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Assessment of urban-scale potential for solar PV generation and consumption

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Abstract. The rise of grid electricity price and a growing awareness of climate change is resulting in an increasing number of photovoltaic facilities installed in buildings. Electricity market regulation and climatic conditions, in particular solar radiation, are the main factors that determine the economic viability of a photovoltaic facility. This paper describes a method for evaluating the potential for photovoltaic (PV) production and self-consumption for the building stock of a particular city. A GIS 3D city map is used to calculate solar irradiation. Building-level electricity use is calculated based on building type, geometry and other characteristic inferred from building age, taking the cadastre GIS as main input. The methodology identifies the realistic potential for rooftop photovoltaic installations, as well as the optimum size to be installed from an economic perspective. To represent different regulations that can affect economic viability of PV installations, calculations should adapt for the specific installation conditions and regulatory situation, as for example self-consumption and net metering. The proposed methodology is applied to a case study in Irun (Spain), where results for potential of PV generation and self-consumption for the building stock are presented. The results offer public administration a realistic view of economically viable PV potential for the city and allow to analyse different mechanisms to promote their installations. It also serves for individual electricity consumers to evaluate and optimize new photovoltaic energy facilities. Finally, it serves policy makers to estimate the repercussion of electricity market regulations on the economic viability of PV systems.

1. Introduction

Energy consumption in cities currently represents between 60% and 80% [1] of the global energy use. As the population living in cities increases worldwide, this percentage is bound to increase in the future. The expected trends for progressive electrification of heating loads and transportation, will also mean that electricity use in cities is likely to rapidly increase in the coming years, and consequently the energy supply and demand profiles in the cities will evolve.

Cities will generally need to upgrade grid and infrastructures to be able to cope with these increasing electricity demands, and this infrastructure should allow to increasingly deliver renewable electricity, if climate change objectives are to be achieved. Generation of renewable electricity on-site within the city is becoming a priority in many cities, as a solution to reduce electricity transportation and distribution losses and potentially reduce investments in grid infrastructure. From all the renewable electricity generation technologies, PV has emerged in recent years as arguably the most competitive and adequate technology for urban areas, due to its good economic and environmental performance. Costs have reduced [2] and levelized costs of PV electricity has reached grid parity in many countries [3].

Environmental benefits of PV installations are also nearly indisputable [4], as long service lives and low maintenance result on a nearly-zero impacts for their operation, and life cycle impacts have greatly reduced due to improved manufacturing processes [5].

Distributed PV electricity generation and consumption is therefore a subject of major interest for most cities, and methodologies and tools for estimation of its potential are needed to facilitate this task. This paper proposes a method for evaluation of PV potential, departing from cadastre data for the cities to create a 3D GIS map, estimate the available solar radiation, and calculate the solar PV electricity production.

As economic viability of PVs largely depends on the specific electricity market, this paper presents an evaluation for the different regulatory approaches, including economic evaluation if self-consumption or net metering schemes are applied.

2. Methodology

2.1 Calculation of building stock energy demand

The calculation of the energy demand of the building stock for the city of Irun has been done through *Enerkad,* software developed by Tecnalia in the European research project PlanHeat [6], completed and improved to allow the electricity energy consumption analysis.

The *Enerkad* tool is a QGIS based software which calculates the energy demand and consumption at the building, district or city level based on cadastral data. *Enerkad* performs a static calculation, based on the degree-day method, and obtains the energy demand for each final use: heating, cooling, Domestic Hot Water (DHW), lighting and equipment, allowing energy consumption to be obtained by type of fuel for each building. Given that the study carried out focuses on the potential of PV generation, the analysis will focus on the electricity consumption. Due to the unavailability of a representative sample of hourly electricity profiles, the national electricity consumption curve for the residential sector has been used for residential buildings [7], and an alternative profile for non-residential buildings [8].

For residential buildings the heating system is introduced in the model (gas boiler, diesel boiler, electric boiler, heat pump, etc.), in case there is an electricity need associated to heating purposes it will be considered in the electricity consumption curve.

For non-residential buildings, it is particularly relevant the fraction of electricity used for heating and cooling, which will largely vary between buildings depending on their use, age and the outside air temperature during each day.

Electricity consumption profiles are defined based on 5 main uses: cooling, lighting, equipment, heating and domestic hot water. Each one of the uses has its own characteristics:

- **Electricity for Cooling**: Covers all the cooling demand supplied by air to air heat pumps, will be mainly found in tertiary buildings.
- **Electricity for Lighting and equipment:** Covers all the electricity demand for equipment and lighting uses. The consumption profile will vary depending on the building use and the day of the week (workday, Saturday, Sunday).
- **Electricity for Heating:** Covers all the heating demand supplied by air to air heat pumps (mainly tertiary buildings) and electric boilers (some residential buildings).
- **Electricity for DHW:** Covers the domestic hot water demand met by electric boilers.
-

A complete description of the energy demand analysis methodology is presented in European projects' public reports[9] and conference papers[10].

2.2 Calculation of solar irradiation

The objective of the solar potential analysis is to quantify the potential for the integration of solar technologies on the roof surfaces of the buildings in the Municipality of Irun, considering orography, urban framework and shading resulting from constructive and natural elements

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The climatic file and the Digital Surface Model (DSM) must be modified in order to adapt it to the requirements of the used tool. It is necessary a filtered DSM file, containing only the points corresponding to the roofs of the buildings and the ground. The rest of the points in the file are deleted.

The annual solar radiation per square meter (resolution of the DSM model) is obtained for any point of the municipality (roofs and urban spaces) by means of the UMEP plugin [11] for QGIS[12]. The solar map is bounded to the municipality limits using the administrative boundary layer of the municipality.

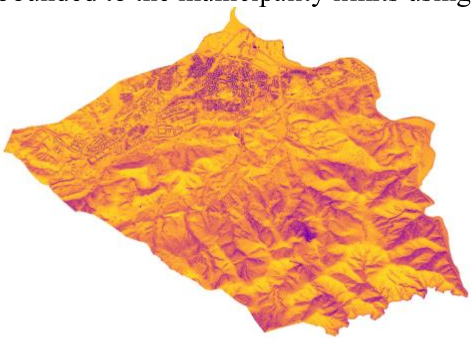

Figure 1. Annual solar radiation map of the municipality of Irun

In the solar radiation map (figure 1) all radiation levels are shown. The areas selected to study the potential PV production will have to meet several requirements and filters, as being part of the building roof and exceeding a specific irradiance threshold. To calculate surfaces where PV could be installed with a minimum economic performance (e.g. maximum return of investment period), minimum irradiance thresholds have been set and are specified in section 3.3.

2.3 Economic performance evaluation of PV installations

The economic performance of PV installations profitability and its relation with different regulations has been calculated considering that the consumer will be connected to the electricity grid, and assuming that the power term tariff will not vary when installing the PV modules. Therefore, all the economic savings quantified correspond to the energy term of the electricity bill.

For the actual electricity production, the calculation method presented in EN 15316-4-6:2007 [13] and the specification of technical conditions of installations connected to the network [14] have been used. PV production is hourly calculated for 12 days each one representing one month of the year. Irradiation values have been taken from PVGis database for the city of Irun [15].

Table 1 shows details of parameters that are used to calculate economic performance of PV installations.

Table 1. Summary of the parameters used for the economic

Parameter	Value
PV module efficiency [16]	16 (%)
Inverter efficiency [17]	95 (%)
Miscellaneous losses [18]	13%
Electricity base price for the first period [19]	0,1347(€/kWh)
Taxes on electricity (VAT) [20]	21 (%)
Annual electricity price variation rate[1]	2 (%)
Interest rate [7]	6.7 (%)
Power density of PV modules [16]	164.95 (W/m^2)

[1] Reports from the European Commission [26] show 4% annual price growth for the past years. A more conservative approach has been taken for this study. Note that higher electricity price variation rates would reduce the return period of the PV modules.

Total installation costs [21]	1.465 (€/W)
O&M costs [21]	0.02 (€/W.year)
PV modules service life [4]	25 (years)
Inverter service life	15 (years)

2.4 Economic evaluation of PV generation and consumption under different policies

There is a large degree of variations and uncertainty on the evolution of regulations for on-site PV production and self-consumption throughout the world. This paper explores three different scenarios which correspond to specific energy policies carried out or proposed in different parts of the world [22].

- **Solely self-consumption (SC)**, this first scenario reflects the current regulation system in Spain where the surplus of small PV producers is not remunerated at all. Consequently, the obligation to feed the grid with free electricity when the production exceeds the producer's energy demand stimulates smaller distributed generation facilities with no surplus electricity production and whose profitability is exclusively based on reducing the electricity bill. This approach brings on a smaller reduction of the greenhouse gas (GHG) emissions associated to electricity savings and is not able to decouple from a fossil-fuel dependent economy.
- **Net-metering,** this regulation has already been put into practice in places like California. In this study, surplus electricity is valued at retail price. Therefore, all the electricity produced with solar panels can be consumed at any other time, using the grid as a storage system. This legislation could consider different periods where the energy fed into the grid can be retrieved, daily net metering, monthly net metering, annual net metering. **Annual net metering (ANM)** is the modality chosen for the present evaluation.
- Finally, a third scenario has been represented, **"theoretical maximum potential"**. This scenario assumes that all the surface available for PV installation within the chosen irradiation threshold could be installed, and the economic return for injecting to the grid will be equal to the economic return for self-consumption. This scenario could represent regulations where electricity transactions with nearby buildings or electricity users could be allowed, or some regulations with feed-in tariffs.

3. Case study characterisation

Irun is the second largest city in the province of Gipuzkoa in the Basque Autonomous Community, Spain. It is located in the border between Spain and France and inhabits 59.508 citizens [23]. The municipality takes part in several sustainability programs and has already published its second sustainability action plan.

3.1 Origin of the data

To carry out the analysis of the potential of solar energy implementation on the roof surfaces in Irun, the following geospatial data are used:

- Digital Surface Model (DSM): 1m^2 resolution, from Geoeuskadi ftp download service [19].
- Climatic information of the study area: The climate model of the city of Donostia (15km west) available in Energy plus format (epw) with hourly resolution [24] has been used.
- Reference cartography: Cadastral basis of the buildings for the municipality of Irun, provided by the City Council of the locality and layer of administrative limits of the Basque Country obtained from Geoeuskadi [25]

3.2 Building stock electricity consumption characterisation

Based on the GIS built from cadastral data, the total rooftop area has been obtained and is shown in Table 2. As this study focuses on the study residential and tertiary buildings' energy consumption, the industrial rooftop area will be neglected. Nevertheless, it represents a significant potential area for PV installations.

Table 2. Rooftop area by building type in the city of Irun

	Rooftop area (residential and tertiary)	Industrial and other rooftop area	Total
Total	774.336,70 m^2	428.017,64 m^2	1.186.305,93 m^2

Table 3 presents the results from the electricity consumption simulation done with *Enerkad* tool [9], [10], as explained in section 2.1.

Table 3. Building stock energy characterisation for the city of Irun

	Unit	Value
Total electricity consumption	kWh/year	124.050.535,95
Cooling	kWh/year	1.145.746,85
Lighting and equipment	kWh/year	71.174.294,34
Heating + Domestic Hot Water	kWh/year	51.730.494,76

3.3 Calculation of surfaces with a minimum solar irradiation threshold

To determine PV installations that would have a minimum economic return under optimum circumstances (all electricity used or sold at cost price) two different irradiation thresholds have been selected. Table 4 shows the thresholds and their estimated return of investment, considering energy savings, installation and maintenance costs,

Table 4. Return of investment periods for different irradiance thresholds

Irradiance threshold (kWh/ m^2 year)	Return of investment (years)
1100 (kWh/ m^2 year)	<10 years
925 (kWh/ m^2 year)	<12 years

As it can be seen in figure 2, most roofs with North and even with west slopes are automatically dismissed in the upper threshold, due to the shades associated to their orientation.

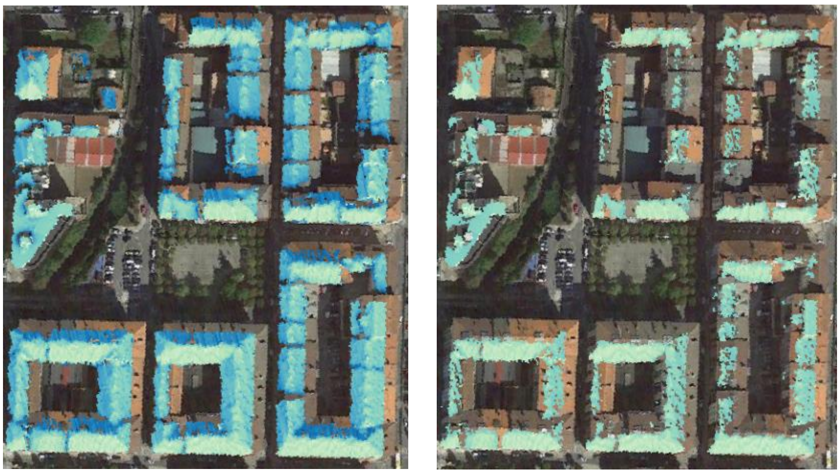

Figure 2. Solar radiation considering different thresholds (left: 925 kWh/m^2 and right: 1100 kWh/m^2)

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Crossing this data with the cadastral base layer of the municipality, 2 parameters will be calculated: the roof surface with a radiation greater than the established threshold and the average radiation in the surface in which the radiation is greater than the stablished threshold. Based on the average solar irradiation and available roof surface, solar production potential will be calculated building by building.

3.4 PV optimization based on economic performance and possible legislations

Since solar resource is not available on demand and must be exploited during a limited period of time, the correct planification and dimensioning of the facility is of great importance to pursue its maximum profitability. National regulation for distributed generation plants has a direct impact on the design of the facility, as it determines the economic revenue of the installation, or the size of installation to achieve a minimum profitability.

For the calculation of the energy balance to determine the optimum profitability of a PV installation, a standard building, representative for Irun has been used as a reference. The building consists of 32 dwellings divided into 5 floors and it is oriented north to south with a flat rooftop. For the purpose of this study, the solar electricity production will be shared by all the dwellings in the building.

Taking such building as a reference, the energy consumption and PV production curves have been calculated for each month of the year. Then, the costs and savings for the PV facility have been calculated and a sensitivity analysis performed to find the optimum peak power of the PV installation.

When considering the legislation in the calculation of costs and savings, it is necessary to study the coupling of the electricity production and consumption, especially in the "self-consumption only" case, where all the surplus electricity would be lost without obtaining any profitability. In figure 3 the generation and consumption coupling can be seen for two PV installations cost-optimized for both regulations (optimized based on the results from the sensitivity analysis shown in figure 4).

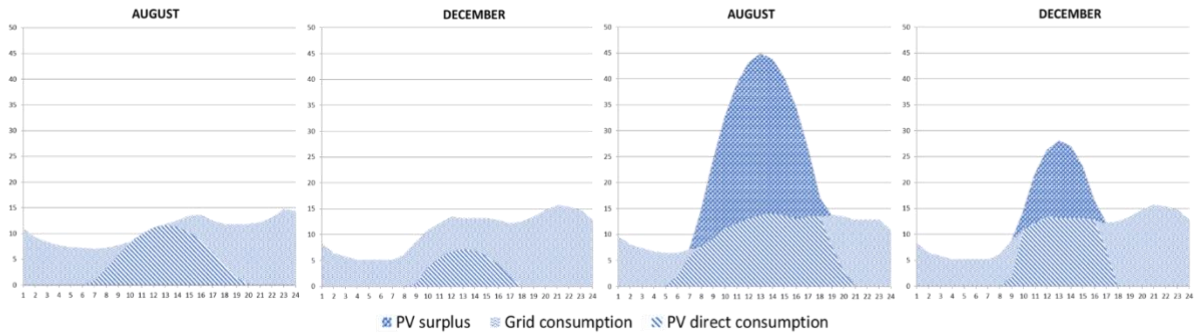

Figure 3 Comparison between the month with the highest electricity surplus (August) and the month with lowest electricity production (December). Installation designed for an optimum profitability under Self-Consumption and Annual net Metering regulation according to results from figure 4.

As the installed power of a PV facility increases or decreases, the energy balance pictured above varies, consequently varying the amount of surplus electricity and savings. In Figure 4 it can be seen how this modification on the size affects the benefits and how the profitability starts dropping once the energy surplus increases. The optimum point for a PV power plant stands as for 1kW per dwelling in case of self-consumption regulation and about 2,25 kW per dwelling in case of annual net metering regulation.

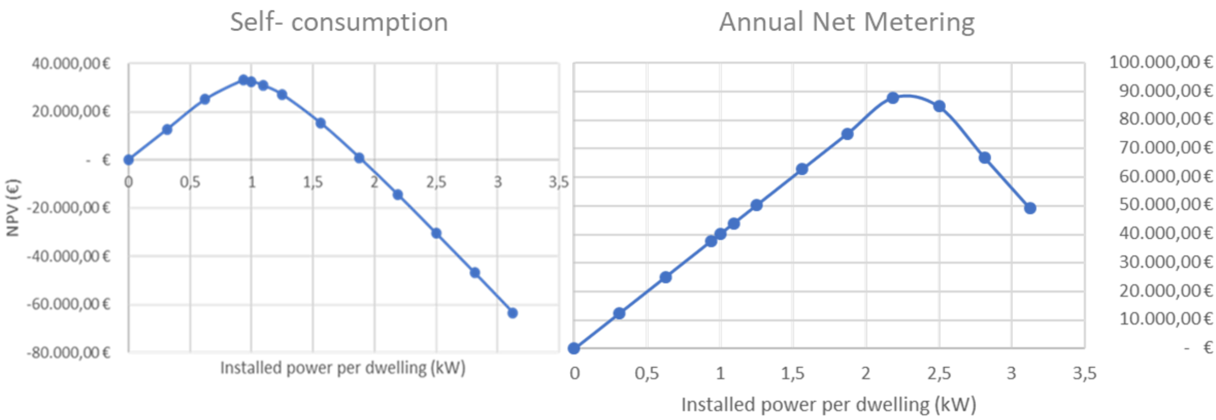

Figure 4. PV plant dimensioning NPV curve for Self-consumption and Annual Net metering regulations.

The optimum points from the NPV curves presented above follow the next behaviour:

- **Self-consumption:** the optimum case consumes 100% of the electricity consumption. No electricity in injected into the grid and **29,23%** of the annual electricity demand is met by PV panels.
- **Net metering:** In this case the grid is used as a storage and the optimum PV installation should be able to feed a **100% of the total annual electricity demand** of the dwelling, even if only **48,90%** of the electricity produced by the PV panels is **instantaneously consumed**.
- **Theoretical maximum potential: 100%** of the electricity produced by the panels could be indistinctly used and sold, with the same economic return.

For the analysis of the economic profitability of PV installations, maximum size of PV installation will be therefore determined as follows, for the different irradiation thresholds:

- Self-consumption: 29% building demand
- Net metering: 100% building demand
- Theoretical maximum potential: 100% available building roof surface

4. Results

Combining the calculations presented in the previous sections the optimized PV potential of the city of Irun has been calculated. These results show the available area which complies with good solar irradiance and sufficient economic profitability, considering also the current legislation.

Table 5. Installable surface for investment return period under 10 years

	Theoretical maximum	Self-consumption only	Annual net metering
Installable surface	269.822 m^2	149.039 m^2	248.452 m^2
Percentage of rooftop surface in the city	35%	19%	32%
Approximate installable power	44,50 MW	29,73MW	40,99 MW

Table 6. Installable surface for investment return period under 12 years

	Theoretical maximum	Self-consumption only	Annual net metering
Installable surface	550.287 m^2	207.098 m^2	439.466 m^2
Percentage of rooftop surface in the city	71%	27%	57%
Approximate installable power	90,79 MW	34,17MW	72,51 MW

In the following table the energy share of PV power in the city is calculated.

Table 7. Solar power energy share. Percentage of building stock electricity consumption fed by solar PV.

Threshold	Theoretical maximum	Self-consumption only	Annual net metering
1100 kWh/m^2.year	32%	17%	29%
925 kWh/m^2.year	59%	24%	48%

For PV installations to have a return of investment below 10 years (irradiation above 1100 kWh/m^2.year), with current regulation in Irun (self-consumption), only 19% of the roof surface could be installed, and 17% of the total electricity use of the building stock could be produced and consumed. If regulation would evolve to an annual net-metering scheme, 32% of the available roof surface and up to 29% of the electricity use in buildings could be supplied by PV. The theoretical maximum potential of PV installations in the city for this 10-year return of investment could reach 35% of the roof area and provide 32% of the total electricity use.

These numbers largely increase if the return of investment is extended to 12 years (irradiation above 925 kWh/m^2.year, as many other roof surfaces would become available. As it can be seen in Table 7, for this case up to 24% of the total building electricity use could be supplied under self-consumption scheme, 48% for annual net metering, and 59% for the theoretical maximum production.

5. Discussion and conclusions

This study has shown a methodology to calculate the potential for PV electricity generation and consumption in cities. The methodology allows the calculation of potential for installation of economically viable PV generation systems in buildings across a city, under different regulatory schemes such as self-consumption or net metering. This type of study is expected to be very useful for city energy planning, as it allows to estimate PV generation potential in roofs, which could represent a significant share of the total building energy use in the cities.

For the presented sample case of Irun city, located of North Spain with an average annual radiation of 1,300 kWh [15], which is one of the lowest for a Spanish city, up to 24% of the total building electricity use in the city could be supplied by PV panels under current self-consumption regulation. This percentage of building electricity supply would rise up to 48% if annual net metering were in place, and to 59% for the theoretical maximum production of PV panels in roofs. These calculations are for profitable installations with a return of investment of 12 years, which equals a IRR of 7%, taking into account that these installations have a service life of 25 years. With this attractive economic performance, business models and financial schemes should be explored to promote the progressive and rapid deployment of installations and make use of this solar resource currently unexploited.

Even though cities embark in sustainable energy strategies and climate change mitigation action plans, it is important to note that in coming years building electricity use is expected to increase, due to the progressive electrification of transport and heating loads. It can be expected that a larger share of the available solar PV surfaces in the roofs in the city could be used for building self-consumption. The implications of this PV generation on the electricity grid would in principle be beneficial, as would mean practically no changes to the current electricity grid and can reduce new infrastructure requirements for the grid.

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References

[1] European Commission, "Policies, information and services. International action on climate change." [Online]. Available: https://ec.europa.eu/clima/policies/international/paris_protocol/cities_en. [Accessed: 28-Feb-2019].

[2] IRENA, *Global Energy Transformation: A Roadmap to 2050*. 2018.

[3] International Renewable Energy Agency (IRENA), *Technology Roadmap*. 2018.

[4] A. Sagani, J. Mihelis, and V. Dedoussis, "Techno-economic analysis and life-cycle environmental impacts of small-scale building-integrated PV systems in Greece," *Energy Build.*, vol. 139, pp. 277–290, 2017.

[5] V. V. Tyagi, N. A. A. Rahim, N. A. Rahim, and J. A. L. Selvaraj, "Progress in solar PV technology: Research and achievement," *Renew. Sustain. Energy Rev.*, vol. 20, pp. 443–461, 2013.

[6] European Comission, "European Union's H2020 Programme, 'PLANHEAT Project.' 'Grant Agreeement' 723757, as part of the call H2020-EE-2016-RIA-IA." .

[7] L. Basterra and C. Legarza, "Instalaciones fotovoltaicas aisladas y conectadas a la red eléctrica," 2017.

[8] De Monfort University, "Demand side in the non-domestic sector Final report," Leicester, 2012.

[9] PLANHEAT project, "D2.1 –Models for mapping and quantifying current and future H&C demand in cities."

[10] X. Oregi, N. Hermoso, E. Arrizabalaga, L. Mabe, and I. Munoz, "Sensitivity assessment of a district energy assessment characterisation model based on cadastral data," *Energy Procedia*, vol. 147, pp. 181–188, 2018.

[11] F. Lindberg *et al.*, "Urban Multi-scale Environmental Predictor (UMEP)." .

[12] QGIS Development Team, "QGIS Geographic Information System." Open Source Geospatial Foundation, 2009.

[13] BSI, "EN 15316-4-6:2007 (E). Heating systems in buildings. Method for calculation of system energy requirements and system efficiencies. Part 4-6: Heat generation systems, photovoltaic systems," 2008.

[14] Institute for Energy Diversification and Saving - IDAE, "Energía Solar Fotovoltaica: Pliego de Condiciones Técnicas de Instalaciones Conectadas a Red," *IDAE*, p. 46, 2011.

[15] Institute for Energy and Transport and Joint research centre, "JRC's Directorate C, Energy, Transport and Climate - PVGIS - European Commission." [Online]. Available: http://re.jrc.ec.europa.eu/pvgis/. [Accessed: 19-Jul-2018].

[16] Jinkosolar, *JKM270P-60 255-270 Watt Polycristaline module*. 2015, pp. 1–2.

[17] Technosun, "Catálogo de energías renovables. Equipos y componentes para instalaciones solares fotovoltaicas," Valencia, Spain.

[18] S. Ekici and M. A. Kopru, "Investigation of PV System Cable Losses," *Int. J. Renew. ENERGY Res.*, vol. 7, no. 2, 2017.

[19] "2.0A | GoiEner," 2018. [Online]. Available: https://www.goiener.com/tarifas/2-0a/. [Accessed: 23-Jul-2018].

[20] Agencia Tributaria, "Tipos impositivos en el IVA," no. 1, 2019.

[21] Spain's Photovoltaic Union - UNEF, "National Survey Report of PV Power Applications in Spain," p. 7, 2016.

[22] J. López Prol and K. W. Steininger, "Photovoltaic self-consumption regulation in Spain: Profitability analysis and alternative regulation schemes," *Energy Policy*, vol. 108, no. June, pp. 742–754, 2017.

[23] Eustat. Instituto Vasco de Estadistica, "Datos estadísticos de la C.A. de Euskadi." [Online]. Available: http://es.eustat.eus/municipal/datos_estadisticos/irun.html.

[24] National Renewable Energy Laboratory (NREL), "EnergyPlus." .

[25] Eusko Jaurlaritza / Gobierno Vasco, "geoEuskadi." .

[26] European Comission, "Energy prices and costs in Europe," no. August, pp. 1074–1083, 2014.