Techno-economical potential of photovoltaic solutions in the urban environment

A web-based decision support model at high spatio-temporal resolution for residential buildings in Portugal

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Abstract

There are currently multiple tools available for the assessment of the technical and economic potential of photovoltaic installations in urban environments. The research described in this paper aims to close some gaps identified in these tools which compromise the applicability of the information obtained, namely in respect to the scale, potential use of building integrated photovoltaics on façades, integration of high granularity morphological and meteorological information and detailed modeling of the performance of photovoltaic systems.

To this end, a calculation methodology for the technical and economic performance of photovoltaic solutions at the local scale for urban residential buildings was developed and implemented, adapting it to the Portuguese reality. A comprehensive gathering of information about the current state of the art, analysis methods and legal framework was carried out, and from it a new methodology was derived to integrate 3D-GIS morphological and meteorological information with technical and economic performance models of photovoltaic systems and their legal and fiscal constraints, enabling the determination of financial performance indicators for user designed photovoltaic solutions.

This methodology is subsequently applied to a case study in the borough of Alvalade in Lisboa, and the results for rooftop and façade mounted photovoltaic systems are analyzed and discussed, revealing good agreement with current market reality and reinforcing the notion of the economic viability of both types of photovoltaic systems, contributing to their potential for dissemination. The inclusion of façade photovoltaic systems as a complement to rooftop systems is desirable and economically advantageous, lending support to further uses of 3D-GIS for these applications.

Key Words: *PV* *BIPV* *Modeling* *Technical* *Economic* *Local* *3D-GIS*

Introduction

The European commission set itself ambitious goals towards decarbonization of the economy, with targets to reduce greenhouse gas emissions to 40% below their 1990 level by 2030 (Psomopoulos, et al., 2015), whilst making energy systems more competitive, secure and sustainable. Nowadays 40% of photovoltaic (PV) installations occur on buildings, so the building sector has a significant role to play in PV development, reflected in the directive delivered by the EU on Energy Performance in Buildings (EU, 2010).

It is against this background that the main goal of this research is developed, consisting in the creation of a web-based decision support tool for residential PV systems in urban buildings in Portugal. To this end, it includes the study and development of a methodology to assess the technical and economic potential of urban PV solutions on rooftops and façades, adapting the existing approaches to the requirements of a web-based GIS user interface and its underlying datasets.

The methodology will employ commonly used tools in wide scale urban solar potential estimation, for a local bespoke application on tilted rooftops and façades within a 3D-GIS city information model (CIM), with high spatio-temporal detail, explicitly modeling the photovoltaic system technical and economic performance, its behavior throughout the lifecycle, and tailoring it to the constraints of Portuguese urban PV legal and fiscal framework.

This methodology will quantify the technical and economic potential of urban photovoltaic (PV) and building integrated PV (BIPV) solutions on rooftops and façades, with a view to support decision making by the stakeholders of different urban photovoltaic systems.

This paper details the steps in the development and application of this tool. Firstly, the state of the art was reviewed for solar potential assessment methods in cities, technical and performance characteristics of PV technologies, PV system technical, production and economic assessment methods, cost breakdown of PV systems components and the legal framework for this kind of technological deployment.

The possible contributions to the current state of the art were thus identified and formed the basis for the development of a conceptual model. This involved the choice of a software tool for the PV simulation, its adaptation for the stated objectives, and the development of the model´s three components: Input Data, Interface and Simulator. The model is then applied to a case study in Lisbon, with both rooftop and façade systems´ performances and sensitivities to external factors analyzed in depth. This paper concludes with the appraisal of its contributions to the current literature and the limitations of the approach.

State of the Art

Assessing Solar Energy Potential in Cities

To quantify solar resource availability solar radiation, models estimate the extent of radiation incident at a specific point at the earth's surface, direct or indirectly, by taking into consideration geographic, meteorological and temporal factors.

Bearing this in mind, besides the geographic location and natural features of the surrounding area being determining factors in the solar irradiance, other topographical features such as the building´s footprints, volumetric distribution, shape, color and albedo can all have a significant impact on the amount and quality of available sunlight for electricity production in an urban setting (Compagnon, 2004). As such, a detailed model of the study area is recommended to account for all impacting variables.

GIS tools are particularly adequate for solar exposure and shadowing calculations (Biljecki, et al., 2015), given the extensive availability of GIS databases with planimetry, altimetry and surface features of many urban areas, and many energy models and techniques have been developed for this purpose in recent years (Ratti et al., 2005). Extensive reviews of the multiple solar potential analysis models and their evolution can be found in Freitas et al., (2015) and Martin et al., (2015), and 3D-GIS approaches are currently implemented in commercial software products specific for climatic and energy analysis, often by integrating tools for quantifying the incident solar radiation such as *EnergyPlus* and *Ecotect* (Marsh, 2004). Recent applications of 3D solar potential assessment methodologies include Eicker et al. (2015), Liang et al. (2015), Sarralde et al. (2015), Peronato & Rey (2016), Machete, et al., (2016) and Rodriguez et al. (2017), which address a wide range of issues in the fields of urban planning, solar exposure estimation, vegetation modeling and urban PV production.

PV production is also dependent on the available irradiated area for PV deployment. GIS methods use 3D models to account for area limitations to deployment given a range of constraints, including but not limited to construction constraints, legal constraints, shading effects, and service and separation requirements of PV panels (see Gagnon et al., (2016) and Rodriguez et al., (2017)). A complete review of existing methods for estimating the fraction of rooftop area suitable for PV deployment over large areas can be found in Melius et al., (2013), and a methodology for the estimation of façade suitability can be found in Esclapes et al. (2014).

Solar and photovoltaic energy potential analysis is progressively adapting to detailed 3D representations and spatial analysis, with no standardized procedures or consensus on methodologies. Most of the research has focused on urban-scale assessment of solar radiation of PV yield, with simplistic assumptions regarding the technical performance of PV panels when installed in complex 3D environments. The current open-source state of the art for spatial attribute query and manipulation is CityGML, while another common option is the ESRI CityEngine (complemented with analysis tools from ArcGIS, see Freitas et al., (2015)). Much effort is still needed to accomplish the creation of a 3D urban model that brings together all the features that existing 2D models can offer.

The most complete simulation methods to estimate PV technical and economic performance start out by generating a solar map, detailing the potential for urban PV production with varying levels of spatiotemporal resolution, then combine this information with technical and economic variables specific to photovoltaic performance, enabling analysis of bespoke PV solutions for a certain area or building, while detailing the costs and savings associated with it. Making it web-based (web-based solar maps) and user-friendly allows for a wider audience (e.g. residents, business owners, urban & energy planners and decision makers) to analyze the potential for solar PV, facilitating the proliferation of distributed renewable energy generation (Dean, et al., 2009). An extensive review of commercially available web-based solar mapping tools was undertaken, which included Mapdwell, PVGIS, PVWatts, SAM, CH2M Hill, RET Screen, Solargis and HOMER, with in depth comparisons found in Dean, et al. (2009), Yates & Hibberd (2010), Kuiper, et al. (2013), Psomopoulos, et al., (2015) and Freitas, et al., (2015). For a review of PV component technical performance models see Yates & Hibberd (2010), and for examples of their application for PV production estimation consult Jakubiec & Reinhart (2013) and Chow, et al. (2016). For a complete overview of models for PV economic performance assessment refer to Short, et al. (1995), Eiffert & Thompson (2000), Eiffert (2003), and Brown, et al. (2016), with for application examples consult Bortolini, et al. (2014), Fath, et al. (2015), Lang, et al. (2016), Pereira, et al. (2016b), Lazard (2017) and Fu, et al. (2017).

Conceptual Model

Following the state of the art review, a conceptual model was designed, divided into three blocks consisting of the Input Data (i.e. the 3DGIS/CIM model and irradiance, shading and meteorological model for the study area), the Interface (between the user, the model and its many components) and the Simulator, modeling the PV Technical, Production and Economic Performance (Figure 1).

Input Data

The starting point for the analysis will be a 3DGIS/CIM model of solar radiation exposure in Lisbon´s Alvalade neighborhood, based on the work of Machete (2016) and Silva (2016) providing the necessary data on solar resource availability, quality and physical availability of area for deployment.

The 3D model of the Alvalade neighborhood in Lisbon was developed resorting to a computer-generated architecture (CGA) created in ESRI CityEngine. Based on the buildings´ footprints a volumetric representation of the neighborhood was achieved at LoD2. Individual surfaces representing typical PV panel dimensions are created within CityEngine on the 3DGIS/CIM model, for both rooftops and façades, and imported into ArcGIS. The irradiation data was derived by the methodology in Machete (2016), building on the model of Silva (2016), to compute the incident solar radiation on the study area, accounting for shading at the urban level and excluding vegetation. For each surface, a yearly plane-of-array irradiation profile for all 8760 hours is generated using EnergyPlus software and the Lisbon TMY 2005 meteorological data set, which is stored in a Database, along

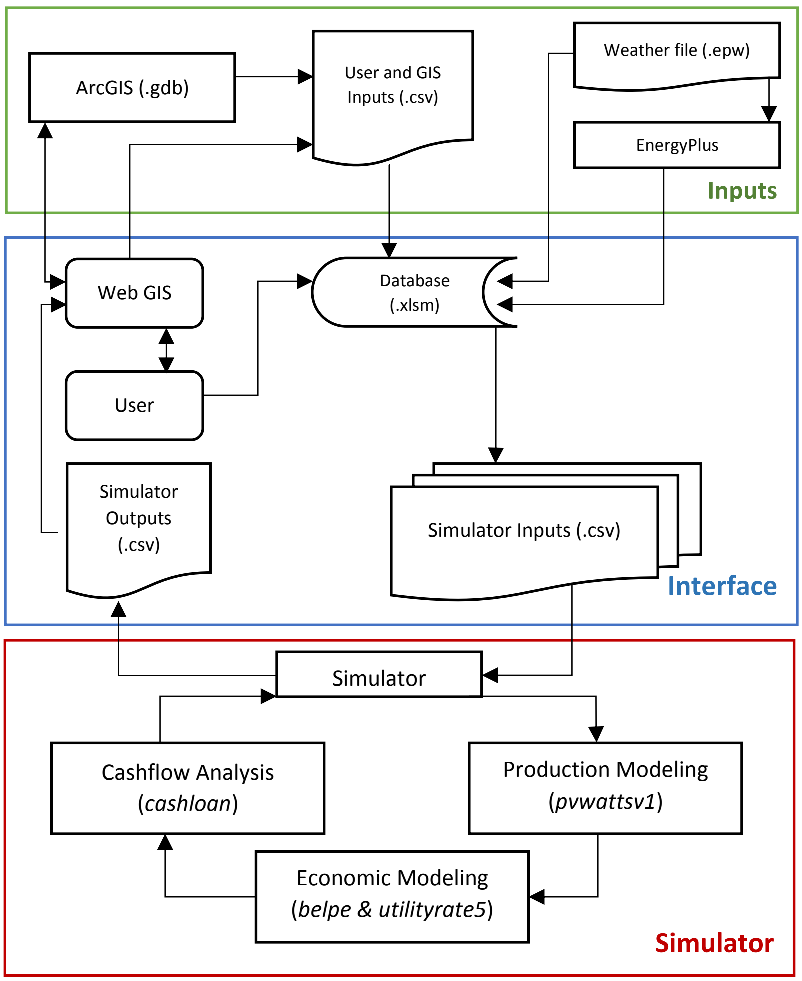

Figure 1 - Flowchart for the Conceptual Model

with the weather file, and user inputs for PV system design and simulation assigned through the user interface in ArcGIS described in the next section.

Interface

To connect the inputs of the previous section and the PV simulator, an interface had to be designed, to allow the two-way communication across software platforms and between the user and the simulator.

The query and manipulation of the data will be done via a webGIS interface available on the internet, which will enable the user to interact with the 3D-GIS model within ArcGIS, select and design the PV system and run the simulation. The GIS and irradiance data shall be displayed on a 3D model within the web GIS platform, with appropriately defined access policies for the manipulation of the model by the user. While visualizing the buildings´ morphology and its irradiation levels, the user will be prompted to design his PV system by selecting pre-determined building surfaces on the rooftop and façade and defining, on a standardized form, the variables relevant to the technical (e.g. module type, system losses, inverter type and efficiency) and financial performance (e.g. financing structure, occupancy, utility bill details). The selected panels and the systems´ user defined design properties are then run through the Database to retrieve the corresponding yearly irradiation profiles for each panel, and generate the required input files for the simulator. At this point three different assumptions are made about system performance dependent on inverter choice, and reflective of their operational characteristics: i) if no inverter type is chosen, an average of the irradiation in each time step for all panels is assumed as the input for all panels; ii) if a string inverter is selected, the minimum irradiation at each time step on the PV array is assumed on all panels (representing thusly the production cap set by the lowest producing panel at any given moment); and iii) if micro inverter is selected, the real irradiation incident on each panel is assumed, and each panel is simulated individually.

Simulator

NREL´s SAM software development suite was chosen (version 2017.1.1), implemented through an Excel macro written in VBA language (Visual Basic), on a macro-enabeld Excel workbook, running SAM´s Simulation Core (SSC) with the macro, and interacting with ArcGIS via shared *.csv* files. The flat plate PV modeling was handled by the PVWatts calculator (*pvwattsv1* module in the SSC) followed by the financial model for a residential project. This involves the determination of a load profile and produced energy value, calculated by SAM´s inbuilt modules (respectively referred to in the SSC as *belpe* (building electricity load profile estimator) and *utilityrate5)*, to subsequently determine and analyze the cash flow of the project.

All of SAM´s computation modules were extensively adapted for the specifics of this case, the most notable changes affecting the *pvwattsv1* module, namely the use of user provided irradiation values and the inclusion of different module types and different calculation methods dependent on inverter choice. The use of user supplied plane-of-array (POA) irradiance values overrides the in-built irradiance calculator of *pvwattsv1*, directly applying the POA values to assess the performance of the system by explicitly modeling the reflective behavior of the module cover, the operating temperature, the PV module DC output, the inverter´s AC output and all losses incurred in this energy transformation according to the user supplied system design inputs, to create an hourly production profile for 8760 hours for the user defined system. For string inverters (or no inverter type chosen) the Production Modeling of the array will be simulated as a single entity, the capacity being the sum of the individual panels´ nameplate capacities, while for micro inverter systems individual simulations of Production Modeling are run for each panel, with the sum of the panels´ resulting AC output serving as inputs into the remaining modules of the simulator. A detailed analysis of the PVWatts modules can be found in Dobos, (2013) and Dobos (2014).

For economic modeling, the inbuilt *belpe* module was used which estimates hourly consumption load profile following the guidelines laid out in Hendron & Engenbrecht (2010), taking as its inputs the building´s square footage, occupancy, type and number of appliances and temperature settings, coupled with weather parameters from a weather file and monthly aggregate consumptions for one year (corresponding to the utility bill consumptions for each month).

Because the residential system is a UPAC (*unidade de produção de auto-consumo*), the metering structure of the *utiliyrate*5 module should correspond to a single bidirectional meter, with no monthly rollover in credits, representing the compensation calculation of net-billing, with cumulative hourly excess credited to current month bill at sell rate (i.e. the system only buys the difference in each time step between the load and the system production at buy rate, and only sells if system production is above load in that hour, at the appropriate sell rate).

The utility bill costs for the consumption profile with and without the PV system can thus be calculated and subtracted, giving for each year the estimated utility bill savings.
The cash flow analysis takes as its inputs, besides the yearly production, load and utility bill savings calculations of the previous modules, the following: i) system costs, including installation, operation and maintenance costs for the system; ii) financial parameters, including loan (type, rate, period and share), inflation, discount, tax, and insurance rates, and iii) incentives. The total installed cost is accounted for in Year 0 of the project cash flow, and it is the sum of direct (modules, inverters, BoS, installation labor, installer margin and overhead) and indirect (permitting, engineering and development, grid interconnection, land purchase, sales tax rate) capital costs. O&M costs represent annual expenditures on equipment and services that occur throughout the lifetime of the project and are reported in the cash flow in years 1 and later
For all years in the analysis period, annual utility bill savings, installation and operational costs, loan payments and taxes are reflected in the after-tax cash flow (net of financing) and the project cash flow, which in turn are used to calculate the payback period, Net Present Value (NPV), equity and project Internal Rate of Return (IRR) and real and nominal Levelized Cost of Energy (LCOE) of the PV system over its lifetime. These calculated financial performance metrics are subsequently exported and can be displayed on the 3D-GIS model, and appended to the attribute table of the user designed PV array.

Case study

Case presentation

The case study for the model will be a residential UPAC on nº10 in Rua José d´Esaguy, with residential uses on all 4 floors and 2 apartments per floor. The building was modeled in CGA, imported into ArcGIS, with 222 detailed building surfaces representing useable areas for PV deployment and irradiation calculations. Of these, 16 rooftop surfaces and 56 façade surfaces (Figure 2 and Figure 3) were selected as the basis for analysis.

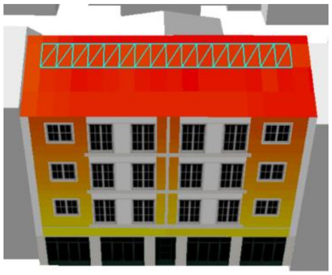

Figure 2 – Selected Rooftop Surfaces

Figure 3 – Selected Façade Surfaces

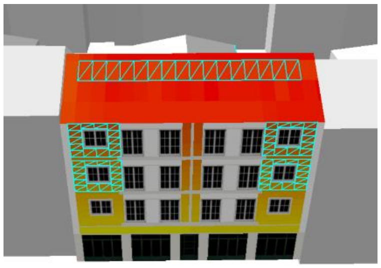

Figure 4 – Selected Rooftop+Façade Surfaces

To assess the impact of the different input variables on the system economic performance, a large set of comparative simulations was run for both rooftop, façade and mixed solutions (Figure 4). Starting from a reference simulation, the impacts of module type, inverter type, varying consumption, utility buy-rate structure, installation cost, VAT, debt parameters, inflation, sell-rate and irradiation are analyzed and quantified for rooftop and façade systems. From these comparisons ideal rooftop and façade PV system designs are proposed and their isolated and joint performances assessed.
For the load estimation, building attribute characteristics are provided by the user, while standard values for energy consumption and occupancy are assumed, derived from ENERTECH (2002) and updated with census data from PORDATA (2016), but can be user defined.
No production or consumption load escalation is assumed for the whole simulation, and system hourly calculations are only run for the first year, with all other years scaled according to the specified panel degradation (assumed 0.75%/year over a 25-year analysis period).
To estimate the utility bill annual savings in *utilityrate5*, two of EDP Comercial´s (Portuguese electricity retail leader) buy-rate structures are used: a flat structure and a bi-hourly, daily cycle time-of-use (TOU) structure, with the user given the option to select the structure and the contracted capacity to the retailer. The sell rate is determined by the DL 153/2014, and dependent on the average wholesale electricity price for each month.

Previously obtained estimates of total installed system costs/W_{DC} in Portugal (dependent on the user´s PV module and inverter choices, and new or retrofit construction) will serve as input into the model (Table 1), and multiplied by the aggregate system nameplate capacity. These costs are based on the analysis in IEA (2017), complemented by the research of Heinstein, et al., (2013), Barbose & Dargouth (2016), Horowitz, et al., (2017) and Fu, et al., (2017).

PT Installed System Cost [€/W]						
Standard; Source: IEA (2017)				**Premium and New Construction**; Source: Barbose & Darghouth (2016)		
Total Installed System Cost in 2016	Module Cost (45.37%)	Inverter Cost (16.01%)	BoS Cost (16.01%)	Premium vs. Standard (-13.33%)	New Construction vs. Retrofit (-11.36%)	Premium and New Construction vs. Median (-16.67%)
2.2	1.00	0.35	0.35	1.91	1.95	1.83
Thinfilm; Source: Heinstein, et al.(2013) & Horowitz, et al. (2017)				**Inverters**; Source: Fu, et al. (2017)		
Total Thinfilm installed system cost		Thinfilm module cost		Weighted scenario (IEA, 2017)	Microinverter vs. mixed case (+11.8%)	String inverter vs. mixed case (-5%)
1.18		0.40		2.2	2.46	2.09

Table 1 - Calculated Installed cost metrics for PV in Portugal in 2016

Estimates for O&M costs vary considerably between studies, but this model will adopt the Fu, et al., (2017) estimate of 19.01€/kW_{DC}. For component replacement cost, as micro inverters typically have a warranty beyond lifetime of the project, this model will assume they require no replacement. For the string inverters, which typically last about 15 years before replacement, this model will assume replacement halfway through the lifetime of the project, and the cost associated with it is 16.01% of total installed cost, applying to all simulations for the "No Option" or "String" inverter choices.

A standard loan type will be assumed for this project with a conservative value of 3% on the interest rate, with a loan term of 7 years (with these values being editable by the user). The analysis period for the project will be 25 years, and the default inflation rate will be the forecast from the *Banco de Portugal* for the period 2018-2020 of 1.5% (Banco de Portugal, 2018), extended to the remaining analysis period, with a possibility for the user to specify an alternate inflation rate.

The real discount rate will be assumed equal to the weighted average cost of capital (WACC) reflecting the actual cost of financing the project, but this will be editable by the user to reflect his own return expectancies.

For the purposes of this analysis, the default income tax will be of 35% corresponding to the middle income tier in the *Escalões de IRS 2018* (Economias, 2018), but will remain editable by the user to reflect his own income bracket and taxation. The current value-added tax (VAT) in Portugal is of 23%, which will be the default value used for the analysis, applicable to all costs, and editable by the user.

Results and Analysis

From a first set of comparative rooftop system simulations the most impacting input variables on system performance were identified. The module type variations showed that the use of premium modules is highly justified, seeing as a 20% increase in annual production easily compensated the approximately 4% increase in installed costs over the reference scenario. The thin film (TF) module performed very well compared with the reference, with the very low installation cost (less than 40% the reference case) compensating the lower energy yield (approximately 68% of the reference, a less significant reduction than might be expected, in part due to the high performing nature of this technology under higher temperatures compensating its lower nameplate capacity). Because the rooftop is evenly irradiated throughout the year, micro inverters provide no significant enhancement to production, increasing costs and losing out to string system, even though it incurs a component replacement cost halfway through the system´s lifetime. The system is quite sensitive to temporal mismatch between production and consumption loads, and any change that results in increases to grid sales in the hours of peak production (Figure 5) negatively affects economic performance, revealing the importance of the correct sizing of the system relative to its expected consumption, both in absolute terms and in load shape profile.

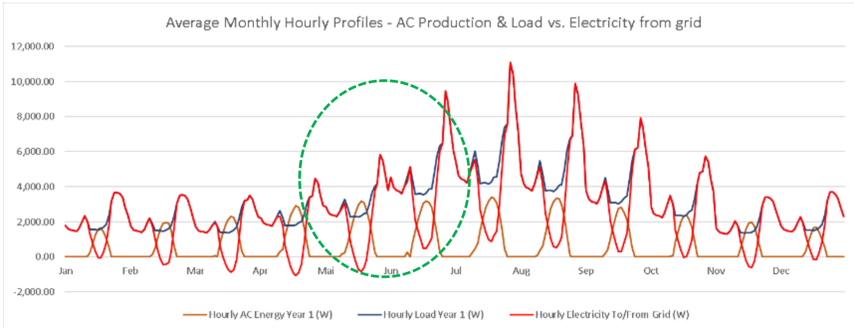

Figure 5 – Average Hourly Profile per month in the reference scenario

Because bi-hourly rate structures price electricity higher during peak consumption hours (partially overlapping with peak PV production hours), the hourly profile of grid demand resulting from the inclusion of a PV system makes these TOU rate structures more attractive than flat rate structures. Reductions in installation cost improve the economic performance of the system without impacting production or utility bill savings, with all financial metrics faring better under this scenario, while reductions in VAT have negligible effect on project economics, as the effects on income (e.g. utility bill savings) and expenses (e.g. installation and maintenance costs) mostly cancel each other out.

Changes to the financing structure of the project significantly affect the economic performance of these systems, with lower debt burdens preferred, over longer periods and with low interest, to improve the present value of investment and reduce the production costs, at a cost of higher upfront capital costs and a less balanced cash flow profile over the life time of the system

The impact of the small variations in assumed inflation on the economic performance of the system is quite subdued, directly affecting lifetime utility bill costs in current euros, with a reduced inflation improving the present value of the investment and decreasing the production costs, while simultaneously increasing the payback time and decreasing the return on investment. Because the system is sized to effectively limit the sale of excess energy to the grid (as the current sell rates are below wholesale prices, while the LCOE of these systems is closer to utility grid prices), sell-rate changes have negligible impacts on system performance. Finally, increasing or decreasing the irradiation that falls on the system has the expected and significant positive and negative impacts on economics, with the particularity that the system is more sensitive to the downside than the upside, possibly due to PVWatts´ low irradiation correction to PV module DC output that curtails production for lower hourly irradiations.

Similarly to the rooftop systems, comparative simulations for façade systems were used to identify key variables. Because only TF technology was assumed viable for façades, other module types were not compared. Façade PV systems truly showcase the impact different inverter choices can have for unevenly irradiated arrays. The simulation´s resulting AC generation is more than doubled in the system with a micro inverter, whilst the system with string inverter only decreases its output by 10% relative to the reference scenario. The micro inverter system thus performs substantially better than the alternatives and more than makes up for the added cost. When compared to rooftop systems, façade systems evidenced that their economic performance is less sensitive to consumption variations and sell rate variations, on account that production is so low that grid sales seldom occur, but are more exposed and impacted by buy rate-structure, by that very same lack of grid sales. The irradiation variations produced more pronounced effects in the TF façade systems, where a 25% increase in irradiation leads to a 32% increase in AC output (due to the comparatively better performance of TF cells under high temperatures than their c-Si counterparts) vastly improving the economics, but a 25% decrease in irradiation leading to a net loss with negative present value and a 20-year payback on investment. All remaining façade simulations (pertaining to cost variations, inflation, VAT and financing variables) displayed similar economic impacts as the ones noted for their corresponding rooftop PV systems.

From the previous analyzes it was concluded that an ideal rooftop system should use premium panels, a string inverter, limit sales to the grid, contract to the utility at a bi-hourly buy-rate and use the least amount of debt possible. This is also true for thin film façade systems, but these should include micro inverters. These ideal systems were modeled (PV20 and TF18) and then compared to optimistic and pessimistic scenarios (cases PV21, PV22, TF19 and TF20 respectively) by changing the occupation (hence the consumption), inflation and irradiation assumptions. The analysis concluded with the assessment of a combined use of the best performing rooftop and façade systems (PV23). The inputs to these simulations are laid out in Table 2, the results of which can be found in Table 3.

Input Variations	PV20	PV21	PV22	TF18	TF19	TF20	PV23
Module Type	Premium	Premium	Premium	Thinfilm	Thinfilm	Thinfilm	Premium+Thinfilm
System Losses	11.42%	11.42%	11.42%	11.42%	11.42%	11.42%	11.42%
Inverter Efficiency	96%	96%	96%	96%	96%	96%	96%
Inverter	String	String	String	Micro	Micro	Micro	String+Micro
Nº Pers/Household	2.6	3	1	2.6	2.6	2.6	2.6
Average Surface Area/Household (m2)	116.05	116.05	116.05	116.05	116.05	116.05	116.05
Nº Stories	4	4	4	4	4	4	4
Nº Households	8	8	8	8	8	8	8
Cycle	Bi-hourly	Bi-hourly	Bi-hourly	Bi-hourly	Bi-hourly	Bi-hourly	Bi-hourly
Household Contracted Capacity (kVA)	6.9	6.9	6.9	6.9	6.9	6.9	6.9
New Construction	0	0	0	0	0	0	0
VAT (%)	23%	23%	23%	23%	23%	23%	23%
Debt Fraction (%)	0%	0%	0%	0%	0%	0%	0%
Loan Interest (%)	3%	3%	3%	3%	3%	3%	3%
Loan Term (Years)	7	7	7	7	7	7	7
IRS (%)	35%	35%	35%	35%	35%	35%	35%
Inflation (%)	1.5%	0.5%	2.5%	1.5%	0.5%	2.5%	1.5%
Discount Rate	WACC	WACC	WACC	WACC	WACC	WACC	WACC
Sell Rate	Standard	Standard	Standard	Standard	Standard	Standard	Standard
Irradiation (W/m2)	Energy+	Energy+ + 25%	Energy+ -25%	Energy+	Energy+ + 25%	Energy+ -25%	Energy+

Table 2 - Simulation Input for New Reference Scenarios

Results	PV20	PV21	PV22	TF18	TF19	TF20	PV23
Total Installed Capacity (kW)	5.01	5.01	5.01	2.66	2.66	2.66	7.67
Number Panels	16.00	16.00	16.00	56.00	56.00	56.00	72.00
Tilt (º)	30.00	30.00	30.00	90.00	90.00	90.00	30&90º
Azimuth (º)	247.86	247.86	247.86	247.86	247.86	247.86	247.86
Local	Rooftop	Rooftop	Rooftop	Façade	Façade	Façade	Roof + Façade
Total Area (m2)	27.78	27.78	27.78	26.31	26.31	26.31	54.08
Savings in Y1 (€)	1357	1635	956	778	980	555	1750
Total Installed Cost (€)	11485	11485	11485	4437	4437	4437	15811
NPV (€)	10343	19631	1161	10839	18383	4414	12861
Payback Period (Years)	8.95	7.58	14.98	5.91	4.72	8.23	9.62
Equity IRR (%)	9.75%	11.79%	5.99%	17.59%	21.67%	12.49%	9.07%
Real LCOE (€c/kWh)	13.46	9.91	19.82	8.90	6.18	14.23	11.72
Higher than Reference	Lower than Reference						

Table 3 - Simulation Results for New Reference Scenarios

Assuming all other inputs set to their default value, the ideal rooftop system (PV20) is expected to generate annual utility bill savings of close to 1.4k€ (24% off the monthly bill), for an initial investment of approximately 11.5k€. The resulting LCOE of 134.6€/MWh puts electricity generation cost at or below socket parity, and the investment can generate over its 25 years a NPV of over 10k€, IRR close to 10% with a payback within 9 years. The optimistic scenario (PV21) shows that under ideal conditions these economic indicators can further improve, almost doubling the NPV, reducing the payback period by 17 months, increasing the IRR to close to 12% and bringing the real LCOE to 99€/MWh, comparable with the off-peak retail buy-rate and putting production costs on par with utility scale PV production. Even under the most pessimistic of conditions (PV22) the performance is still acceptable, with a non-negative NPV, a long (but still within the life cycle) payback period of close to 15 years, a low but still sizeable equity IRR of 6% and a real LCOE of 198€/MWh, still below the retail peak buy rate. Even with the most pessimistic of assumptions, the correct choices in sizing and system design have far-reaching impacts on system performance and can practically guarantee, even in the worst conditions, a positive NPV and a decent return on equity.

The new ideal façade system (TF18) can generate a NPV of close to 11k€ from a 4.4k€ initial cost, monthly utility bill savings of approximately 14%, an equity IRR above 17% and a LCOE of 89€/MWh (the lowest for all the reference cases simulated) with a payback just under 6 years. Under optimistic conditions (TF19), the system can generate over 18k€ in NPV, payback before 5 years and a real LCOE on par with peak wholesale prices of 62€/MWh, bringing it, under these conditions, very close to grid parity. Even under the most pessimistic assumptions (TF20), the system still gives an acceptable performance level, revealing the importance of adequate inverter choice in the system design phase of the project. This results in a system with a NPV above 4k€, the equity IRR above 12% and an acceptable payback period of 8.2 years, a testament to the resilience of a micro inverter façade TF system even under a pessimistic outlook. This comparative analysis supports the assessment in Heinstein et al., (2013) regarding the economic performance of TF technology in real life conditions being comparable to, or even better than, traditional c-Si technology due to the better thermal and shaded performance, and to the lower costs/m^2 outweighing the lower efficiency.

To assess the advantages of including façade PV production on a more traditional rooftop PV installation a final simulation was run for a PV system that includes the best performing rooftop and façade systems (PV20 and TF18, see Figure 4) with all other variables remaining unchanged. This shows that even though the production and installed costs are the sum of their constituents, the utility bill savings are not, a sign that a portion of the additional electricity produced by the façade is being squandered on grid sales. Compared to PV20 this results in a lower IRR (-0.7%), an extra 8 months in payback period, compensated by an increase in the NPV of approximately 2.5k€ (on account of higher utility bill savings) and a lower LCOE (the generation of TF panels diluting the cost of the more expensive premium panel AC generation) of only 117€/MWh, on the lower bound of the socket parity range. These results show that with an additional initial investment of only 4.4k€, the monthly utility bill savings can increase to 30% (from a previous 24%, corresponding to an additional 300€/year), the LCOE can drop by 17€/MWh, the NPV increase, and all this at the cost of a few months´ extension to the payback period and less than 1% reduction in IRR. The selection of a TF façade solution is thus a viable and desirable complement to a rooftop system, improving key financial performance metrics.

Conclusions

Contributions

A methodology to transform highly spatiotemporally detailed 3DGIS/CIM urban solar exposure data into useable economic assessment metrics of residential PV systems was developed and applied successfully, using widely available or open-source software tools. It provides for a clearer understanding of the possible benefits stemming from an integration of PV technologies in the urban fabric and is a step in the direction of further dissemination of BIPV to the public, allowing for any potential investor to assess the performance of his own PV system, and supporting city planners in their goal of zero emission cities.

The applied method involves a highly detailed modelling of the technical and economic performance of small scale isolated residential PV and BIPV systems, including features not usually addressed in the related literature. These include using high granularity irradiation data accounting for urban shading, modeling façade implementations, providing inverter options, calculating operating temperature, detailed PV system components modeling, accounting for building characteristics for deployment area and modeling lifetime economic behavior, all within the applicable legal and fiscal frameworks and retaining high customizability from the user´s perspective. This makes it adaptable to any other project and paving the way for its implementation on an accessible platform for wide dissemination taking full advantage of the 3D environment. To the best of the researchers´ knowledge, no other GIS based user-oriented PV system assessment methodology allows for façade inclusion or is as detailed in its calculations of irradiation and PV performance.

This methodology was applied for standard rooftop and façade implementations of PV and BIPV systems and their performance assessed. The results are in line with current market expectations supporting the notion that both c-Si and TF technologies are currently economically viable and a justifiable environmental and economic choice from the project developer´s perspective. The correct design of these systems can provide a large return on investment, support continuous savings throughout the lifetime of the project, guarantee a payback on investment in an acceptable timeframe and compete with retail electricity grid prices, making it an alternative source of energy worth considering. The insights provided into the sensitivity of the systems to several variables should help steer the decision process, complement the understanding of the risk factors in these residential PV deployments, and support the design of more robust and economically viable systems in Portugal and elsewhere. The current methodology implemented on a 3D-GIS urban model can further facilitate the deployment of urban PV projects and opens for consideration the inclusion of façades which complement standard rooftop arrays, reducing production costs per kWh and increasing monthly savings, while taking full advantage of the available solar resource.

The modeled results lend support to the notion that TF technology can be cost competitive both on rooftops and façades, as a standalone or as a complement to standard rooftop installation, a step forward in dissipating the mistaken and widely-held beliefs that their integration is more expensive than conventional roof installations and that their lifetime performance is significantly lacking. It is demonstrated that TF technology can be cost competitive and present a low-cost investment with significant economic upside and should be seriously considered for any building that aims to shift part of its load to green technology. It cannot yet cover the total consumption of a building as other PV technologies do, but it is an economically viable solution for distributed generation.

Limitations

Using PVWatts will tend to underestimate AC output. particularly for thin film technology. Tough steps were taken to account for this, some limitations remain so real-life AC outputs will probably be higher, which should positively impact economic performance of the systems. As it stands, flat-roofs cannot be modeled by this method, so subsequent research could account for this by making explicit calculations with the self-shading behavior of PV panels in mind.

As it stands, the current code implementation for calculations with micro inverters is too computationally intensive and requires better programming skills to manipulate the large and numerous arrays. There is room to develop this method into a Python application (e.g. creating a tool within ArcGIS) to use the same modules in the SSC library, as the SAM Development Kit includes a Python wrapper. This would bypass the need for the use of Excel/VBA, guaranteeing the correct implementation of the methodology in a purely ArcGIS/CityEngine/WebGIS environment.

The results for thin film models on rooftops, tough promising, are theoretical in the sense that this technology is usually not implemented on rooftops, as it isn´t mature and the weathering solutions aren´t as developed as for c-Si technology (negatively impacting the warranties). It is a promising start, but TF solutions aren´t yet ready for commercial widespread use on rooftops.

Finally, there is currently no way to validate the production results with real life production, nor the economic outputs of the model, as to the best of the researchers’ knowledge, there is no systematic campaign to collect and analyze real world residential PV production and economic performance in Lisbon.

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