Self-production Systems for Household Electricity and Hot Water Consumptions

Alejandro Durá González
alejandro.dura@tecnico.ulisboa.pt
Instituto Superior Técnico, Lisboa, Portugal

September 2016

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.

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.

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. This is achieved using the self-produced electricity to feed the heat pump which produces the Domestic Hot Water (DHW). 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 Log^{TM}, 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 1 shows an scheme of how the system works

2. Methods

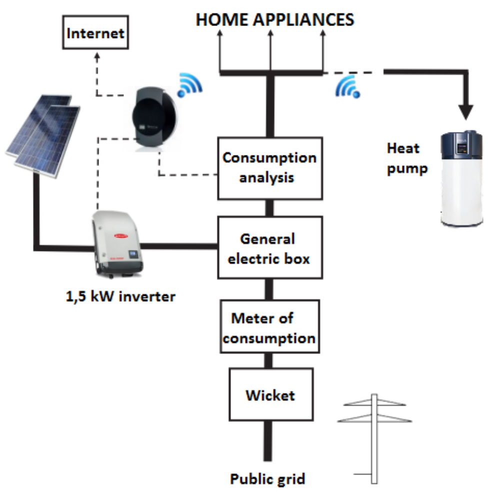

Figure 1 Scheme of the system of study.

For all simulations the next features remain equal except for particular changes named in the corresponding section. All economic calculations are done using an inflation rate of 2% and the prices of EDP (electricity supplier of Portugal) for a contracted power of 3.45 kVA. The net present value (NPV) of each of the future savings is calculated to get the return period.

The DHW profile is the H45 of Polysun (family with working parents and two children). The yearly consumption of the electric profile is 2000 kWh and for the DHW profile, the needs in hot water are 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 PV panels is 6 and they have a power of 250Wp.

2.1. System configurations

The demand of all the electricity needs of a house can be supplied in many different ways. Five systems are considered to study their energy needs, they are:

A. The one explained in section 2.
B. A house with 2 solar thermal panels and a tank to accumulate the DHW with an electric boiler to produce heat when the solar panels cannot. The number of thermal panels is 2 ($4m^2$).
C. A house with photovoltaic panels which feed first the home appliances and use the excess of production to feed an electric boiler.
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.

E. The system is similar to system A but it has not self-production. All the electricity need is taken from the electric grid.

2.2. Parameters that influence the energy production of the system.

2.2.1. 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. Energy production increases approximately linearly with irradiance. Influence of temperature affect less the production and is dependent on the type of cell technology. For this reason five locations with different values of irradiances are chosen in the Iberian peninsula. Table 1 shows the coordinates of each place, their average, maximum and minimum temperature and the average radiation they have.

	Radiation	Temperature		
Place	Averg. [W/m2]	Averg.	Max.	Min.
Berasategui, Spain	251	13	33	-4
Salomonde, Portugal	314	13	33	-3
Sintra, Portugal	340	17	36	5
Chiclana de la frontera, Spain	363	18	37	4
Sagres, Portugal	384	18	36	6

Table 1 Latitude, longitude and altitude of the places of study.

2.2.2 Stratification in the DHW tank

Stratification affects positively the behaviour of the water tank and the installation. (Altuntop, Arslan, Ozceyhan, & Kanoglu, 2005; Hariharan, Badrinarayana, Srinivasa Murthy, & Krishna Murthy, 1991; Laine, 2015; Spur, Fiala, Nevrala, & Probert, 2006) explain why the stratification enhance the performance of the DHW tank and also they show how to improve stratification. The ways to improve stratification extracted from these studies 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.

A simulation in Polysun was carried out for three different heat exchanger positions (up,medium and bottom) in a tank of 300 litres.

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.

2.2.3 Consumption profiles affect the self-consumption

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).

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 electric profiles from Polysun data base are the H45 (family with two children and working parents), the profile G0 (average commercial activity) and the profile H11 (student house). For the DHW profile a residential profile is chose. Figure 2 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.

Figure 2 From top to bottom Polysun H45, G0 and H11 electricity consumption profiles for the first week of the year. (Polysun graphics).

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.

3. Results

3.1. Comparison with other systems

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 table 2. “Total consumed” make reference to

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 2 Overview of consumptions for all systems.

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.

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.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 3 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.

If the system would be installed in a new house (see table 3 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 3 System configurations table, it shows: the devices needed for each change, the price of these changes, the savings achieved and the payback period.

The smallest payback period 6.7 years of table 3 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 2).

3.2. Parameters that influence the energy production of the system

3.2.1. Location of the system in the Iberian Peninsula

Table 4 shows the annual values for self-produced electricity, the self-consumption of each profile and the total and the payback period for each place. Southern places have higher rates of self-production than northern places.

	Self-production [kWh]	Self-consumptions [kWh]			Payback [years]
		Electricity	DHW	Total	
Berasategui	1687	537	764	1301	22.9
Salomonde	2147	607	764	1371	21.45
Sintra	2250	639	651	1290	23.1
Sagres	2519	666	629	1295	23.1
Chiclana	2339	668	628	1296	23

Table 4 Self-production, self-consumption and payback

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. The higher self-consumptions in the electric profile in southern places are because of the higher self-productions. The yearly energy needs to produce hot water depend on the ambient temperature. The lower temperatures in the north of the Iberian Peninsula together with the flexibility for self-consumption to produce DHW increase the self-consumed electricity for these 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.

3.2.2. Stratification in the DHW tank

Table 5 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 5 Heat exchanger values for the three different positions of study.

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 temperature difference 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 higher average temperature. For the medium and upper heat exchangers the heat loss of the tank is less than half of for the bottom heat exchanger.

In conclusion, it can be said 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. Differences are not found between the medium and upper heat exchangers in the simulations.

3.2.3. Consumption profiles affect the self-consumption.

Table 6 shows the yearly self-consumption for each profile having from 3 to 8 PV panels. In all cases can be found that self-consumption energy increases as the number of PV panels increase. Table 7 shows the price of the whole installation for each number of PV panels and also the prices of each device. It can be seen that the price per Wp decreases as the power of the installation grows. This is because the inverter decreases his price (€/Wp) with the increase of power.

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 6 Self-consumptions for each configuration of installation.

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 installatior	4.104 €	4.353 €	4.595 €	4.840 €	5.071 €	5.306 €

Table 7 Detailed prices of the installations.

In some cases because of the different self-consumptions of each profile and the configuration of prices an optimum power of the installation can be found. In the table 8 the payback period for each profile of consumption with an inflation rate of 2% is shown. For profiles H45 and G0 exist an optimum number of panels that decreases the payback period. For H45 profile, the number of panels for is 5. For G0 profile, 4 PV panels is the optimum number of panels that decrease the payback time.

In conclusion the electricity consumption profiles can impact in the self-consumption of energy of the system. The study of the profile of consumption where the installation is going to be placed can decrease the payback period.

Payback[years]	Inflation 2%		
nº panels	H45	G0	H11
3	23,96	18,81	23,88
4	23,57	18,39	24,44
5	23,18	18,44	25,08
6	23,32	18,81	25,95
7	23,58	19,29	26,81
8	24,01	19,89	27,73

Table 8 Payback time for all consumption profiles from 3 to 8 PV panels with an inflation of 2%.

4. 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.

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 and E to the system of study give paybacks of 8.6 years and 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 and Sintra. 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. 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. 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 (1000 W-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 the optimum location of the coil within the tank as the simulation results of the top and medium coil do not show any differences. Also a study could try to adjust the smart meter solar-log to improve the self-consumption for each different consumption profiles.

References

Altuntop, N., Arslan, M., Ozceyhan, V., & Kanoglu, M. (2005). Effect of obstacles on thermal stratification in hot water storage tanks. *Applied Thermal Engineering*, *25*(14-15), 2285–2298. http://doi.org/10.1016/j.applthermaleng.2004.12.013

Fraunhofer ISE. (2015). Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems. *Agora Energiewende*, (February), 82. http://doi.org/059/01-S-2015/EN

Glunz, S. W., Nozik, A. J., Conibeer, G., & Beard, M. C. (2014). Crystalline Silicon Solar Cells with High Efficiency in Advanced Concepts in Photovoltaics. *The Royal Society of Chemistry*, 1–29.

Hariharan, K., Badrinarayana, K., Srinivasa Murthy, S., & Krishna Murthy, M. V. (1991). Temperature stratification in hot-water storage tanks. *Energy*, *16*(7), 977–982. http://doi.org/10.1016/0360-5442(91)90057-S

Health, I. (2004). European Commission. *European Journal of Health Law*, *11*(3), 309–317. http://doi.org/10.1163/1571809042388581

Hoeven, M. Van Der. (2014). IEA Technology Roadmaps for Solar Electricity An Energy Revolution is needed.

Laine, M. (2015). Basics of thermal QCD, 1–99.

Richter, A., Hermle, M., & Glunz, S. W. (2013). Reassessment of the Limiting Efficiency for Crystalline Silicon Solar Cells. *IEEE Journal of Photovoltaics*, *3*(4), 1184–1191.

Shockley, W., & Queisser, H. J. (1961). Detailed balance limit of efficiency of p-n junction solar cells. *Applied Physics*, *32*(3), 510–519.

Solaris, V., Sma, A. G., & Technology, S. (2014). Fast Simulation Algorithm for Pv Self-Consumption With Heat Pump Systems, (September).

Spur, R., Fiala, D., Nevrala, D., & Probert, D. (2006). Influence of the domestic hot-water daily draw-off profile on the performance of a hot-water store. *Applied Energy*, *83*(7), 749–773. http://doi.org/10.1016/j.apenergy.2005.07.001

Würfel, P. (2005). Physics of solar cells - from principles to new concepts.