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Assessing E3 impacts of RES integration using residential consumer's willingness to invest in PV systems

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Abstract

This paper presents an assessment of the Economic, Energy and Environmental (E3) impacts of different scenarios related to the penetration of renewable energy systems in an urban context. For this purpose, Coimbra, a medium sized Portuguese city, has been chosen as decision-making set. The results of a survey aiming at analysing and evaluating the perceptions and willingness to invest in residential photovoltaic systems, along with a technical and economic evaluation of different photovoltaic systems focusing on the installed power, together with the data characterizing the housing stock of the city, have been used for the definition and analysis of three scenarios. The obtained results, pointing to a relatively small contribution from the photovoltaic component to the overall city residential electricity consumption, may be considered by electricity operators and can help policy-makers to define stronger measures to support the installation of residential renewable energy systems.

Keywords: Economy-Energy-Environment (E3) impacts, photovoltaic systems, renewable energy systems, residential sector, willingness to invest.

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1. Introduction

Renewable energies, being of infinite supply, decentralized, and uniquely suited to their location, are the solution for cleaner and safer energy production. Increasing the generation of electricity from renewable energies can contribute to reduce greenhouse gas emissions, to decrease dependence from fossil fuels and fuel imports, to increase the safety of energy supplies and to meet sustainable energy development targets.

Portugal has privileged natural conditions for the generation of renewable energy. However, most of the energy from renewable sources is nowadays generated from large wind and photovoltaic farms, despite the fact that the potential for new small-scale installations for the distributed generation, namely in the residential sector, using endogenous renewable sources, is very considerable. Among the various renewable technologies, solar Photovoltaic (PV), or PV-based electricity, is dubbed as the most environmentally friendly and sustainable technology for electricity production and it is believed to have the largest potential for the residential sector [1].

Although the Portuguese positive attitude towards investments in innovative Renewable Energy Systems, namely solar projects and new hydropower units is high [2], the number of residential consumers adopting solar PV technologies is still relatively low, despite the fact that this activity is licensed through specific laws and there may be support measures.

Increasing the installation of PV solar systems in the residential sector could contribute to the compliance with European Union (EU) legislation on the energy performance of buildings (Energy Performance of Building Directive, 2010/31/EU). According to this directive, member states shall ensure that from the year 2020 all new buildings will have to be 'Nearly Zero Energy Buildings' (NZEB), which means, "a building that has a very high energy performance, as determined in accordance with Annex I. The nearly zero or very low amount of energy required should be covered to a very significant extent by

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energy from renewable sources, including energy from renewable sources produced on-site or nearby".

However, despite the potential of PV systems as an energy option in the urban energy system, several factors affect PV deployment [3, 4, 5]. Based on an extensive range of literature in the broader field of renewable energy, five main types of barriers that limit site suitability, economic viability, and social acceptance of large-scale deployment of the solar option are identified in [3]: 1) technical barriers - space constraints, intermittency, and power grid connection limitations; 2) economic considerations – high investment costs and long payback period; 3) market factors - misplaced incentives, unpriced costs, insufficient information and difficulty in accessing reliable information; 4) access to finance and institutional regulations - the existence of vested interests against new energy options, difficulties in dealing with permission requirements; 5) social barriers – lack of public acceptance of new energy technologies and low perceived usefulness of a new energy technology.

The Feed-In-Tariffs (FITs) scheme is the most common market driven instrument that governments, including the Portuguese Government, have been using to facilitate RES market development [6, 7, 8]. The central principle of FITs policies is to offer guaranteed prices for fixed periods, to enable a greater number of investors [9]. The scheme has rapidly increased the deployment of PV technologies at small scale since its introduction in 2008 (Portuguese Ministerial Order 201/2008). However, some researchers criticize the solar PV FITs used to incentivize consumers to acquire solar PV, because they are funded through increased electricity prices affecting lower income groups who are less capable of investing in solar technology [6].

The decline of the feed-in tariff rates is increasing the interest in self-consumption of PV electricity from residential systems (defined as the share of the total PV production directly consumed by the PV system owner) among PV system owners and in the scientific community [7, 10]. Moreover, the success of policies that encourage the uptake of solar PV in the residential sector requires consumer acceptance and engagement with new and emerging energy technologies, and their role is crucial to the implementation of energy policies [6].

In this context, the main objective of this paper is to assess the economic, energy and environmental impacts of the integration of different scenarios related to the penetration of residential PV systems, taking into account the residential consumer's willingness to invest in these systems, the individual technical and economic evaluation for different PV systems and the data characterizing the housing stock of the city of Coimbra, the city used for this purpose.

This paper is organised as follows: After the introduction, Section 2 gives a brief overview of the evolution of PV systems' legislation and support measures. The third section (Section 3) presents the consumers' willingness to invest in PV systems, while the individual technical and economic evaluation of different PV systems, considered to be installed in the residential sector, is presented in Section 4. The assessment of the E3 impacts for different integration scenarios is presented and discussed in Section 5. Finally, some conclusions are drawn, including expected future developments in this field of research.

2. Residential PV systems - the Portuguese legal framework and support measures

Some key findings of a study focused on residential prosumers in the European Energy Union [11], with prosumers as "energy consumers who also produce their own energy from a range of different onsite generators", using small scale solar PV to generate electricity, reveal that there is no harmonised regulatory framework for residential prosumers in the EU.

Member states take different approaches, have simplified procedures for setting up residential prosumer installations and differ in terms of the financial incentives given to prosumers. Furthermore, in most member states, the regulatory framework has evolved rapidly over time. The study also concludes that incentives have played an important role in promoting the development of self-generation, especially in the more mature solar PV markets.

In Portugal, renewable energy policy is in line with EU 2020 targets and Portuguese targets on renewable energy, that is, 31% of renewable energy in gross final energy consumption. The policies and measures to meet the targets were set out in the Portuguese National Renewable Energy Action Plan (NREAP) in July 2010. The Cabinet Resolution 20/2013 approved the new NREAP 2020, aiming to adjust the energy supply to the demand and to review the objective of each RES in the national energy mix, taking into account, namely, the maturity of the technology and its competitiveness [12].

Regarding electricity generation with residential PV in Portugal, Decree-law 68/2002 initially regulated microgeneration: installations that use a single production technology and have a single-phase or three-phase load operating at a low voltage, and with a capacity of no more than 5.75 kW for single houses and 11.04 kW for condominiums. According to this law, at least 50% of the electricity produced by generators and solar panels should be consumed by the producer or by connected third parties. A Ministerial Order established the method for calculating the payment due for energy produced by microgeneration units. After five years of coming into effect, the number of microgeneration units did not achieve an expressive number.

In the end of 2007, a new law promoting the microgeneration of electricity was approved. Decree-law 363/2007 defined a special and fast process of licensing where producers could register their installations via an electronic platform or SRM - System for the Registration of Minigeneration, and an interesting tariff - initial tariff of 650 €/MWh for PV systems.

The Ministerial Order 201/2008 introduced the FITs scheme and rapidly increased the deployment of PV technologies at small scale.

As of October 2010, Decree-law 118-A/2010 modifies some aspects of the microgeneration law by simplifying the application procedure and by streamlining the access to the microgeneration regime for public, social, education, defence and local institutions. Moreover, access to the benefits regime was adjusted to the cost of the equipment used in the microgeneration and subject to certain conditions, namely the compliance with energy efficiency rules and the use of solar thermal collectors or biomass boilers.

Decree-law 34/2011 and Decree-law 25/2013 complement the microgeneration regime. This new regulation simplifies the licensing regime through the new SRM electronic platform managed by the Directorate-General for Energy and Geology (DGEG).

At this time, the microgeneration law defines two regimes: the general regime, applicable to any type of microgeneration up to a limit of 5.75 kW and the special regime, applicable to renewable electricity production up to a limit of 3.68 kW. For the special regime, a reference FIT was established and applied to each technology according to a different percentage. The reference FIT for new producers reduces each year and, once defined, is valid for 15 years divided into two periods, one period of eight years and another for the remaining seven years with different tariffs for each. In 2010, the tariffs were 400 €/MWh for the first period and 240 €/MWh for the second. The mechanism includes an annual reduction rate of 20 €/MWh. In 2014, the reference FIT was 66 €/145 € per MWh for PV technologies. By mid-2014, there were 25000 installations in the special regime and 900 in the general regime, delivering a total capacity of 93 MW and 4 MW, respectively [12].

The more recent legislation in Portugal, Decree-Law 153/2014, was designed to streamline distributed electricity production, ensuring the technical and economic sustainability of the power grid, simplifying the old model of micro-production and mini-production and enabling entities with less constant consumption profiles, to be also included in this scheme.

The new Portuguese legal framework is applicable to the installation of a generation unit or *Unidade de Produção* (UP), which may take the form of a small-scale generation unit - *Unidade de Pequena Produção* (UPP) or a generation unit for self-consumption - *Unidade de Produção para Auto-Consumo* (UPAC). It provides for the same simplified licensing procedures as the previous legislation and the potential producers could conduct their licensing using the Electronic System of Registration of Generation Units (SERUP). The procedure is similar for both generation units – UPP or UPAC.

The producer must submit a request to the SERUP and pay the registration fee to the DGEG. Once the generation unit has been registered, the producer must install it using an authorised installation entity and submit a request for the inspection of the unit. If the unit has neither defects nor irregularities, the exploitation certificate will be issued, the unit will be definitively registered and the generation unit can be connected to the power grid – in the UPP case, or to the producer installation – in the UPAC case. However, there are different rules according to the type of generation unit.

A UPP is applicable to any type of RES up to a limit of 250 kW, with power grid energy injection and with a FIT for each primary energy used, according to a different percentage contained in Ministerial Order 15/2015. The reference FIT for new producers in 2015 is valid for 15 years, and has a value of 95 €/MWh, to which 5 €/MWh are added if there is 2 m^2 of solar thermal panels in the consumer's installation or of 10 €/MWh if there is an electric vehicle charging power outlet connected to the mobility grid in the consumer facility [12].

A UPAC is applicable to any kind of source since it does not benefit from a FIT, and has the possibility of injecting the surplus into the power grid, which is paid by the last-resort supplier at 90% of the average monthly market price. Optionally, a UPAC, either power grid connected or off-grid, can also trade the electricity surplus or the generated electricity by green certificates [12].

3. Consumers willing to invest in PV systems

To analyse and evaluate the residential consumer's perceptions and willingness to invest in the installation of PV systems, a survey supported in a questionnaire has been conducted in the city of Coimbra. The questionnaire design and respondents profile were presented in a previous study [13].

The questionnaire was prepared considering three groups of questions, all of multiple choice: the first group is related to the socio-economic characterization of the household; the second group deals with building characteristics; the third and last group considers questions regarding the ownership of renewable energy systems, renewable energy awareness, interest in investing in renewable energy systems and how much the household would be willing to invest in a PV system.

The questionnaire was made anonymous, distributed through Google Forms to a universe of 110 residential consumers and had 80% of the sent requests successfully answered. All the 88 respondents to the online survey are residents of Coimbra, the Portuguese city chosen for this study.

The average age of the respondents is 52, and their ages range from 25 to 78 years. Most respondents are between the ages of 25 and 40 years old (55.7%), 33% are between 40 and 60 years old, and only 11.7% above 70 years old.

Regarding the educational level of respondents, the majority are university-educated where 68.2% hold a Bachelor's or a Master's Degree and 20.5% hold a PhD Degree. Only 11.4% have graduation from a secondary school as educational level.

Besides the age and educational level, residents have been questioned about the number of persons per household, net household income and house type. Almost half of the interviewed, 48.9% live in a three or four-person household. Another large share, 43.2%, lives in a one or two-person household. Only for about 8% of the answers, the household composition is higher than 4 people.

Half of the households have an income between 1000 and 2500 €/month, 11% have an income lower than 1000 €/month and only 39% of households have an income higher than 2500 €/month.

The great majority of the respondents, 80.1%, own their house, 29.5% live in a single-family house, 12.5% live in a condominium with more than eighteen households and the majority, 58%, live in a condominium with a number of households between three and eighteen. Almost all the buildings in the sample are exclusively used for housing (85.2%).

When questioned about the interest in investing in PV systems, about two-thirds of respondents (67%) expressed no interest in this investment. Figure 1 illustrates the results obtained regarding how many residential consumers are willing to invest in a PV system, expressed as a percentage, by investment value range considered [13].

As it could be expected, the percentage of consumers willing to invest more than 5000 € is low. However, the percentage of consumers willing to invest up to 1000 € is the lowest. This result may be related to the pre-conceived idea of the cost associated with a PV system, together with the net household income of inquired consumers.

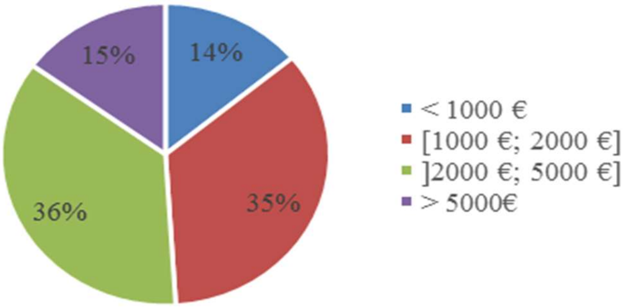


Figure 1. Percentage of residential consumers willing to invest, by investment value range.

Figure 2 (a), Figure 2 (b), Figure 2 (c) and Figure 2 (d), depict how much residential consumers are willing to invest in a PV system according to the buildings' characteristics and according to their socio-economic characterization [13].

From the analysis of the results presented in the graphs of Figure 2, as expected, there is a direct relationship between net monthly household income and investment in PV systems. 75% of respondents willing to invest more than 5000 € have a net monthly income of more than 2500 €. This percentage decreases as the income decreases, reaching no responses to incomes less than 1000 €.

Moreover, given the data on the economic evaluation of different PV systems, presented in Tables 1 and 2 of Section 4, the number of options for consumers who are willing to invest up to 1000 € is reduced. Of course, the options will increase as the amount that the consumer is willing to invest increases.

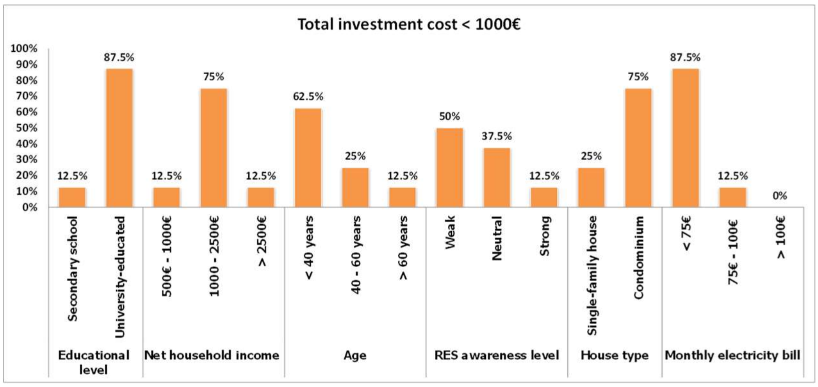
The same direct relationship exists regarding educational level. The totality of respondents who are willing to invest more than 5000 € are university educated. The younger respondents are more willing to invest. This is not surprising, as this group will correspond to consumers with greater knowledge regarding renewable energy and environmental concerns. The respondents aged over 60 represent the largest percentage of consumers willing to invest more than 5000 €.

There is no direct relationship between the amount of the monthly electricity bill and the amount willing to invest. The majority of respondents indicate a monthly electricity bill less than 75 €. Those with the highest monthly electricity bill (higher than 100 €) correspond to the highest percentage of respondents in the investment range between 1000 € and 2000 €. For consumers with monthly electricity bill between 75 € and 100 €, the largest number of responses (45%) corresponds to the investment range between 2000 € and 5000 €.

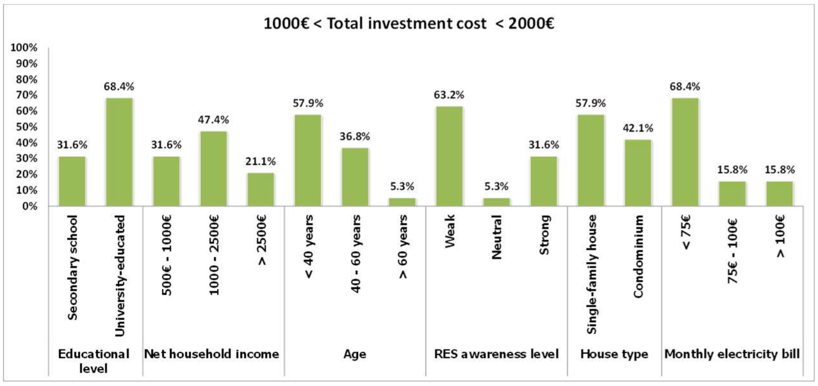
Regarding the type of household involved in the survey, we can observe that, except for the investment range between 1000 € and 2000 €, the majority of respondents live in condominiums, where the installation of a PV system may be more difficult, requiring the acceptance of all condominium owners.

The information presented in this section, about residential consumers' willingness to adopt and to invest in renewable energies, namely in the installation of PV systems, will serve as the basis for the definition of different scenarios related to the penetration of solar PV systems in the residential sector, aiming at the assessment of the economic, energy and environmental impacts of the integration of renewable energies in an urban context, to be presented and discussed in Section 5 of this paper.

To further support the definition of the different scenarios, an economic analysis of different residential PV systems, considered to be installed in the residential sector, is also conducted in Section 4.



(a)



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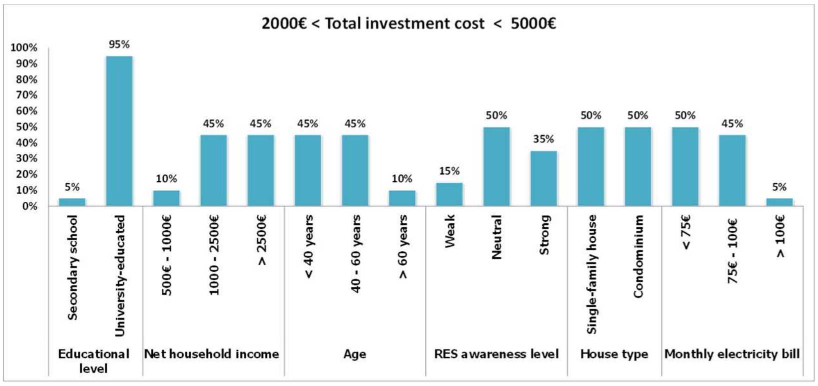

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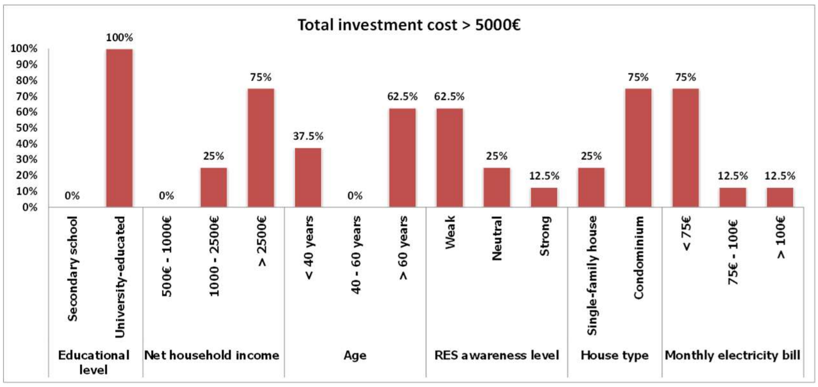

(d)

Figure 2. How much are residential consumers willing to invest in a PV system: (a) investment lower than 1000 €; (b) investment between 1000 € and 2000 €; (c) investment between 2000 € and 5000 €; (d) investment higher than 5000 €.

4. Economic analysis of different residential PV systems

An economic analysis of different PV systems that can be installed in the residential sector had been conducted. This analysis took into account the local availability of solar radiation, existing market technologies and the new Portuguese legislation concerning the promotion of renewable energy sources in households [14, 15, 16].

As referred in [17], regarding designing and sizing a stand-alone PV system, the first step of the process for the evaluation of any PV system begins by knowing the monthly and annual solar radiation values for the site and the amount of energy to be provided. In our study, the PVSYST® software has been used for the simulation of electricity production from the different PV systems considered, taking into account the average monthly values of solar radiation collected through the Meteonorm 7.2 software for the city of Coimbra (Figure 3).

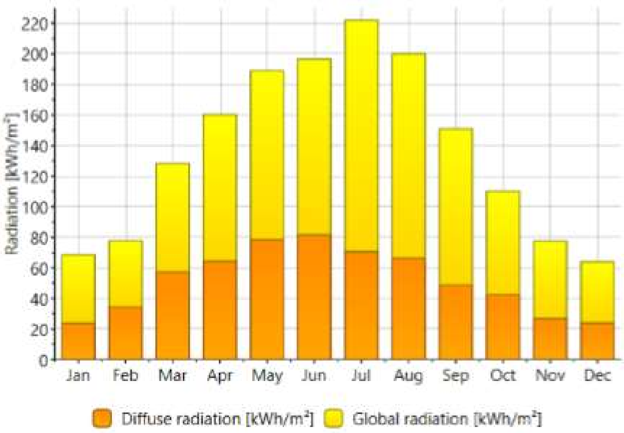

Figure 3. The monthly diffuse and global solar radiation values for the city of Coimbra.

For the economic analysis of PV systems, criteria such as Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period (PB) and Levelised Cost of Electricity (LCOE) can be used. Some of these criteria have already been used in previous works related to RES systems in general and PV systems in particular. In [18] the authors used NPV, IRR and LCOE, among other economic criteria, to assess the cost-competitiveness and profitability of fixed and PV systems with tracking mechanism. The same three criteria were selected in [19] to undertake a techno-economic analysis or three small PV self-consumption projects located in different cities of Peru. The criteria NPV, IRR and LCOE are referred in [20], where the authors use a customer-driven investment model to examine the feasibility and market potential of rooftop PV installations in an urban environment. To maximize the absolute returns for the property owners the NPV for energy production is optimised. The cost-effectiveness analysis of three different sized PV systems for the residential market is performed in five Chinese cities under China's new regulation is presented in [21] and is based on the NPV and IRR calculation along with the Discounted Payback Period (DPBP). NPV was used as the decisive financial metric in the economic analysis conducted in [22], regarding the economic feasibility study of PV rooftop systems in Sweden, carried out to examine the effects of current market conditions, incentives programmes and building specific parameters. NPV is also used as the validation index in [23], where the authors present a profitability analysis of a PV project connected to the power grid in the Argentinian residential sector, considering Net Billing scheme remuneration and comparing with the FIT scheme adopted by other countries.

The economic analysis of the different residential PV systems herein considered to be installed in the residential sector – UPAC and UPP systems, is based on the Net Present Value, Internal Rate of Return, Payback Period and Levelised Cost of Electricity, which are shortly described below.

Net Present Value

The NPV (€) takes the value of the money over time into consideration and is the most accepted standard method used in financial assessments for long-term projects. It is one of the most common metrics for measuring and comparing investments [20, 21]. The NPV of a PV project is the difference between the present values of the cash flows (in and out) generated throughout the lifetime of the project [18, 19, 20] and it can be calculated by the expression:

$$NPV = -C_0 + \sum_{j=1}^{n} \frac{C_f}{(1+d)^j}$$

where C_0 is the investment cost of the PV system, C_f is the cash flow in period j, d represents the discount rate and n is the lifetime of the considered PV system.

The decision boundary for the NPV is as follows [18,20]: for positive values of NPV the investment can be accepted and the bigger the NPV value, the more appealing it becomes. Otherwise, if negative values of NPV are obtained, the investment should be rejected.

Internal Rate of Return

The IRR is the profitability (%) expected from a project and it is the value of the discount rate (d^*) that leads to NPV=0. It represents the average earning power of the money used in the project over its lifetime [18, 19, 21]. A high IRR indicates that the investment opportunity is favourable, and in order for a project to be feasible, the IRR has to be greater than the discount rate used for the economic calculations [18, 19] and can be calculated from the equation:

$$IRR = -C_0 + \sum_{j=1}^{n} \frac{C_f}{(1+d^*)^j} = 0$$

Payback Period

The PB of a project is the time necessary to recover the project cost of the considered investment [24]. The simple PB period, used in our study, only considers the sum of the Annual Cash Flows (ACF) and the initial cost of the Investment (I). The simple PB period can be calculated according to the equation:

$$PB = \frac{I}{ACF}$$

Levelised Cost of Electricity

The LCOE (€/kWh) is defined as the constant cost of generating a unit of PV elecricity, levelled throughout its entire life cycle and referenced to the year in wich the investment is made [19, 25]. The LCOE approach considers overall installation costs occurring during the project lifespan (the initial investment cost and the annual operation and maintenance costs) and the associated energy production [26]. It can be estimated using the equation:

$$LCOE = \frac{C_{inv} + \sum_{t=0}^{N} CO\&M}{N \times E_a}$$

where C_{inv} is the total investment cost, $CO\&M$ refers to the operation and maintenance costs, N is the lifetime of the PV system and E_a is the total energy produced during the project lifespan. In our study, for the calculation of the LCOE, interest and capital appreciation are not considered.

The main results of the economic analysis for the different small-scale PV generation units, or UPP, are presented in Table 1. The life span of the PV system is assumed to be 25 years. For the investment costs of both UPP and UPAC units, 250 W polycrystalline panels were considered, together with inverter, slanted roof structure, transportation and installation, as well as registration fees. In addition, for UPAC units, the cost of batteries was also taken into consideration. The presented price values for PV systems were obtained by consulting several local suppliers, preserving their confidentiality. Also, for both UPP and UPAC units, neither liability insurance nor equipment replacement (for example batteries in UPAC units) was accounted for in the calculation of the PB.

According to the results presented in Table 1, one main conclusion is that the in-vestment in a 500 W UPP is very appealing from the prosumer point of view, in what concerns the total investment cost. However, this system presents a negative NPV, meaning that it will be a non-economically viable project.

For production units for self-consumption, or UPAC, the installed capacity considered for evaluation was decided according to the most frequent registrations in Portugal, in the SERUP platform, from March 2015 to July 2017. For the present study it was also considered that, since these are energy production systems that store the surplus not consumed by the house in batteries, to fill energy needs in periods when there is no production, all the energy produced by PV panels is consumed and not sold to the power grid. In addition, for the calculation of the PB, the simple tariff electricity price of 0.1646 €/kWh was used as reference tariff.

Table 2 presents the main results of the economic analysis for different PV generation units, for self-consumption.

An economic analysis for UPAC systems selling the surplus produced electricity to the power grid was not performed in this study. This was because, for those cases, detailed knowledge is needed on the energy consumed in the dwelling and on the energy that is sold or not sold to the power grid.

Table 1. Economic analysis of different UPP units.

UPP				
Installed capacity (W)	500	1 500	3 000	5 000
Total investment cost (€)	725	1 923	5 247	9 517
Annually electricity production (kWh)	825	2 475	4 952	8 251
Net Present Value (€)	-102.98	1 161.99	1 535.42	2 189.86
Internal Rate of Return (%)	1.55	8.12	5.59	5.06
LCOE (€/MWh)	69.09	42.39	48.04	49.53
Payback (years)	19.93	10.13	12.84	13.56
O&M costs (€)	35	35	35	35
Discount Rate (%)	3	3	3	3
Reference Tariff (€/kWh)	0.095	0.095	0.095	0.095

Table 2. Economic analysis of different UPAC units.

UPAC				
Installed capacity (W)	500	1 500	3 000	5 000
Total investment cost (€)	1 025	4 189	9 294	15 111
Annually electricity production (kWh)	825	2475	4 952	8251
Net Present Value (€)	499.25	1 602.66	2 903.95	5 619.19
Internal Rate of Return (%)	7.25	6.34	5.75	6.24
LCOE (€/MWh)	83.64	79.01	80.73	76.65
Payback (years)	10.87	11.94	12.66	12.08
O&M costs (€)	35	35	35	35
Discount Rate (%)	3	3	3	3

5. E3 impacts of the integration of residential PV systems

For the assessment of the Economic, Energy and Environmental impacts of the diffusion of residential PV systems in the city of Coimbra, three scenarios have been defined, according to the rate of PV systems considered for installation. Namely, a conservative scenario (leading to a lower rate of integration of PV systems), an aggressive scenario (leading to a higher rate of integration of PV systems) and a moderate scenario.

The definition of the different scenarios has been supported on the consumer's perceptions and willingness to invest in the installation of residential PV systems (presented in Section 3), along with the individual technical and economic evaluation for the different PV systems considered in this study (presented in Section 4), and together with the data characterizing the housing stock of the city of Coimbra (a total of 26 693 buildings, available from the last Census [27].

For each scenario, only the economically feasible PV systems (UPP and UPAC) were considered, i.e. PV systems with positive NPV values. In addition, it was assumed that the integration of the UPAC will be preferable to the UPP, taking into account the awareness for the installation of these units and the fact that the purchase price of electricity is higher than the sale price of electricity. The time horizon for the scenario analysis was set to five years.

The assessment of the environmental impacts for each scenario is based on the potential of CO_2 emissions reduction through implementing PV systems. The mitigated CO_2 emission for PV installations has been determined assuming that each renewable energy based kWh of electricity produced substitutes each kWh of electricity generated by the conventional energy systems [26]. Thus, the CO_2 emissions reduction for each scenario can be calculated by multiplying the annual electricity production by the carbon emission factor (when considering that the same amount of energy was produced by conventional options). In the present study, the considered CO_2 emission factor was 369 kg of CO_2/MWh.

Conservative Scenario

The conservative scenario corresponds to the situation where the integration rates of the different PV systems are lower. For this conservative scenario it was considered a 0% diffusion rate for the following PV systems: UPP 5000 W, UPAC 3000 W and UPAC 5000 W, taking into account the initial investment cost. For the UPP 1500 W and UPP 1500 W systems a 1% adhesion rate was considered. Finally, for UPAC 1500 W and UPAC 500 W systems, adhesion rates of 1.5% and 3% were assumed, respectively.

Once the integration scenario of the different PV systems was considered, it was possible to obtain the corresponding global impacts, which are presented in Table 3. Under a scenario with a modest rate of integration of PV systems in the residential sector, an initial investment cost just over € 181 thousand is estimated in a set of systems that will allow an annual local production of electricity of approximately 144 MWh, corresponding to a very small fraction of the total electricity consumption in the residential sector [28], and that will contribute to an annual CO_2 emissions reduction exceeding 53 tonnes.

Moderate Scenario

For a more realistic scenario, only a 0% compliance rate was considered for UPAC 5000 W systems. For the other PV systems, the integration rate varies between 1% for UPAC 300 W and UPP 5000 W and 5% for UPAC 500 W. For the remaining systems, UPP 3000 W, UPAC 1500 W and UPP 1500 W, the installation rates considered were, respectively, 2%, 3% and 3.5%.

The overall impacts obtained with the moderate scenario for the integration of PV systems in the residential sector are presented in Table 4. As expected, given the increasing number of PV systems considered to be integrated, the global impacts are more significant, assuming higher values. Both the initial investment and the annual electricity production, as well as the CO_2 emissions reduction, exceed by more than two and a half times the corresponding values obtained in the conservative scenario. The annual local production of electricity reaches approximately 385 MWh, still representing only a very small fraction of the total electricity consumption in the residential sector [28].

Aggressive Scenario

For the third and last scenario of integration of PV systems in the residential sector to be analysed, the integration rates of the different production units are more generous. In this context, more encouraging global impacts are expected and this is why this scenario can also be called the optimistic scenario. In this scenario it was assumed that all types of analysed production units will be considered for installation, with the following rates of integration: 1% for UPAC 5000 W and UPP 5000 W; 1.5% for UPAC 3000 W; 2% for UPP 3000 W; 3.5% for UPAC 1500 W; 4% for UPP 1500 W and 6% for UPAC 5000 W.

Similar to the previous integration scenarios, based on the integration rates considered for the different production units, which were defined considering the consumer’s willingness to invest in the installation of residential PV and on the other parameters previously referred, the overall impacts were obtained for the aggressive scenario and are listed in Table 5.

As expected, the Economic, Energy and Environmental impacts assume the highest values of the three analysed scenarios. However, if on the one hand the local annual production of electricity reaches almost half a million MWh, and CO_2 emissions reduction exceeds 175 tonnes annually, on the other hand, the initial investment needed exceeds € 600 thousand. Overall, it still represents a very small fraction of the total electricity consumption in the residential sector [28].

Table 3. E3 Impacts - Conservative Scenario.

PV system	Installed Capacity (W)	Investment Cost (€)	Annual Production (kWh)	CO_2 Emissions Reduction (kg)
UPP	1500	28 103.72	36 170.94	13 347.08
	3000	21 741.71	20 519.33	7 571.63
	5000	-	0	0
UPAC	500	44 939.65	36 170.94	13 347.08
	1500	86 778.28	51 271.48	18 919.18
	3000	-	0	0
	5000	-	0	0
	TOTAL	**181 563.35**	**144 132.68**	**53 184.96**

Table 4. E3 Impacts - Moderate Scenario.

PV system	Installed Capacity (W)	Investment Cost (€)	Annual Production (kWh)	CO_2 Emissions Reduction (kg)
UPP	1500	98 363.03	126 598.28	46 714.76
	3000	43 483.41	41 038.66	15 143.27
	5000	39 435.07	34 189.21	12 615.82
UPAC	500	74 899.41	60 284.89	22 245.13
	1500	173 556.55	102 542.96	37 838.35
	3000	38 511.04	20 519.33	7 571.63
	5000	-	0	0
	TOTAL	**468 248.51**	**385 173.34**	**142 128.96**

Table 5. E3 Impacts - Aggressive Scenario.

PV system	Installed Capacity (W)	Investment Cost (€)	Annual Production (kWh)	CO_2 Emissions Reduction (kg)
UPP	1500	112 414.89	144 683.75	53 388.30
	3000	43 483.41	41 038.66	15 143.27
	5000	39 435.07	34 189.21	12 615.82
UPAC	500	89 879.30	72 341.87	26 694.15
	1500	202 482.65	119 633.46	44 144.75
	3000	57 766.55	30 779.00	11 357.45
	5000	62 614.62	34 189.21	12 615.82
	TOTAL	**608 076.49**	**476 855.16**	**175 959.55**

6. Conclusions

The main objective of the present study was to analyse, evaluate and assess the economic, energy and environmental impacts of the integration of PV systems in the residential sector of the city of Coimbra, a medium sized Portuguese city. For this purpose, three scenarios have been defined according to the rate of PV systems considered for installation. Namely, a conservative scenario - leading to a lower rate of integration of PV systems, an aggressive scenario - leading to a higher rate of integration of PV systems, and a moderate scenario. Information about consumers' socioeconomic profile and about their willingness to adopt and to invest in renewable energies, namely in the installation of PV systems, collected through an online questionnaire carried out in a previous study, served as the basis for the definition of the scenarios to be analysed, according to the buildings' characteristics and according to the consumers' socio-economic characterization and electricity consumption profile.

The technical and economic evaluation for the different PV systems considered for integration in the residential sector - UPP and UPAC has been performed considering the average monthly values of solar radiation for the city of Coimbra and four criteria, commonly used in similar works: Net Present Value, Internal Rate of Return, Payback Period and Levelised Cost of Electricity.

The environmental impacts for each scenario have been based on the potential for the reduction of CO_2 emissions, through implementing PV systems, and calculated assuming that each renewable energy based kWh of electricity produced substitutes each kWh of electricity generated by the conventional energy systems. In addition, a five-year time horizon was considered for the defined integration scenarios and only economically viable PV (UPP and UPAC) systems were included. Each of the scenarios was evaluated considering the economic impacts (global investment cost), energy impacts (installed power and annual electricity production) and environmental impacts (evaluated on the basis of avoided CO_2 emissions). As expected, the higher the adoption rates for the different PV systems - UPP and UPAC units, the more significant the corresponding impacts will be.

Our classification of scenarios and associated rates of implementation were performed considering the conducted survey and the questionnaire's results in terms of the consumer's willingness to invest in PV systems. However, even for the scenario that we classified as aggressive, or optimistic, the electricity that would be produced through residential PV systems would represent only a very small fraction of the total residential energy consumption for the city of Coimbra. This means that, assuming this study can have similar results in most cities with similar characteristics and population, a much more ambitious set of incentives would be required, before a substantially higher contribution from the residential PV production can be expected.

Although the presented methodology has been developed in a national context, using a medium-sized Portuguese city as a decision-making scenario, and considering the applicable national and international legislation and support programs, it can be applied to other national municipalities, or in other countries, taking into account the specificities of each urban energy system, population and associated legal framework.

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