Sizing of PV installations based on economical pre-feasibility analysis according to self-consumption in Portugal

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ABSTRACT: Portugal is one of the leading countries in Europe in terms of renewable energy mainly due to the large installed capacities of wind and hydro power. In order to achieve the ambitious climate goals – in the most efficient way – an increase of solar energy in the electricity mix is required. The regulatory scheme in Portugal that allows consumers to generate their own solar energy with the focus on local direct self-consumption, referred to as UPAC, is one of the means to incentivize the private investment in – decentralized – solar energy in the country's energy mix.
This thesis has the main objective to promote investment in self-consumption PV system by providing an illustration of the benefits of these projects through savings in energy cost and through internal rate of returns on investments. Also, a methodology is provided and applied in the form of a model using Python that allows to determine the optimal sizing of a PV system for self-consumption that can be applied on specific cases following Portuguese legislation. The methodology is applied on a specific case study, on a logistics warehouse in greater Lisbon, as a means of illustrating the benefits of a self-consumption PV system for the consumer, and the importance of the system size and configuration for the projects rentability. This model was developed because there is no PV system design software available that takes into account the specific Portuguese UPAC regulations.

1. INTRODUCTION

Portugal is one of the leading countries in Europe in terms of renewable energy, mainly due to the large installed capacities of wind and hydro power (APREN, 2018). In order to achieve the ambitious climate goals – in the most efficient way – an increase of solar energy in the electricity mix is required (APREN, 2018). The regulatory scheme in Portugal that allows consumers to generate their own solar energy with the focus on local direct self-consumption, referred to as UPAC, is one of the means to incentivize the private investment in – decentralized – solar energy in the country's energy mix. From the point of view of a consumer, a self-consumption PV system is attractive because over recent years the prices of PV installations have decreased, Portugal's electricity prices are in the top 5 in Europe for industrial consumers, and the country is blessed with high levels of solar irradiation.

This combination of relatively high electricity prices, good solar resource, and regulatory scheme make that PV projects have the tendency to be good investment options for businesses with available space for PV modules, and therefore, are worth investigating for these consumers. Due to the focus on self-consumption, it is important for a projects profitability to be sized and configured taking into account the consumption profile of the case under study, and the applicable electricity tariff scheme. In the remainder of this paper, a methodology and model will be provided aimed at determining the optimal size and configuration of a PV system. This model is applied to a case study, a logistics warehouse in greater Lisbon, to illustrate its working and the possible benefits of a PV system for a consumer in Portugal. The model has been developed to accommodate the specific UPAC legislation in Portugal, as this is not available in commercial software packages for solar system design. In the paper, households and businesses with consumption levels similar to households have not been considered therefore it is applicable on consumers that are in connected power and voltage categories of special low voltage (BTE) up to very high voltage (MAT).

2. PORTUGUESE REGULATION: DISTRIBUTED GENERATION THROUGH UPAC

One aspect of the current regulatory framework regarding distributed electricity generation, in place since 2014, is the self-consumption regime, referred to as UPAC (Ministério do Ambiente, Ordenamento do Território e Energia, 2018). The primary focus is to stimulate the local consumption of the produced energy through a rational installed capacity, adapted to the consumption load through a more direct and subsidy-free regulatory scheme. More specifically, the installed capacity of a UPAC is limited to the contracted power. The production unit has to be registered through an online platform and a small registration fee has to be paid before starting the operations. Once in operation, the consumer (owner of the installation) uses the produced electricity to meet the load, the excess production can be sold to the retailer of last resort. So, the benefit for the consumer mainly comes from the reduction of the amount of electricity to be bought from a retailer, the transportation and distribution costs and, to a smaller extent, from selling the excess electricity to the grid. The system owner is remunerated for the electricity fed into the grid by a certain value per kWh. This value amounts to 90% of the monthly averaged electricity closing price on the daily Iberian wholesale market (OMIE) which, on average, amounted to 0.3967 and 0.5224 euro per kWh for the years 2016 and 2017, respectively. This results in an average selling price of 0.0357 and 0.047 euro per kWh for 2016 and 2017, respectively.

3. METHODOLOGY AND MODEL

The model is developed in Python 2.7 and makes use of the PVLib python library (Holmgren, Clifford, & Mikofski, 2018) to simulate the production profile of the PV systems under study.

3.1. AC-output and savings

To determine the optimal configuration of a PV system, the model simulates the outputs of a wide range of possible PV system configurations. These configurations vary in the orientations, inclinations, installed capacity, and the type of mounting of the PV modules. A single PV system configuration can consist of up to two arrays of PV modules, that are considered as subsystems, each of which can have its own orientation, inclination, installed capacity and mounting type. This is done to align the model better with real-world PV configurations as it is very common to see one PV system with modules on both sides of a triangular roof structure for example. The AC-output of a system is the sum of the AC-output of the two subsystems, which are obtained by scaling the output of a 24-kWp reference PV system linearly to the actual capacity of the subsystem. The AC output of the reference plants depends on the orientation and inclination that are put in as parameters – and align with the specifications of the subsystems under study – and are calculated through the PVLib python library. The reference PV system consists of 24 kWp, 4 strings of 20 300 W monocristalline modules connected to a 20 kW inverter. This means the module arrays are oversize with a factor of 1.2 in relation to the inverter, which is generally advised for commercial projects. In order to obtain the AC electricity output of a reference PV system, the model incorporates the NREL solar position algorithm, Kasten and Young airmass model, Perez irradiation model, SAPM temperature model, SAPM DC model, and Sandia's AC output model that are applied on weather data from Meteonorm and PV module and inverter parameters of Sandia and CEC databases, respectively.

For every system, the AC-output is compared to the load (of the consumer) for an entire year in 15-minute intervals. Based on this comparison the amount of energy that is self-consumed, the excess energy, and the reduction of power consumption during peak periods is determined. This information is used to determine the savings that are obtained in the first year after the installation of the PV system. Taking into account the installation and operations costs for every system, the savings can be put into perspective by calculating key financial indicators for the 25-year lifetime of the system. These indicators are the internal rate of return, payback period and NPV and allow for the comparison of the different PV systems as investments.

3.2. Costs

There are three types of PV module mounting considered. The first type is mounting directly on the roof, following the roofs inclination and orientation. The second type is referred to as roof-inclined and is the mounting of panels on the roof using structures to change the inclination of the panels as is generally done on flat rooftops. The last type is ground-mounted, where the panels are placed on structures on the terrain with the ability to choose the orientation and inclination of the panels. The installation cost of the PV system depends on the installed capacity and the type of mounting, as illustrated in Figure 1. Through three professional solar project developers, a wide range of PV system costs has been obtained, which allowed to perform a regression on the cost, with the installed capacity as variable, for the three types of mounting. It is important to note that these prices are the minimum value for an optimal installation. They are likely to be higher due to a specific type of roof, or a longer distance to the grid connection point for example.

Based on the advise of one of the PV project developers, the maintenance cost is set to € 10 per kWp, the insurance cost to 0.35% of the installation cost, and the inverter replacement cost to € 70 per kWp. It is assumed the inverter has to be replaced every 10 years. Also in line with the advise of the PV project developers and in line with general assumptions, the annual degradation of the PV system is assumed to be 1%. The inflation rate of electricity prices and costs is set to be 1.5%, and the discount rate is set at a conservative value of 10%.

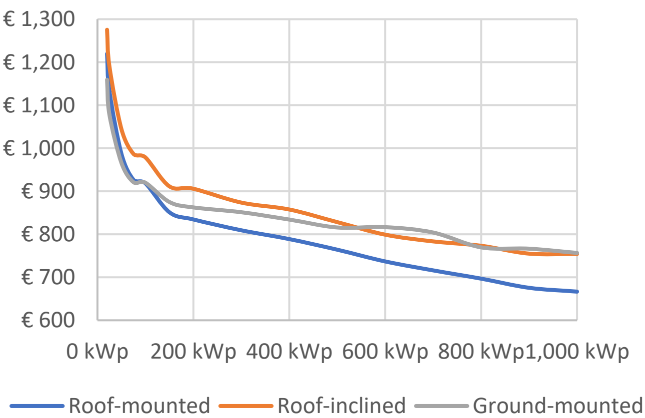

Figure 1: Overview of the reference prices used for different sizes of roof-mounted, roof-inclined, and ground-mounted systems in € per kWp.

4. CASE STUDY

In the case study the electricity consumption of a logistic warehouse in the Lisbon region is used as the main input to scale a PV system to its consumption following the self-consumption regime, UPAC, in Portugal. The warehouse falls under BTE and has an annual consumption of 1,529 MWh. The consumption data available is for the year 2017, expressed as the average active power consumption for every 15 minutes of the year. The calculated total electricity cost for 2017 amounts to € 157,875. This cost is made up of active energy consumption, grid access fees, and power connection fees.

The active energy and grid access fees are based on 4 tariffs: super off-peak (Super Vazio), off-peak (Vazio), high (Cheia), and peak (Ponta). Excluding VAT (23%), these amount to 5.36, 6.17, 8.93, and 9.99 c€/kWh. The applicable tariff depends on whether it is winter or summer, the time of the day and whether it is a working day, a Saturday or, a Sunday or holiday and is referred to as ‘weekly cycle tariff’.
The remuneration for power consumption during peak hours also has a significant impact on the overall energy bill, and is impacted by the PV system. This fee is charged in order to incentivize consumers to reduce their consumption during the peak periods (Ponta). Also, this fee is billed on a monthly basis and is based on a tariff of 0.2641 €/kW.day. This fee is determined according to Equation 1.

$$Fee\ Power_{Ponta} = Consumption_{Ponta}\ (kWh) \times \frac{Days\ in\ month}{Hours\ of\ ponta} \times 0.2641\ {}^{€}/_{kW} \times day \quad (1)$$

Figure 2: Satelite image of the warehouse indicating the suitable space for the installation of solar PV (Source: Google Maps)

The logistics warehouse has a roof layout as shown in Figure 2, in which the green rectangle indicates the roof area suited to mount solar panels. The inclination of the roof is 15 degrees and as can be seen in Figure 2, half of the available space is oriented towards the NE, while the other half is oriented towards the SW. The available roof area suited for solar panels amounts to about 5,600 m^2 which offers space for an installation of about 700 kWp (350 kWp with NE-orientation and 350 kWp with SW-orientation.

5. RESULTS

In this section, three main scenarios are investigated. In the first it is assumed that all modules are mounted directly on the roof, following its inclination and orientation. In the second scenario, the modules on the SW-facing side of the roof are placed directly on the roof while on the other side of the roof with NE orientation, the panels are mounted on structures in order to orient them to the SW as well. In the last scenario, it is assumed the modules are mounted on terrain next to the warehouse, so the inclination and orientation of the panels can be chosen freely.

5.1. Roof-mounted following the roof inclination

The simulation was performed for a range of system sizes ranging from 0 to 700 kWp in steps of 10 kWp with a maximum size per orientation of 350 kWp which results in 1296 different system combinations. The results show that the optimal system consists of 280 kWp, with all the PV modules placed on the sides of the roof that have SW-orientation. For this configuration, the savings in year 1 amount to 33% of the annual electricity cost. The 10 best performing systems consist of those systems that are completely oriented SW with sizes from 240 kWp up to 330 kWp with a minimum IRR of 21.4%. These IRR’s lie very closely to each other because of the trade of between the share of self-consumption and investment cost.

System	NE	SW	NE + SW
IRR (%)	17.56	21.5	19.63
NPV (€)	140,333	218,957	181,368
Production (kWh/kWp)	1,269	1,616	1,442
Year-1 savings (€)	43,804	52,155	48,162
Payback period	5.55	4.6	5.01
Self-consumption	93%	90%	92%
Self-sufficiency	22%	27%	24%

Table 1: Key performance indicators for different configurations of a 280 kWp roof-mounted PV system

More specifically, if the system size increases the share of self-consumption is reduced which in turn reduces the savings per kWp because the feed-in tariff is only about 4 c€/kWh. With the increase in size, the per-kWp investment cost is reduced due to economies of scale, offsetting the reduction in savings per kWP. The key performance indicators (KPI) of the optimal configuration are provided in Table 1 in which the self-consumption rate is the share of the total generated electricity consumed by the load, and the self-sufficiency rate is the share of locally consumed solar energy in the total electricity consumption.

The choice for a system with only SW-oriented modules follows the logic of higher solar radiation, and therefore higher productivity of SW-oriented modules. Additionally, for this specific case of the logistics company, the consumption profile shows – on average – higher consumption levels during the afternoon. As in the Northern hemisphere the sun moves from East in the morning towards West in the afternoon/evening, the production profile of SW-oriented panels fits this specific consumption profile better. This is illustrated through a comparison of three system configurations, 280 kWp NE, 280 kWp SW, and 140 kWp NE + 140 kWp SW, in Figure 3 with an overview of KPI's is provided in Table 1. It can be seen that higher generation by SW oriented panels leads to higher savings and in turn, a more profitable project.

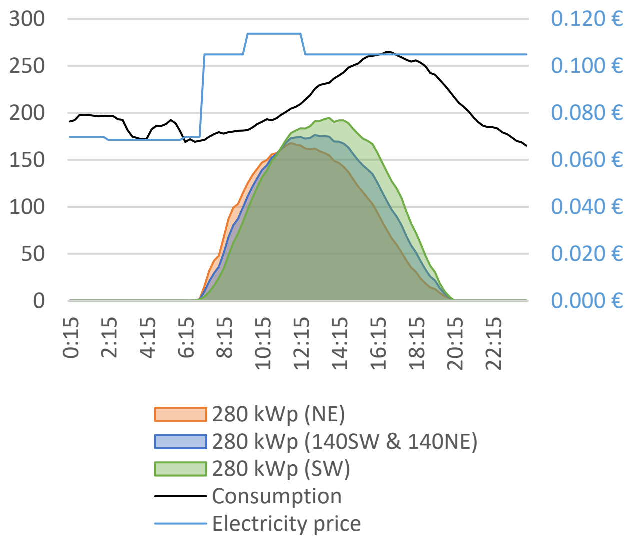

Figure 3: Summer average daily production profile for 3 system configurations along with the consumption profile and electricity price.

5.2. Roof-inclined and direct roof mounting

In this scenario it is assumed that the modules to be placed on the side of the roof facing NE are inclined to face SW, with the inclination angle as a variable, while the modules on the SW-facing roof are mounted directly on the roof as in scenario 1.

When running the model for the actual roof layout with space for 700 kWp in the Lisbon area, the result is exactly the same as in the first scenario described in Section 5.1.1 for inclinations of the panels on structures ranging from 10 to 40 degrees (SW-orientated or SE-oriented). This is a system with 280 kWp installed on the side of the roof oriented to the South-West, without panels on structures on the NE side of the roof. This means that the increase in the overall yield of electricity and/or the increase of electricity generation during peak-hours does not offset the additional cost of placing the panels on structures to such an extent that it is economically more viable than placing the modules directly on the SW-oriented roof. In order to get a more insightful result, it is assumed that the roof size is only half of the actual size. This assumption also strokes with reality of a roof inclined installation because in order to avoid shading, there needs to be more space between the modules on the roof. Therefore, in this variation the maximum size of the system amounts to 340 kWp of which half can be placed along the roof's inclination facing SW and half on structures with an inclination ranging from 0 to 40 degrees (with steps of 5 degrees), facing SW, on the other side of the roof (with NE orientation).

In this case the optimal configuration consists of 170 kWp directly on the roof (maximum capacity) and 80 kWp inclined to an angle of 25 degrees as compared to the horizontal. The 25-degree inclination is a result of a trade-off between maximizing the overall production and maximizing the production during peak hours as it has a stronger effect on the savings, both through electricity cost as peak-power cost. More specifically, the annual generation reaches its maximum for an inclination of 30 to 35 degrees (for SW orientation) and decreases when the inclination angle decreases. The absolute generation during peak hours however increases with a decrease of the inclination angle. Table 2 provides an overview of the KPI's of the best performing system configuration for an inclination of 20, 25, and 35 degrees. Comparing the KPI's of the systems with 20- and 30-degree inclination as provided in Table 2, it can be seen that the year-1 savings and IRR of both systems are almost identical, although the annual production of the first system is lower by 2 MWh per year. It is interesting to note that the better inclination of the panels results in higher generation in kWh per kWp than in scenario 1, which is one of the main reasons why the overall optimal system size is smaller than in scenario 1.

System **Inclination**	**NE** **20º**	**SW** **25º**	**NE + SW** **30º**
IRR	21.12%	21.14%	21.12%
Total cost (€)	200,446	208,061	200,446
Year-1 Savings (€)	45,590	47,378	45,602
Production (kWh/kWp)	1,625	1,632	1,633
Self-consumption rate	93%	92%	93%

Table 2: System key performance indicators for the optimal systems consisting of direct roof-mounted modules and roof-inclined modules with inclinations of 20, 25, and 30 degrees

5.3. Ground-mounted PV system

Installing the modules on the terrain allows for flexibility in both the orientation and the inclination of the modules. In order to reduce the calculation time to obtain the optimal configuration a 3-step approach has been followed. In the first step a range of systems is simulated whose orientation and inclination differ in steps of 30 degrees and 5 degrees, respectively. The first step indicates that systems with an orientation between 150 to 210 degrees and an inclination of 30 or 35 degrees are performing best. In the second step the orientation is varied between 150 and 210 degrees with steps of 5 degrees. In line with expectations the results indicate that a system with modules oriented due South and an inclination of 35 degrees are performing best. In the last step orientation and inclination were varied with steps of 1 degree between 175 and 185, and between 30 and 38 degrees, respectively. The result of this last step indicates that the optimal system configuration consisted of 210 kWp with an orientation of 179 degrees and an inclination of 33 degrees. The difference in IRR between this system and the system that is expected to be optimal, due South with an inclination of 35 degrees, only amounts to 0.01%. Therefore, for real-world applications it is advisable to design according to the latter configuration. It needs to be remarked that, based on IRR, the ground-mounted system of 210 kWp outperforms the optimal roof-mounted system of scenario 1. This means that the higher installation cost of the ground-mounted system is offset by the higher electricity production due to optimal placing. A comparison between the KPI's of the optimal system, the expected optimal system, and the roof-mounted optimal configuration of system 1 is provided in Table 3.

System	**210**	**210**	**0 + 280**
Inclination	**179º - 33º**	**180º - 35º**	**225º - 15º**
Production (MWh/yr)	356	357	453
Production (kWh/kWp)	1,696	1,698	1,616
Year-1 Savings (€)	42,916	42,887	52,155
Cost (€/kWp)	874	874	821
Total cost (€)	183,565	183,565	225,056

Table 3: Overview of the key performance indicators of the optimal configuration of the ground-mounted system and of the roof-mounted system

6. ADAPTATIONS AND SENSITIVITY

6.1. The logistics warehouse moved to Faro and Porto

In order to obtain an understanding of the effect of location on the optimal system configuration, the analysis of scenario 1 is repeated with the weather data of a location close to Porto, in the North of Portugal, and of Faro, in the outer South of Portugal. In line with the expectations, the PV system outputs are higher in the South than in the North, which makes that the optimal size of the system is the largest in the North and decreases towards the South to fulfill the logistics warehouse demand for electricity in an economically optimal way. Projects have the potential to obtain higher IRR's in the South than in the North. An overview of the optimal system designs for the three locations, along with some of the KPI's is provided in Table 4.

Location	**Lisbon**	**Faro**	**Estarreja**
System (kWp)	**280 SW**	**260 SW**	**350 SW**
IRR (%)	22	23	17
Production (MWh/yr)	453	452	438
Payback (years)	4.6	4.3	5.7
Year-1 savings (€)	52,155	52,178	51,802
Initial cost (€)	225,056	211,128	272,789

Table 4: Optimal size and key financials of the PV system for the locations Lisbon, Faro, and Estarreja

6.2. Change in the consumer's electricity tariff and the wholesale price of electricity

As expected, a reduction in the consumer's electricity price negatively affects the first-year savings and the IRR of the project. It is assumed that the electricity price changes directly after the PV system has been installed and connected. The IRR goes down to 11.6% for electricity prices that are only half of the current prices as used in the case study. When electricity prices increase by 10%, the overall project IRR increases to 23.4%. When looking at the first-year savings, it can be seen that they do not follow the change in electricity price exactly. For example, a 50% reduction in electricity price only reduces the first-year savings by about 38% from € 52,155 to € 31,945. This is because the first-year savings for the reference system is made up for 78% by the avoided cost of buying electricity, while the remaining 22% stems from the grid revenues and the reduction of peak-power consumption fees. This means that only 78% of the savings are affected by a change in the electricity price.

Due to the relative low contribution of the grid revenues (from selling excess electricity) to the overall revenues, the effect of a change in the wholesale price of electricity has a limited effect on the project's rentability. More specifically, if the wholesale price decreases by 1 c€ to c€ 0.03 per kWh the first-year savings decrease by € 458 and the IRR by 0.17%. Similarly, an increase of c€ 1 results in an increase of €459 of the year-1 savings and an increase of 0.25% of the IRR.

An interesting aspect is the effect of the wholesale price on the system's optimal configuration. In order to obtain an insight in this effect, the optimum system configuration of scenario 1 is determined for a range of wholesale prices. An increase in the wholesale price makes the excess generation more valuable, therefore changing the balance between the amount of self-consumption and the excess electricity generation, resulting in a lower self-consumption rate and a larger system size, and an increase in the project IRR. The results of this analysis are presented in the form of a graph in Figure 4.

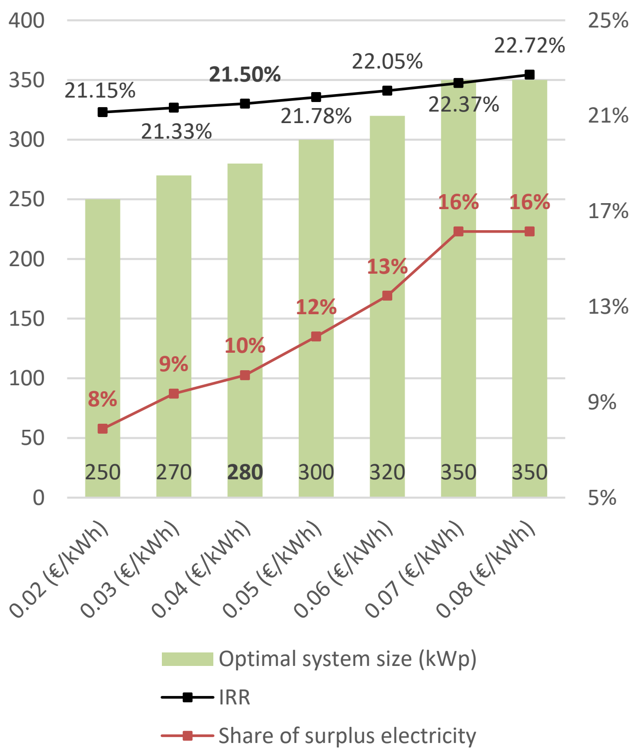

Figure 4: Optimal system configurations for direct roof-mounted modules for different wholesale prices

6.3. Change in the PV installation cost

The cost for the PV systems used in this model are based on low-end estimates by PV project developers. For this reason, it is important to assess the effect of increased capital investment requirements on the economic viability of this case. More specifically, the effects of price increases of 10% to 50% in steps of 10% are examined.

As the increase in cost only changes the annual savings to a small extent, through the increase of the annual insurance cost, there is no change to the optimal system configuration as compared to the base case of scenario 1. The key performance indicators that are affected are the initial investment cost, the NPV and the IRR. If the installation cost rises by 10%, the project IRR is reduced by 2%, if the installation cost rises by 50%, the project IRR is reduced down to 13.8% as illustrated in Figure 5. In line with the expectations, the NPV of the system decreases with an increase in the PV installation cost as illustrated in Figure 5. A 10% increase of the PV installation cost, induces a reduction in the NPV of the project of 11.4 %. The change in NPV is more profound than the change in the PV installation cost, as it also takes into account the change in the annual insurance cost.

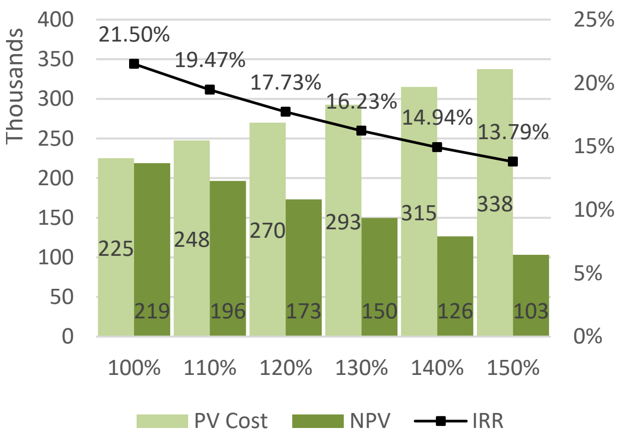

Figure 5: The effect of a change in the PV installation cost on the IRR and NPV of the PV project

7. CONCLUSION

Portugal's regulatory framework for PV self-consumption, UPAC, stimulates the choice for PV system sizes that correspond to the consumption source it is connected to. From the perspective of an electricity consumer the relatively high electricity cost in Portugal as compared to the rest of the EU and lowered PV system cost make a PV self-consumption unit an attractive way of reducing their electricity. The optimal size of a system is a delicate balance between the capital expenditure – which shows economies of scale but of course, increases with the size in absolute terms –, the applicable electricity tariff scheme, the remuneration for excess electricity which varies with the wholesale price on the market, the solar irradiation, and the consumption profile. All of these factors are subject to variability, which induces risk associated with the investment. As the lifetime of a PV system typically ranges from 25 to over 30 years, it is important to take into account this variability when deciding on the optimal PV system.

Overall it can be concluded that a self-consumption unit tends to be a good investment as it is possible to achieve attractive IRR's of well over 15% for the Northern part of Portugal and over 20% for the Southern part of Portugal. Depending on the case, it is not always the best option to maximize the energy output of the system through the orientation and inclination (35-degree inclination due South), as the peak-price periods do not align with the peak of the PV production but are rather before noon and in the late afternoon. Additionally, as a system's self-consumption rate depends strongly on the consumption profile, it is important to analyse this profile. Peak consumption in the afternoon throughout the year might make that an orientation more towards the west can be a better option and an orientation perfectly to the South.

It is important to note that the optimization of the system configuration in this thesis did not take into account all the risks associated with a project with a lifetime of about 30 years. Changes in internal or external factors such as the consumption profile, or the electricity tariff directly affect the optimal size and configuration, and the profitability of the project. For this reason, it is advisable to be rather conservative when deciding on the size, in order to reduce the risk associated with the project.

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