increasing the electric bills.

In the case of system C the electric resistance to produce DHW needs close to 3.5 times more electricity than the heat pump to produce the same amount of hot water, which increase the purchase of electricity from the grid. Systems D and E have to get all electricity from the grid but they have high differences in the annual needs due to the way to produce hot water.

The equipment need to built a system sometimes depend on which system we have already as some devices are already installed. This would decrease the investment cost and also the total energy savings achieved as they have to be calculated considering the old system. Table 6 shows for each combination of changes of the systems of study: the devices need for each change, the cost of these devices, the savings achieved and the payback period.

For example, If the system would be installed in a new house (see table 6 lines A new, B new and C new), the self-consumption is considered to calculate the payback period and the price is the price of the whole system that for systems A, B and C is 4840 €, 3850 € and 3740€, respectively.

Systems	Devices needed	Cost	Savings	Payback
A new	PV+BOS+HP	4.840 €	1293kWh	23.1 years
B new	Thermal+ Elect.Boiler	3.850 €	-	-
C new	PV+BOS+Elect. Boiler	3.740 €	1583kWh	13.3 years
D-->A	PV+BOS+HP	4.840 €	3029kWh	8.6 years
D-->B	Thermal	2.950 €	2336kWh	6.7 years
D-->C	PV+BOS	2.840 €	1583kWh	9.8 years
E-->A	PV+BOS	2.840 €	1293kWh	12.3 years

Table 6 System configurations table, it shows: the devices needed for each change, the price of these changes , the savings achieved and the payback period.

If you have in your house already installed system D(Elect. boiler without panels) and you changed to system A (PV+HP), that means that you have to install 6 PV panels, the necessary BOS and a HP. So to calculate the payback period of this change, from D to A, the cost of the 6 PV panel, the BOS and the HP is divided for the difference of the energy purchased from the grid of system D and A. (see table 6 line D→A)

If the change would be from system D to system B (line D→B of table 6) , the price of the system would be the thermal panels as system D uses also the electric boiler to produce DHW. The savings would be 2336kWh and the price 2950€ as the price of the electric boiler is considered 900€.

If the change would be from system D to system C, as they produce DHW in the same way, with an electric boiler, to calculate the payback period the price of the electric boiler would not be consider. So this change would have 1583kWh of savings and a price of 2840€.

If the change would be from system E to system A, as they produce DHW in the same way, with a HP, to calculate the payback period the price of the HP is not consider. So in this case the price would be 2840€ as the price of the HP is consider 2000€.

The smallest payback period 6.7 years of table 6 happen for the change of systems D(elect. boiler + no panels) to B (thermal + electric boiler). This is because the savings achieved are the second highest of the table and the cost is the second lowest. System D produces the DHW with an electric boiler so that it is not needed to buy it to install system B reducing the cost. The second smallest payback period is for the change D to A. The cost of investment is the highest of the table but also the savings are the highest among all systems. The third smallest payback period happen for the change E to A, for this case the cost of investment is the smallest of the table. For new systems, the savings and payback period of system B are not calculated as the panels are not producing electricity. Finally, the system of study, system A, has a payback period of 23.1 years as a new system, being the system that less energy purchase from the grid 1564kWh (see table 5).

4.2 Parameters that influence the energy production of the system.

4.2.1 Location of the system in the Iberian Peninsula

Figure 18 shows the monthly average temperature of the module for each place. The maximum difference of temperatures in each place in winter is higher than the difference in summer, so the temperature of the panels in summer is closer along the Peninsula. Also this can be seen in figure 19 where module efficiencies in different places in winter are more different than in summer when all the curves are really close to each other.

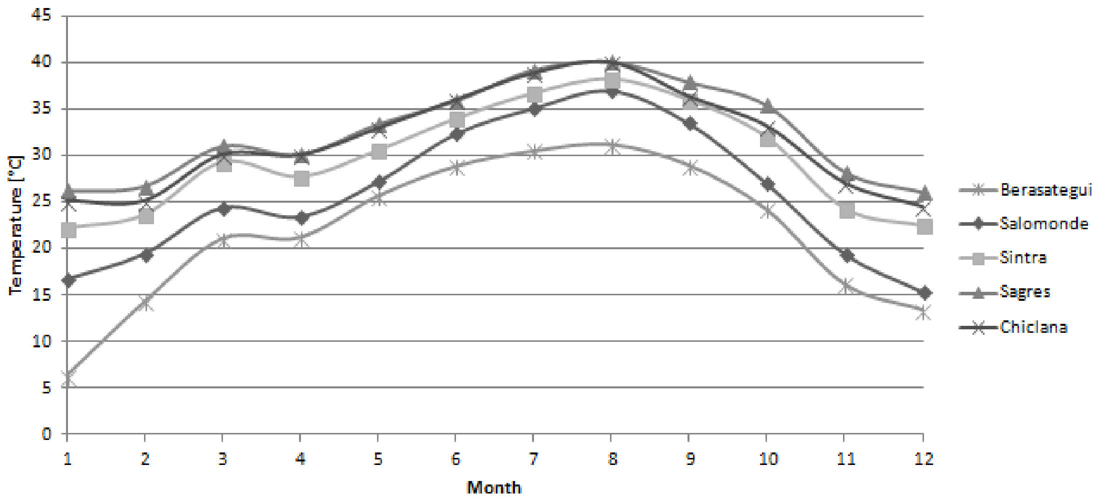


Figure 18 Panel temperature for each location during the year

Figure 19 shows monthly average values of module efficiency for each place. A decrease of all the module efficiencies for all place of study happens in the warmer months. Also it is visible that the module efficiency varies in all places of study during the whole year, between 12.6% and 13.8% so a difference of 1.2 %. It is also important to consider that the heat dissipation value is set in medium for all simulations, differences between winter and summer would increase if heat dissipation would change.

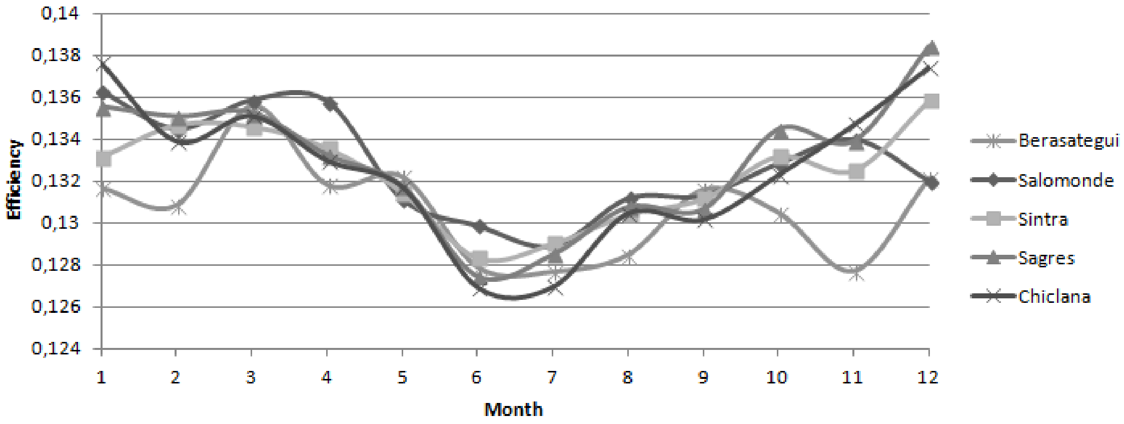
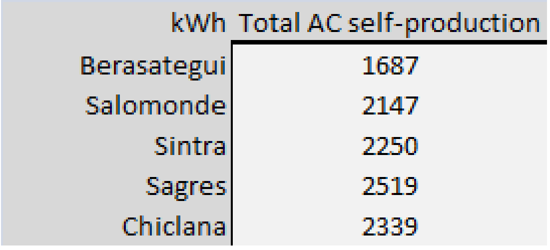


Figure 19 Efficiency of the panel during the year for all locations.

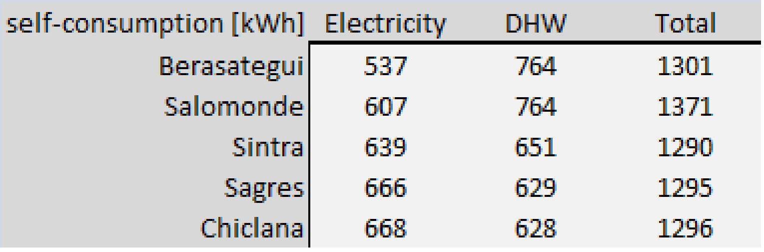
Table 7 shows the annual values for self-produced electricity. Southern places have higher rates of self-production than northern places. These values of self-production follow the same order from high to low as the values of averages radiations shown in table 4. This order is from high to low: Sagres, Chiclana, Sintra, Salomonde and Berasategui.



kWh	Total AC self-production
Berasategui	1687
Salomonde	2147
Sintra	2250
Sagres	2519
Chiclana	2339

Table 7 Total AC electricity produced by the PV panels

Although, southern places have higher self-productions, for all places the amount of energy that the PV panels are producing is higher than the amount of energy needed to cover the profiles of consumption. Nevertheless, due to the electricity cannot be store in batteries, the electricity that is not consumed instantly is always lost. This fact gives priority to consume the self-produced electricity in the electric profile. The self-consumed energy of this profile is slightly higher than a quarter in all cases of the 2000 kWh it needs (see table 8). The higher self-consumptions in the electric profile in southern places are because of the higher self-productions.

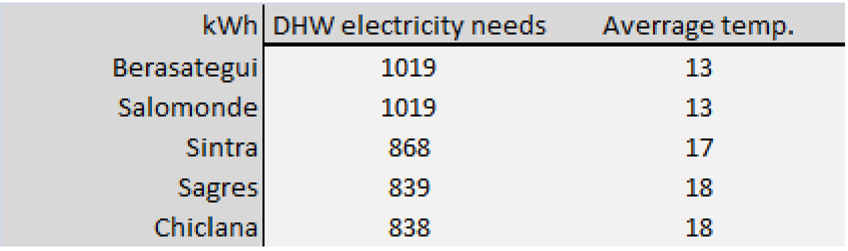


self-consumption [kWh]	Electricity	DHW	Total
Berasategui	537	764	1301
Salomonde	607	764	1371
Sintra	639	651	1290
Sagres	666	629	1295
Chiclana	668	628	1296

Table 8 Profiles and total self-consumptions.

The yearly energy needs to produce hot water depend on the ambient temperature (see table 9). The lower temperatures in the north of the Iberian Peninsula together with the flexibility for self-consumption to produce DHW because of the storage tank increase the self-consumptions for northern places even having less self-production.

The self-consumption among all studied places has a maximum difference of 81kWh that happen between Sintra and Salomonde. The payback period is affected by the self-consumption differences in a maximum of 1.65 years (see table 10).



kWh	DHW electricity needs	Averrage temp.
Berasategui	1019	13
Salomonde	1019	13
Sintra	868	17
Sagres	839	18
Chiclana	838	18

Table 9 DHW electricity needs and average temperatures by place.

Payback period	Years
Berasategui	22,9
Salomonde	21,45
Sintra	23,1
Sagres	23,1
Chiclana	23

Table 10 Payback period by place**.**

The northern places of the study have higher self-consumption and lower payback periods. The ambient temperature affect the efficiency of the panel decreasing it in warmer months but also affects the energy need to cover the DHW profile. Therefore, variations in the location of the system change its self-production but also the required energy to cover the profiles of consumption. A more appropriate installation for each case can be designed if the location of the system is studied. An increase in the self-consumption and a decrease in the payback period can be achieved adjusting the installation to each location.

4.2.2 Stratification in the DHW tank

Table 11 shows the results for the three heat exchanger positions inside the tank. The higher auxiliary energy need to cover DHW consumption happen for the bottom heat exchanger position, when the medium and upper heat exchanger have similar auxiliary energy needs.

	Bottom	medium	Upper
annual auxiliary energy for heating [kWh]	808	767	768
Upper tank temperature [°C]	62	62	62
Bottom tank temperature [°C]	58	18	18
ΔT beetwen the upper and bottom [°C]	4	44	44
Heat exchanged in the HX [kWh]	4411	3936	3936
heat loss in the tank [kWh]	502	220	220

Table 11 Values of the results of simulations to study stratification with Polysun.

Also the upper and medium heat exchangers have equal temperature differences between the bottom and the upper part of the tank of 44˚C. Bottom heat exchanger has just 3.7 ˚C difference of temperature between the upper and the bottom part of the tank. These big differences in temperatures between the medium/upper and bottom heat exchanger are because the bottom heat exchanger is located in the cold water zone and there, the heat exchanger is able to warm up the cold water.

For the same reason explained in the paragraph before, the heat exchanged in the bottom heat exchanger is higher than the one exchanged in the medium and upper, being this one 4411 kWh, 3936 kWh and 3936 kWh, respectively.

Also the annual heat loss in the tank is higher for the bottom heat exchanger because of the average temperature inside the tank is much higher due to its capacity to warm up the water located in the bottom. For the medium and upper heat exchangers the heat loss of the tank is less than half of for the bottom heat exchanger. Higher differences between the values of the medium and upper heat exchanger were expected but differences are not found between them in the simulations.

In the section 2.6.2 is shown some literature review to improve the stratification of the tank. Some features that increase the stratification of the tank are: set obstacles close to the cold water inlet of the bottom preferably those having a gap in the centre, set the inlet pipe facing down, set the outlet exit in the top of the tank and longitude/diameter (L/D) of the tank between 3 and 4.

From the results of the simulations can be extract that the bottom heat exchanger needs more auxiliary energy to supply all the domestic hot water consumption. Also the bottom heat exchanger tank would lose more energy due to the increase in the average temperature of the tank. So from the simulations and the literature review can be extracted that the best position for the heat exchanger in our system is in the top and medium of the tank, reducing the energy needs and also the heat losses.

4.2.3 Consumption profiles.

Figure 20 shows for a 4 PV installation the values of the energy consumed in the home appliances, for the DHW and the energy self-produced and not consumed. The self-consumption of the electric profile for the family with two children and working parents (H45), the commercial activity (G0) and the student house (H11) for 4 PV panels installation is 530 kWh, 981 kWh and 498 kWh, respectively. In the case of the average commercial activity profile, the electric self-consumption is almost double of the other two profiles 981 kWh, this is because the high consumption of electricity during the day light.

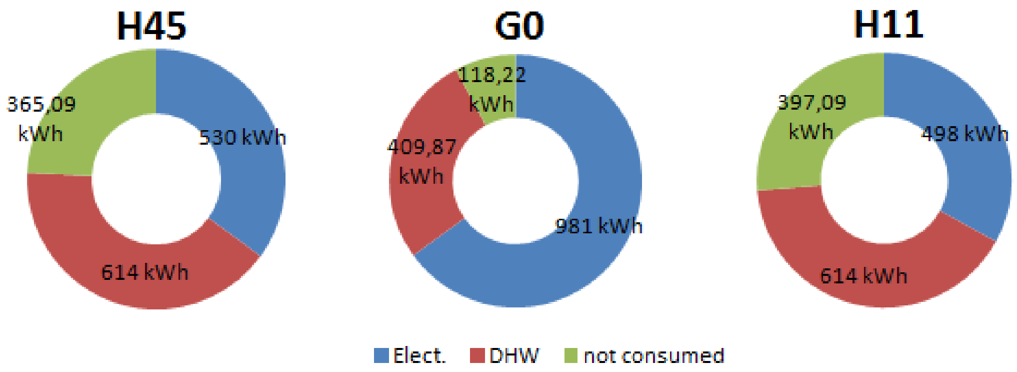
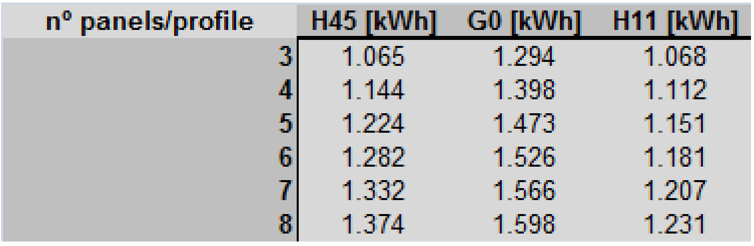


Figure 20 For a 4 PV panel installation values of energy not consumed, electricity self-consumed for home appliances and electricity self-consumed for DHW for H45, G0 and H11 consumption profiles.

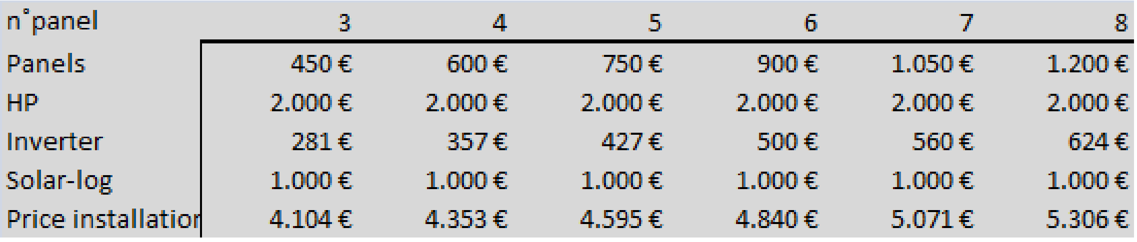
This increase of self-consumption during the daylight decreases the self-consumption for DHW that for H45 and H11 is around 614 kWh and for the G0 profile is 410 kWh. In the end, this decrease of self-consumption of the DHW profile for G0 shows a good result because the total self-consumption compared with the annual electricity produced by the 4 PV panels is much higher than in the other profiles, been 75.85%, 92.63% and 73.74% for H45, G0 and H11 respectively. Table 12 shows the self-consumption values for the three profiles for each number of PV panels.



nº panels/profile	H45 [kWh]	G0 [kWh]	H11 [kWh]
3	1.065	1.294	1.068
4	1.144	1.398	1.112
5	1.224	1.473	1.151
6	1.282	1.526	1.181
7	1.332	1.566	1.207
8	1.374	1.598	1.231

Table 12 Total self-consumption values for the three different profiles from 3 to 8 PV panels in the installation.

Additional economic calculations are done with prices extracted from the market. The price of the panels is considered to be 0.6 €/Wp. In the case of the inverter a reduction of the price per Wp is applied with the increase of the power of the installation. The price of the heat pump remains equal whatever is the power of the installation, since the heat pump does not change. Intelligent meter solar log has also a constant price. An increase of 10% in the price of all the devices is considered as the mounting price. Table 13 shows in detail all the prices.



n˚panel	3	4	5	6	7	8
Panels	450 €	600 €	750 €	900 €	1.050 €	1.200 €
HP	2.000 €	2.000 €	2.000 €	2.000 €	2.000 €	2.000 €
Inverter	281 €	357 €	427 €	500 €	560 €	624 €
Solar-log	1.000 €	1.000 €	1.000 €	1.000 €	1.000 €	1.000 €
Price installatio	4.104 €	4.353 €	4.595 €	4.840 €	5.071 €	5.306 €

Table 13 Detailed prices for the installations with different number of PV panels.

For some consumption profiles an optimum number of panels reduce the payback period of the installation increasing the importance of study the consumption profiles to design the installation.

The system in the study, because of the use of the heat pump to produce the DHW, needs around just one third of the electricity that an electric resistance would need to produce the same amount of hot water. This fact has to be considered to calculate the period of return of the system because it is not just important the amount of electricity self-consumed but also the amount of electricity that is not needed because of the improvements that the system has.

Many ways exist to produce DHW and each of them needs different amounts of electricity. For this reason, in the first place the return period of the system of study is just calculated considering the self-consumption. Then a brief explanation of how the payback period gets reduced with the consideration of the energy that is not needed by the system of study in comparison with a system that uses electrical resistance is shown.

Payback periods are calculated for 2%, 7% and 14% inflation rates (see figure 21). A 2% inflation is the average inflation of the last years two years for Europe electricity area (ECB, 2016). A value of inflation of 6.7% was reached in July 2008 at the beginning of the economical European crisis. A value of 14% is not in the European historical values of the European Central Bank but as the future is unknown it is included in the calculations.

The shortest return periods happen for profile G0, as his self-consumption is higher. For profiles H45 and G0 and optimum return period can be found, been the optimum number of PV panels for H45 5 or 6 depending on inflation rate, as can be seen in the first file of figure 21. For G0 profile, 4 PV panels is the optimum number for all inflations. Profile H11 has not an optimum number of panels between 3 and 8 PV panels configuration, so an increase in PV panels also increases the payback period.

It can be seen in figure 21 that as higher the inflation rate is as flattest the curves become. This happen because an increase of economical savings of the future electric bills makes recover the investment earlier making the payback time for all number of PV panels installation closer.

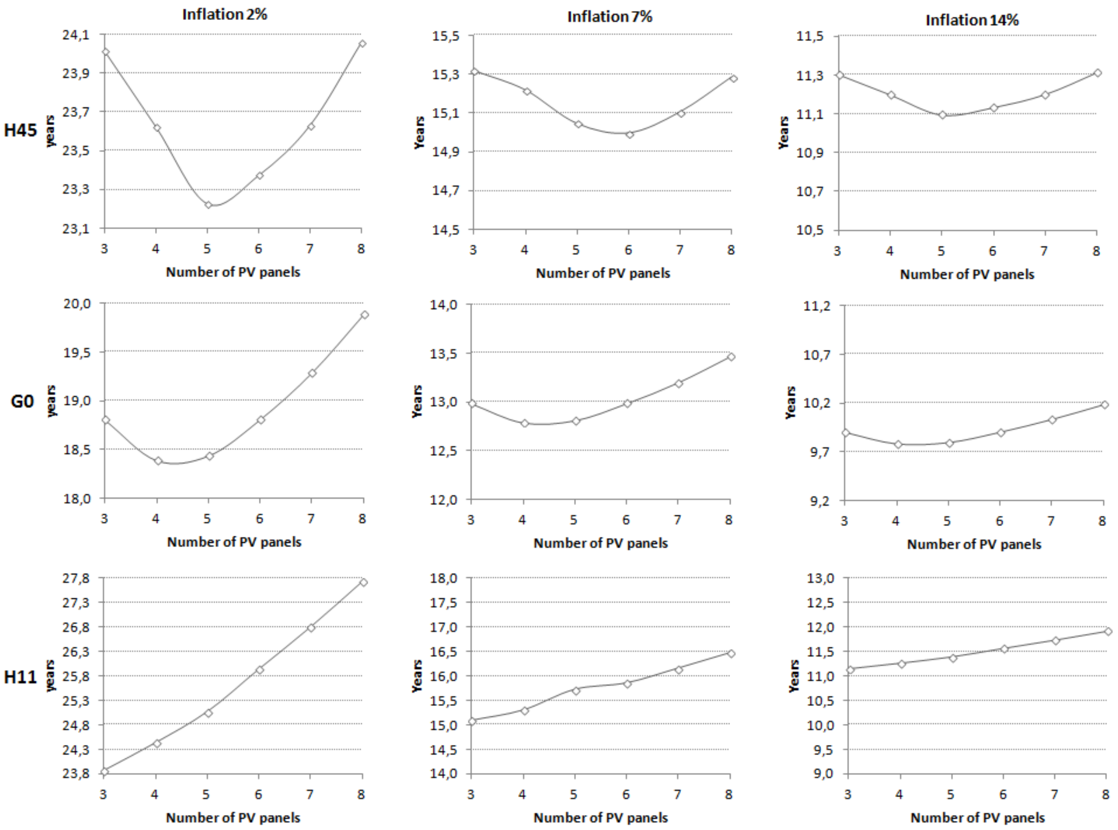


Figure 21 Payback time of the system in years. Columns from right to left show inflation rates 2%, 7% and 14% respectively. Files from up to bottom show profiles of consumption H45, G0 and H11, respectively.

The economical savings in 25 years for each inflation rate are shown in figure 22. In this figure, the graphic of 2% inflation, the payback period is higher than 25 years for 5 PV panel to 8 PV panel configurations in H11 profile, which makes unprofitable the investment before this period time and for this reason they do not have representation in the graphic. For all inflation rates higher savings are achieved for G0 consumption profile even reaching 5000 euro differences with the rest of consumption profiles.

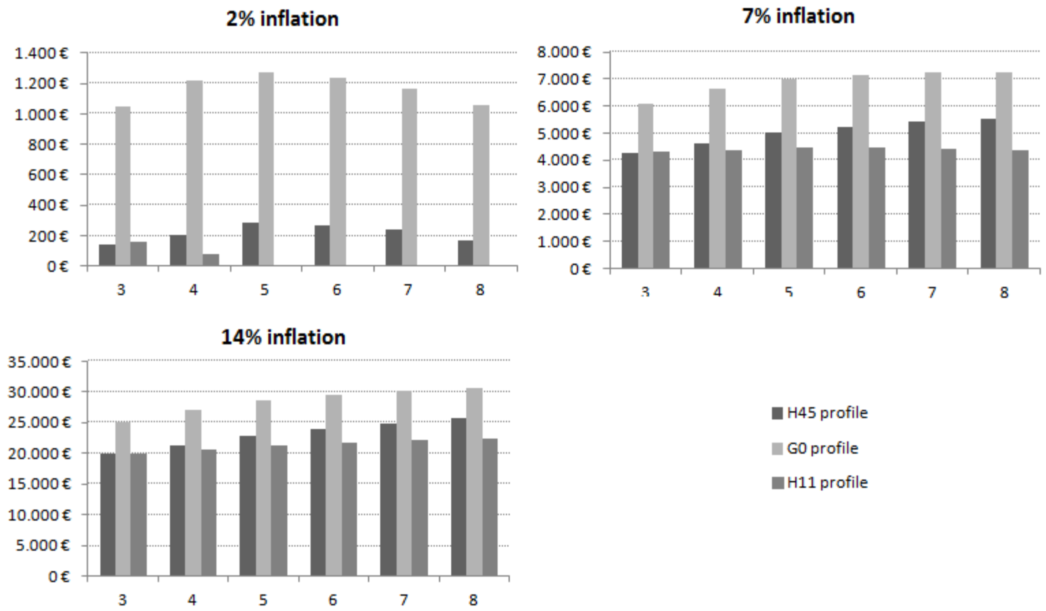


Figure 22 Total savings after 25 years for different inflation rates.

The electricity need for the system with the HP compared with the same system that produces DHW with an electric boiler is around one third. If the energy not needed for the system in comparison with the same system that produces the DHW with an electrical boiler would be considered for the payback period the maximum return period would be of 10 years and the minimum of 6 years considering all consumption profiles and inflation rates. Also higher economical savings in 25 years would be achieved if this amount is considered making the investment even more interesting.

It can be extracted from the results that the highest the electricity consumption is in the installation during the day light, the highest the self-consumption is.

For H45 and G0 consumption profiles, an optimum value for the power of the installation can be found to decrease the payback period. The optimum power of the installation for these two profiles varies between 1000 W and 1500 W. Power values that fit in both legislations of self-consumption (see section 2.1).

The economic results vary in function of the fluctuations of the market for the cost of the installation and inflation rates. Nevertheless, a previous study of the profiles of consumption of the house can found a more adequate installation to achieve shorter return periods and higher savings in the electricity bills.

5 Conclusion

The target of this thesis is the study of a system that produces electricity and DHW with solar PV panels and a HP with the support of the software Polysun and satisfying the laws for self-consumption of Portugal and Spain. In the past these systems were not as profitable as nowadays. The technology available in that time had worst efficiencies and also higher prices. In the future higher profits are expected as the efficiencies of each device of the installation will increase and their price will decrease.

The comparison of the system of study with other systems with the same objective is studied. This comparison shows that the system of study among all studied needs to purchase less energy from the grid. A change from systems D (no PV panels + electric boiler) to the system of study gives a payback period of 8.6 years. A change from system E (no PV panels + HP) to the system of study gives a payback period of 12.3 years. The installation of the system in a new house without any previous system gives a payback period of 23.1 years.

Parameters that influence the energy production of the system are also studied. The impact in the self-consumption and the payback period is studied depending on the location of the system in the Iberian Peninsula. The maximum difference of self-consumptions found is 81kWh between Salomonde (Portugal) and Sintra (Portugal). This difference varies the payback period along the Iberian Peninsula in 1,65 years. Northern places have higher self-consumption rates as they self-consumed more energy to production of DHW because of the lowest temperatures. An increase in the self-consumption and a decrease in the payback period can be achieved adjusting the installation to each location.

The impact of the heat exchanger position of the DHW tank in the energy needs is examined. Also a literature review about how to improve the stratification in the tank is done. Literature review shows some features that increase the stratification of the tank: set obstacles close to the cold water inlet of the bottom preferably those having a gap in the centre, set the inlet pipe facing down, set the outlet exit in the top of the tank and longitude/diameter (L/D) of the tank between 3 and 4. From the results of the simulations can be extract that the bottom heat exchanger needs more auxiliary energy to supply all the domestic hot water consumption. Also the bottom heat exchanger tank would lose more energy due to the increase in the average temperature of the tank. So the best position for the heat exchanger in the system is in the top and medium of the tank, reducing the energy needs and also the heat losses.

Finally some profiles of consumption are simulated in the system with Polysun to study if an optimum power of the installation can be found for each profile in order to reduce the payback period and how they affect the self-consumption. It can be extracted from the simulations that the highest the electricity consumption is in the installation during the day light, the highest the self-consumption is.

For H45 (family with two children and working parents) and G0 (commercial activity) consumption profiles, an optimum value for the power of the installation can be found to decrease the payback period. The optimum power of the installation for these two profiles varies between 1000 W and 1500 W. Power values that fit in both legislations of self-consumption (see section 2.1).

The economic results vary in function of the fluctuations of the market for the cost of the installation and inflation rates. Nevertheless, a previous study of the profiles of consumption of the house can found a more adequate installation to achieve shorter return periods and higher savings in the electricity bills.

Finally can be conclude that the system of study compared with other systems that also aim to reduce the electricity bills has the highest payback period 23,1 years because of its highest investment cost. Nevertheless, it has the lowest total electricity purchase from the grid 1564 kWh. Future reductions in the price of the solar systems and increases in the prices of the electricity bills can make the system more profitable but nowadays the payback period is still the highest compared with the rest of the systems even having the smallest purchase of electricity from the grid.

For future investigations about this topic a real installation can be built to test more consumption profiles and study how the smart meter solar-log improve the self-consumption more in deep.

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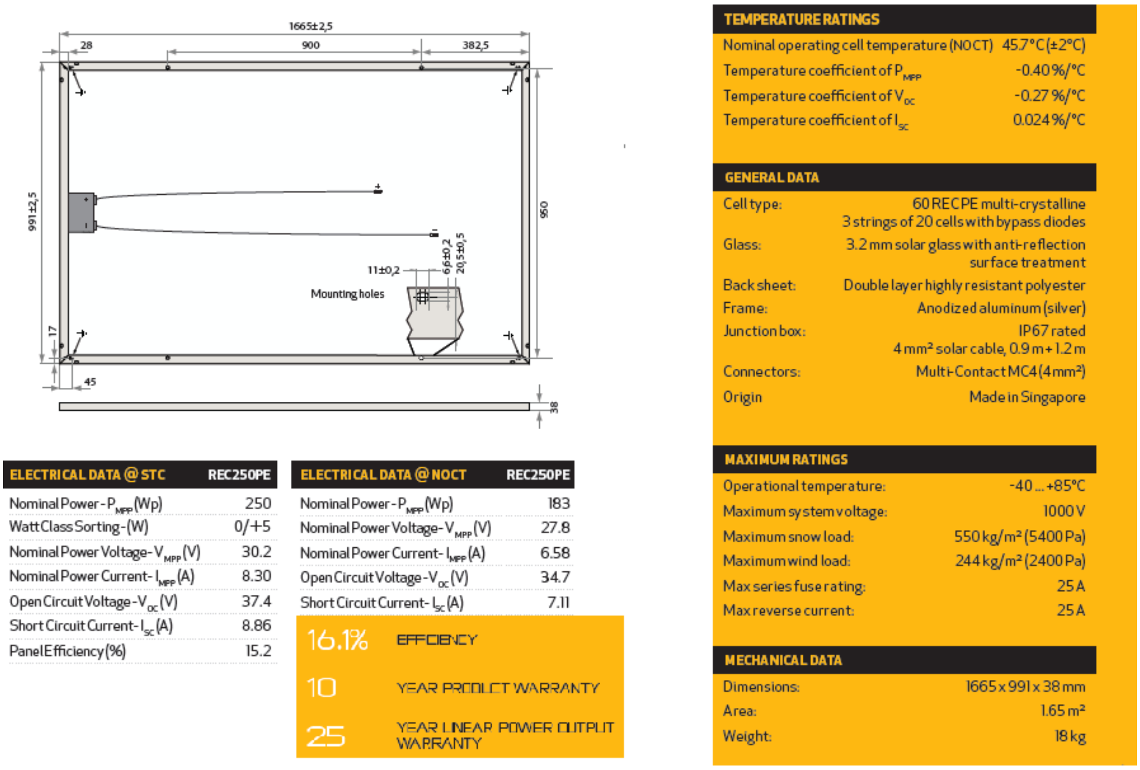
Annex A



ELECTRICAL DATA @ STC	REC250PE
Nominal Power - P_{MPP} (Wp)	250
Watt Class Sorting - (W)	0/+5
Nominal Power Voltage - V_{MPP} (V)	30.2
Nominal Power Current - I_{MPP} (A)	8.30
Open Circuit Voltage - V_{OC} (V)	37.4
Short Circuit Current - I_{SC} (A)	8.86
Panel Efficiency (%)	15.2

ELECTRICAL DATA @ NOCT	REC250PE
Nominal Power - P_{MPP} (Wp)	183
Nominal Power Voltage - V_{MPP} (V)	27.8
Nominal Power Current - I_{MPP} (A)	6.58
Open Circuit Voltage - V_{OC} (V)	34.7
Short Circuit Current - I_{SC} (A)	7.11

16.1% EFFICIENCY

10 YEAR PRODUCT WARRANTY

25 YEAR LINEAR POWER OUTPUT WARRANTY

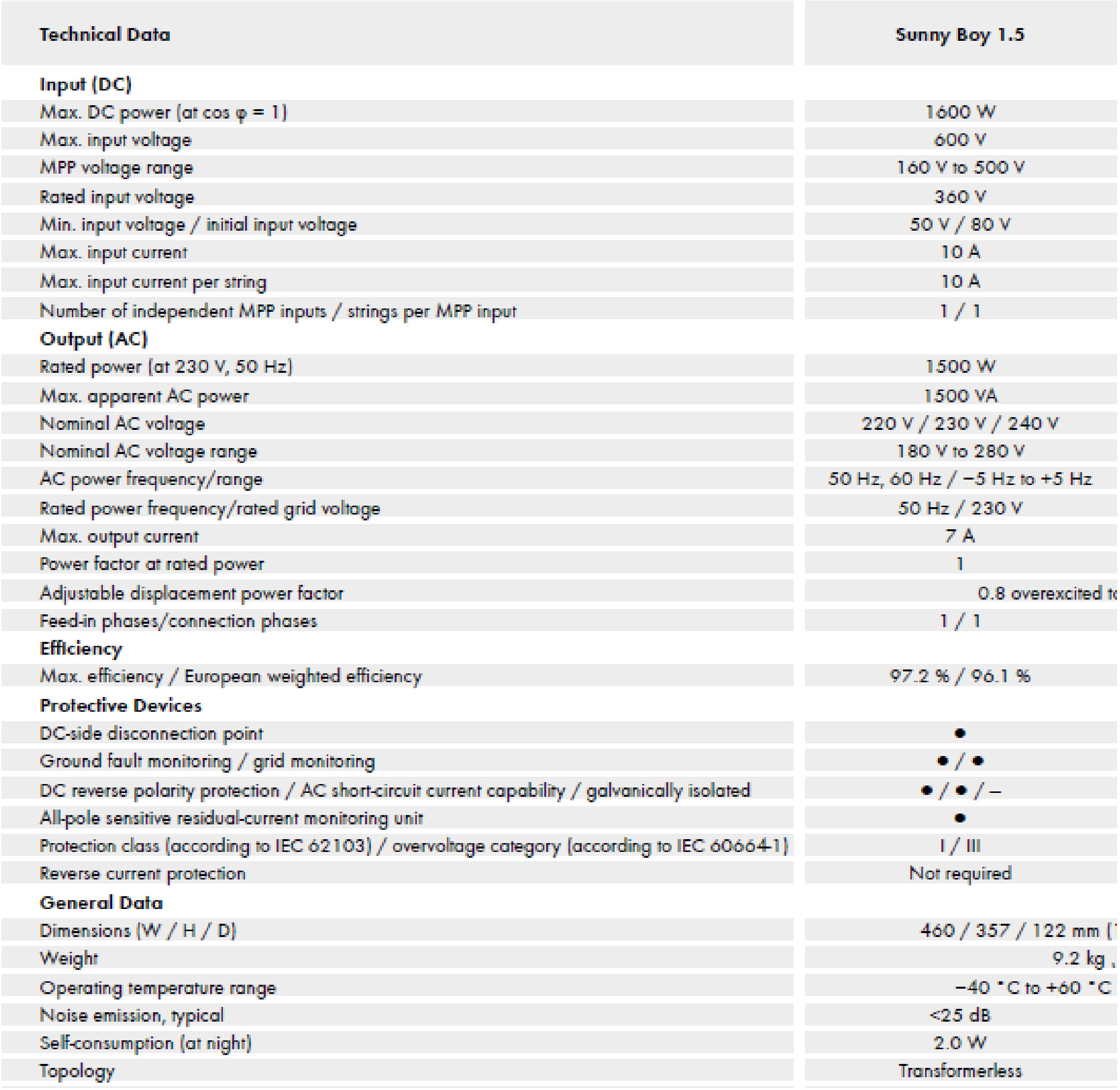
TEMPERATURE RATINGS	
Nominal operating cell temperature (NOCT)	45.7°C (±2°C)
Temperature coefficient of P_{MPP}	-0.40 %/°C
Temperature coefficient of V_{OC}	-0.27 %/°C
Temperature coefficient of I_{SC}	0.024 %/°C

GENERAL DATA	
Cell type:	60 REC PE multi-crystalline 3 strings of 20 cells with bypass diodes
Glass:	3.2 mm solar glass with anti-reflection surface treatment
Back sheet:	Double layer highly resistant polyester
Frame:	Anodized aluminum (silver)
Junction box:	IP67 rated 4 mm² solar cable, 0.9 m + 1.2 m
Connectors:	Multi-Contact MC4 (4 mm²)
Origin	Made in Singapore

MAXIMUM RATINGS	
Operational temperature:	-40 ... +85°C
Maximum system voltage:	1000 V
Maximum snow load:	550 kg/m² (5400 Pa)
Maximum wind load:	244 kg/m² (2400 Pa)
Max series fuse rating:	25 A
Max reverse current:	25 A

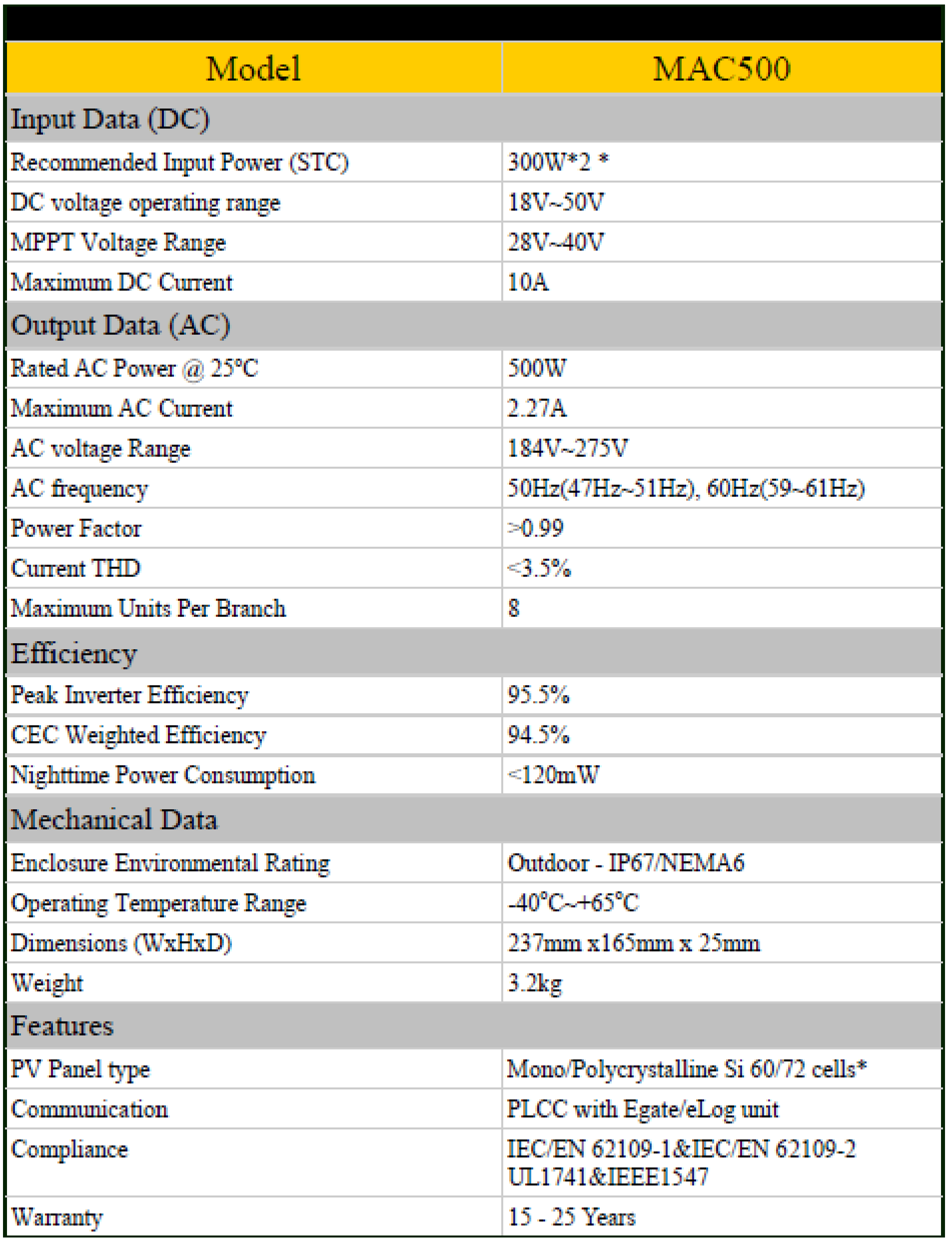
MECHANICAL DATA	
Dimensions:	1665 x 991 x 38 mm
Area:	1.65 m²
Weight:	18 kg

Figure 1 Technical sheet of the PV panels of the installation.



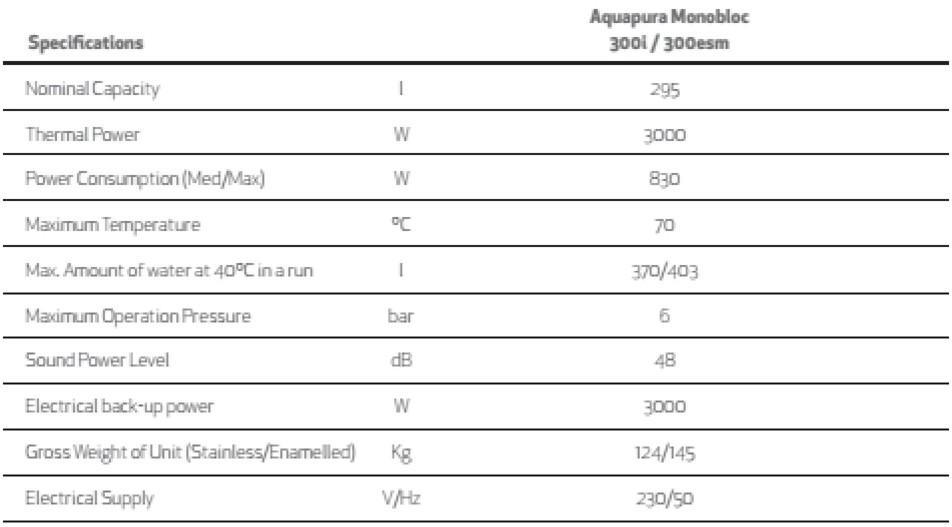
Technical Data	Sunny Boy 1.5
Input (DC)	
Max. DC power (at cos φ = 1)	1600 W
Max. input voltage	600 V
MPP voltage range	160 V to 500 V
Rated input voltage	360 V
Min. input voltage / initial input voltage	50 V / 80 V
Max. input current	10 A
Max. input current per string	10 A
Number of independent MPP inputs / strings per MPP input	1 / 1
Output (AC)	
Rated power (at 230 V, 50 Hz)	1500 W
Max. apparent AC power	1500 VA
Nominal AC voltage	220 V / 230 V / 240 V
Nominal AC voltage range	180 V to 280 V
AC power frequency/range	50 Hz, 60 Hz / −5 Hz to +5 Hz
Rated power frequency/rated grid voltage	50 Hz / 230 V
Max. output current	7 A
Power factor at rated power	1
Adjustable displacement power factor	0.8 overexcited t
Feed-in phases/connection phases	1 / 1
Efficiency	
Max. efficiency / European weighted efficiency	97.2 % / 96.1 %
Protective Devices	
DC-side disconnection point	●
Ground fault monitoring / grid monitoring	● / ●
DC reverse polarity protection / AC short-circuit current capability / galvanically isolated	● / ● / –
All-pole sensitive residual-current monitoring unit	●
Protection class (according to IEC 62103) / overvoltage category (according to IEC 60664-1)	I / III
Reverse current protection	Not required
General Data	
Dimensions (W / H / D)	460 / 357 / 122 mm (
Weight	9.2 kg
Operating temperature range	−40 °C to +60 °C
Noise emission, typical	<25 dB
Self-consumption (at night)	2.0 W
Topology	Transformerless

Figure 2 Technical sheet of the inverter of the installation.



Model	MAC500
Input Data (DC)	
Recommended Input Power (STC)	300W*2 *
DC voltage operating range	18V~50V
MPPT Voltage Range	28V~40V
Maximum DC Current	10A
Output Data (AC)	
Rated AC Power @ 25°C	500W
Maximum AC Current	2.27A
AC voltage Range	184V~275V
AC frequency	50Hz(47Hz~51Hz), 60Hz(59~61Hz)
Power Factor	>0.99
Current THD	<3.5%
Maximum Units Per Branch	8
Efficiency	
Peak Inverter Efficiency	95.5%
CEC Weighted Efficiency	94.5%
Nighttime Power Consumption	<120mW
Mechanical Data	
Enclosure Environmental Rating	Outdoor - IP67/NEMA6
Operating Temperature Range	-40°C~+65°C
Dimensions (WxHxD)	237mm x165mm x 25mm
Weight	3.2kg
Features	
PV Panel type	Mono/Polycrystalline Si 60/72 cells*
Communication	PLCC with Egate/eLog unit
Compliance	IEC/EN 62109-1&IEC/EN 62109-2 UL1741&IEEE1547
Warranty	15 - 25 Years

Figure 3 technical sheet of the micro inverters of the installation



Specifications		Aquapura Monobloc 300i / 300esm
Nominal Capacity	l	295
Thermal Power	W	3000
Power Consumption (Med/Max)	W	830
Maximum Temperature	ºC	70
Max. Amount of water at 40ºC in a run	l	370/403
Maximum Operation Pressure	bar	6
Sound Power Level	dB	48
Electrical back-up power	W	3000
Gross Weight of Unit (Stainless/Enamelled)	Kg	124/145
Electrical Supply	V/Hz	230/50

Figure 4 Technical sheet of the HP of the installation