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TECHNO-ECONOMIC ANALYSIS OF PEROVSKITE SOLAR CELLS

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Abstract

The current decarbonization strategies require the development and implementation of carbon free renewable energy systems, of each solar photovoltaic is one of best options. In recent years, perovskite solar cells (PSC) have gained traction as a potential competitor to the mature silicon-based solar cells in terms of both performance and cost and performance. As a young technology it still has some practical limitations, mainly in terms of stability and real market value potential.

So, to understand at what point of commercialization are these Photovoltaic (PV) devices and evaluate their economic potential, an economic evaluation was performed in an experimental scale PCS, formed by 3 cell PSC modules with a total active area of 105.6 cm^2. A life cycle thinking (LCT) perspective was used, with three economic indicators were chosen: the levelized cost of energy (LCOE), Energy Return on Energy Invested (EROI) or Energy Payback Time (EPBT). Their values were calculated using the materials and energy consumptions required to manufacture the 3 cell PSC module, and the energy generated during was estimated using the PVGIS webtool.

In the current state of development, the module costs € 583.69 / m^2, and the values of LCOE, EROI and EPBT are 8.67 €/kWh, 0.26 and 75.56 years respectively, thus being not commercially competitive when compared with other energy generating technologies available in the market. The back contact layer made of gold is the main sources of costs, contributing a 67% of the materials total costs and a 17% of the electricity total costs, while the mesoporous layer dominates electricity costs with a 74% over the total.

A parametric study was done to to identify which aspects have more impact in the estimates of LCOE, including varying the location and dominant climatic conditions in the Iberian Peninsula with three cities: Porto (warm Mediterranean, Csb), Malaga (hot Mediterranean, Csa) and Bilbao (Oceanic, Cfb). The results showed the cell efficiency, lifespan, and WACC are the most relevant parameters, and inflation and solar yearly degradation being less relevant. Also, the results also showed a significant relevance of the geographic location, with Malaga being superior to Porto and Bilbao the worst location.

Two scenarios were proposed and evaluated to improve the economic performance of the PSC device: i) replacing the gold used in the contact´s layer with carbon paper with the addition of a thin layer of gold: ii) changing the architecture of the device from a N-I-P structure to a P-I-N structure. Although both scenarios reduced the LCOE value significantly, a combined 72%, it is still not enough to reach a target value of € 0.15 / kWh. To accomplish that the capital investment must be in the range of € 3.30 – € 2.24, depending on the location in order to reach that goal.

Keywords (theme): Perovskite Solar Cell, Renewable energy; Levelized Cost of Energy; PVGIS; Scenario Analysis

Declaration

I hereby declare, under word of honour, that this work is original and that all non-original contributions is indicated and due reference is given to the author and source



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Notation and Glossary

FF	fill factor	
η	power conversion efficiency	
I	output curent	A
I_{sc}	short-circuit current	A
V	voltage	V
V_{oc}	open-circuit voltage	V
P_{max}	maximum power	W
P_{in}	solar power input	W
P_T	theoretical power	W

List of Acronyms

ALiCE	Associate Laboratory in Chemical Engineering
APREN	Portuguese Renewable Energy Association
BIPV	Bulding-integrated Photovoltaics
CAPEX	Capital Expenditure
CdTe	Cadmium Telluride
CIGS	Copper-indium-gallium-selenide
DSSCs	Dye Sentized Solar Cells
EPBT	Energy Payback Time
EROI	Energy Return on Energy Invested
EU	European Union
FCT	Science and Technology Foundation
FEUP	Faculty of Engineering of University of Porto
FTO	Fluorine-doped Tin Oxide
HTL	Hole Transport Layer
IEA	International Energy Agency
IRR	Internal Rate of Return
ITO	indium-tin oxide

LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCOE	Levelized Cost of Energy
LCT	life cycle thinking
LEBAPE	Laboratory for Process Engineering, Environment, Biotechnology and Energy
Mc-Si	Polycrystalline Silicon
MPSCs	Mesoporous Perovskite Solar Cells
NPV	Net Present Value
OAT	One at time
OPEX	Operating expenditures
PCE	Power Conversion Efficiency
PPSCs	Planar Perovskite solar cells
PSCs	Perovskite Solar Cells
PSM	Perovskite Solar Module
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
Sc-Si	Monocrystaline Silicon
Spiro-OMeTAD	2,2′,7,7′-tetrakis (N, N-di-p-methoxyphenylamine) 9,9′-spirobifluorene
UV	Ultra-Violet
WACC	Weighted Average Cost of Capital

1. Introduction

There are big number of challenges facing the energy sector today and the following must be emphasized. (Grueneich, 2015):

i. Sustainability - economic growth cannot be linked with depletion of energy resources and global warming.

ii. Security of supply - by ensuring long-term availability of resources.

iii. Security of the energy chain – which have as principal issues: external dependence, accidents, and political stability.

iv. Growing demand in developing countries - where there is still a great lack in supply and where sustainable solutions must be found.

The use of energy in form of electricity has been increasing over the last past years and even with the decrease in energy demand caused by the COVID-19 pandemic (IEA, 2020), it reached a value of 50.78 TWh in Portugal by 2020.

The use of fossil fuels presents a series of big problems such as greenhouse gas emissions which are the main cause of global warming, as well the barely distributed location of the deposits, being non-inexhaustible fuels, etc.

Given the disadvantages, a global change in the way of obtaining energy is crucial. One of the principal advances is the transition from fossil fuels to renewable energy sources. Renewable energies main characteristic and difference measure up to energies from fossil fuels is that they do not generate greenhouse gas emissions. In addition, they do not show reliance on deposits and therefore have greater accessibility. Also, they have several advantages: they allow environmental development, it is clean, abundant, and available globally.

Photovoltaic solar energy represents only 4% of the total generation in Portugal, being the main renewable sources hydraulic (26%) and wind (25%), as shown in Figure 1.

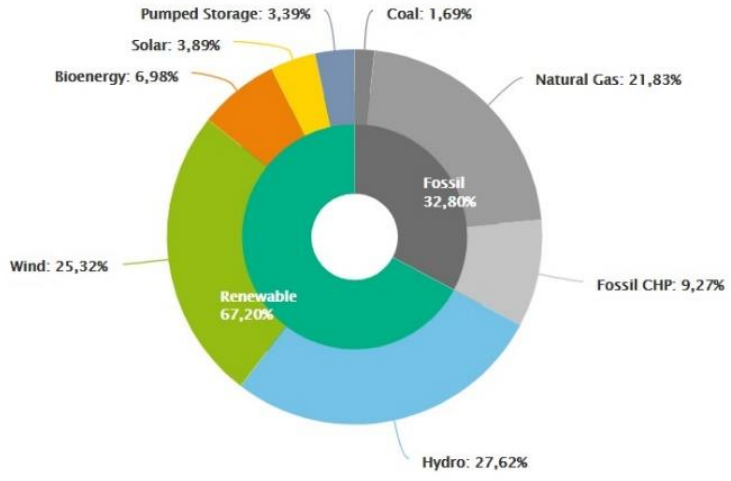


Figure 1. Distribution of the energy generated in Portugal in 2021 (APREN, 2020)

The main renewable sources for producing energy are: Photovoltaic, Wind, Hydraulic, Geothermal and Biomass. Worldwide, only around 27% of energy comes from renewable energies. In Portugal, by 2020 the contribution of renewable energies to the total electricity country's demand was around 61.7%. In 2020, Portugal generated 30.433 TWh of electricity from renewable energies, with an increase of 1.4% compared to 2019. (APREN, 2020)

Other sources of energy are also being implemented, such as biomass and pumped storage, which represents approximately 10% of the renewable electricity generated in Portugal.

From these data, it can be noted that Portugal significantly exceeds the world average percentage of renewable electricity but is still far from meeting the goals set by the European Union to create an economy with net-zero greenhouse gases emissions by 2050 (Ec.europa.eu, 2020).

Portugal roadmap for carbon neutrality has as main objectives the reduction of emissions between 45% and 55% by 2030, between 65% and 75% by 2040, and among 85% to 90% in 2050, which compared to the year 2005, assumes a decreasing values of approximately -10 Mt CO_2.(UNFCCC, 2020)

With these goals in mind, the evolution of the use of renewable energies has been growing over the years. One of the consequences of this expansion is that their prices have to become more competitive.

As can be seen in Figure 2, hydroelectric, wind and solar energy constitute more than 90% of the installed capacity of renewable energy sources worldwide. This shows how consolidated this type of energy source is compared to the others that are still in more stages of development and research.

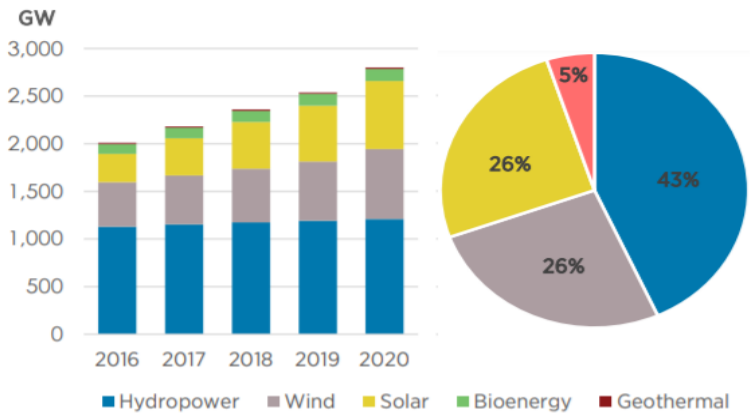


Figure 2. Renewable world power capacity growth and renewable generation capacity by energy source in 2020 (IRENA, 2020)

Photovoltaic (PV) energy is obtained by transforming light from the sun, based on the photoelectric effect, into electricity. Therefore, it is an inexhaustible energy that does not pollute the environment and it can be generated anywhere in the world.

Photovoltaic generation has seen exponential growth in recent years, thanks to the leadership of China, in producing silicon photovoltaic panels going from 1% of the global electricity generation in 2016 to the current 3%. This industry employs 32% of the more than 11.4 million workers that form the total of jobs established through renewable technologies (IRENA, 2020).

In addition, it can be used to provide energy for the air conditioning of buildings and its installation has a wide range (can be both on a large scale in photovoltaic plants or on a small scale like a residential home). Another advantage is its installation in areas where electricity does not reach through power lines.

With these advantages in mind, it is not surprising that investments and studies dedicated to the improvement of PV efficiencies and the discovery of different new mechanisms that make the solar cells more affordable and reliable have increased significantly. This new group of emerging photovoltaic technologies are called thin film cells and have as some of their main representatives the organic solar cells (Marinova, Valero, & Delgado, 2017), the dye-sensitized solar cells (DSSCs) (Błaszczyk et al., 2021) and perovskite solar cells, which are the main focus of the present thesis.

Figure 3 shows the classification of PV technologies and their market share, which, as can be observed, is dominated in a 90% by crystalline-Si.

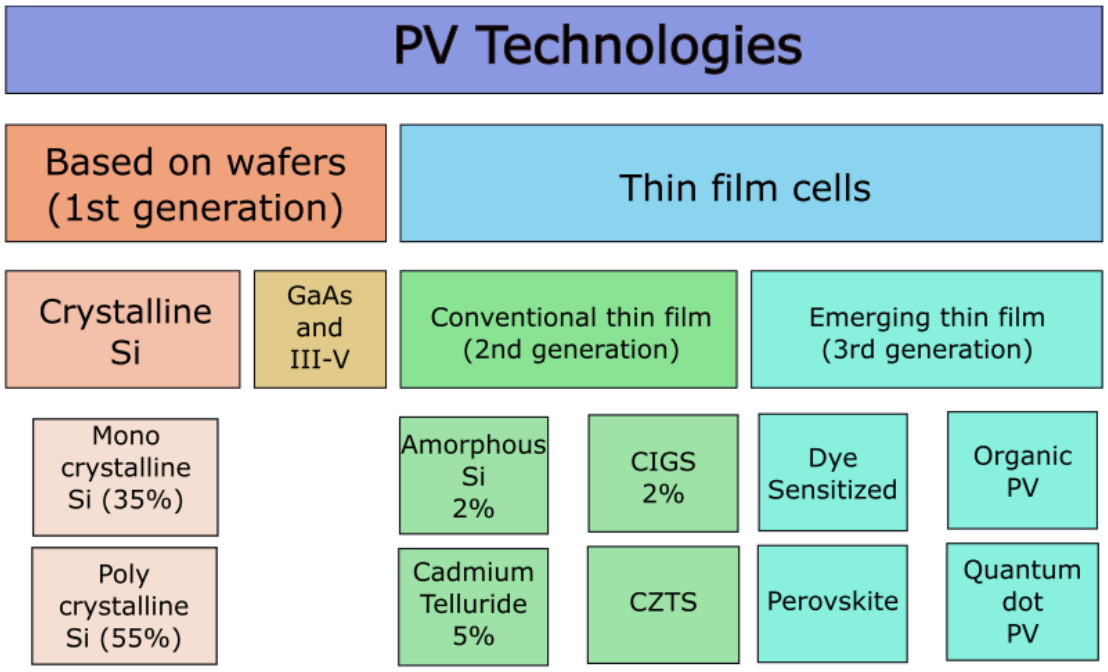


Figure 3. PV technology classification (% indicates market share)(Serrano, 2020)

Perovskites materials family is referred as calcium titanium ($CaTiO_3$) crystal structure during its discovery in 1839 and whose name was given in recognition of the Russian minerologist Lev Perovski. Perovskite solar cells (PSCs) are one of the strongest contenders for lead the next generation of photovoltaic technologies race, holding the promise for high efficiencies, as well as low potential material and reduced cost (Green, Ho-Baillie, & Snaith, 2014).

At the present time, perovskite industrialization phase seems to be taking its first steps with the development of perovskite solar modules (PSM) production lines. Asian-based companies as Microquanta Semiconductor (China) or Panasonic (Japan) already own perovskite module pilot lines and have prospects to increase production by 2022 (Shaw V, 2019). Aiming at upscaling process, Panasonic achieved in January 2020 the manufacturing of the best performing perovskite module with a power conversion efficiency of 17.9 % for an 802 cm^2 It is therefore important to develop techno-economic studies to evaluate the market viability for perovskite solar cells (PSCs) from an industrial point of view. This master thesis pretends to present a detailed technoeconomic model based on the production of a 3-PSC module. Using this model, we use economic instruments such as the levelized cost of energy (LCOE), the Energy Return on Investment (EROI) and the evaluation of data parametric studies from the data to identify the most critical factors that influence the costs and the commercialization of the PSCs

1.1 Presentation of the laboratory.

All the experimental research data referred in this work was developed in the Laboratory for Process Engineering, Environment, Biotechnology and Energy (LEBAPE). LEBAPE was created in 1998 as an interdisciplinary group mainly located at the Chemical Engineering Department. Consistently classified as "Excellent" by international evaluation panels appointed by FCT, it has been growing over the years. In 2021, LEBAPE formed a consortium with FEUP´s other two Chemical Engineering R&D units developing ALiCE – Associate Laboratory for Innovation in Chemical Engineering (www.alice.fe.up.pt), involving ca. 370 researchers.

LEPABE's mission is to develop innovative processes and products to respond effectively to societal challenges, using the basis of chemical and biological engineering to improve quality of life in a sustainable and safe way. These goals are in line with the Horizon Europe common strategic priorities, focusing on research excellence, industrial competitiveness, and societal challenges.

LEPABE's research is based in three pillars of development: Sustainability and Energy, Processes and Products, Environment and Health. Our scientists are stimulated to cooperate with colleagues from different research fields, increasing synergies and seeking advances in cross-cutting areas. The organization in research groups, their strategic objectives and laboratory conditions are available at www.lepabe.fe.up.pt.

1.2 Organization of the master thesis

The present master thesis is organized in six chapters:

- **Introduction (1st chapter):** a summary of the energy paradigm currently facing the society is presented and it emphasizes the importance of developing an energy transition towards the use of renewable energy sources as soon as possible. Photovoltaics plays a dominant role in this sector with special focus on the emergent technology of perovskite solar cell, which has undergone

incredible development over the last years and is already beginning to be present commercially in some energy markets.

- **Context and State of the art (2nd chapter)**: gives a comprehensive analysis concerning the operating principles of PSCs, presenting the different architectures and the correspondent state of the art in terms of power conversion efficiency. The different state of the art economic instruments for evaluation of PSC technology are overviewed; these economic analyses will be then updated along the present study.

- **Materials and Methods (3rd chapter):** provide a detailed explanation of the procedure followed to complete the work on this dissertation dividing the chapter into three main blocks: overall objectives, system description and economic evaluation.

- **Results and discussion (4th chapter):** shows the main results obtained from the calculations carried out in the economic analysis as well some discussion of which parameters have the greater impact over the PSC commercialization.

- **Conclusions (5th chapter):** the main conclusions drawn of the previous section are summarized here.

- **Assessment of work done (6th chapter):** in this chapter the author critically analyzes the preliminary defined objectives and the correspondent answers obtained during the work carried out.

2. Context and State of the art

2.1 Solar Cells

The conversion of solar radiation into electrical energy are carried out using solar cells, capable of transforming the light from the sun into electric current, using the photovoltaic effect. A solar cell is made up of several layers of different materials, each with a different use (Kim, Quy, & Bark, 2021).

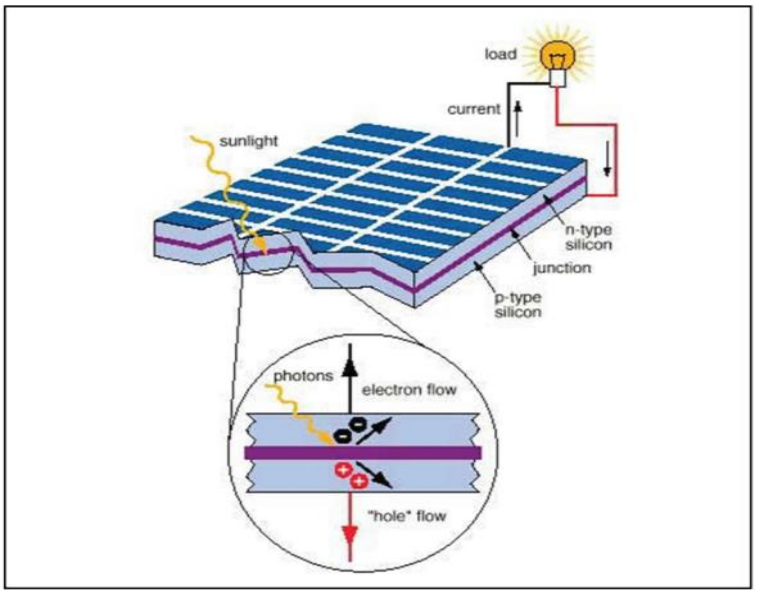


Figure 4. Schematic of the basic structure of a silicon solar cell

As can be seen in Figure 4, the photovoltaic effect is characterized by the production of an electric current thanks to a photoelectric effect. It is a process that generates a voltage or electric current in a photovoltaic cell when sunlight falls on it. The cells are made up of two different semiconductors (p and n), joined by the p-n junction. When the union of these semiconductors takes place, an electric field is generated that allows the electrons to move to the positive zone (layer p) and the holes to the negative zone (layer n).

When light strikes the cell, an electron-hole pair is generated, enabling the electron to move into a higher energy state known as the conduction band. These electrons can move freely through the material, and it is this movement of the electron that generates the electric current (Serrano, 2020).

The I-V curve of an illuminated PV cell has the shape shown in Figure 5 as the voltage across the measuring load is swept from zero to V_{OC} (Open Circuit Voltage) and the current goes from zero to I_{SC} (short circuit current). The open circuit voltage occurs when there is no current passing through the cell while the short circuit current corresponds when the impedance is low and is calculated when the voltage equals 0.(Uchqun, 2019)

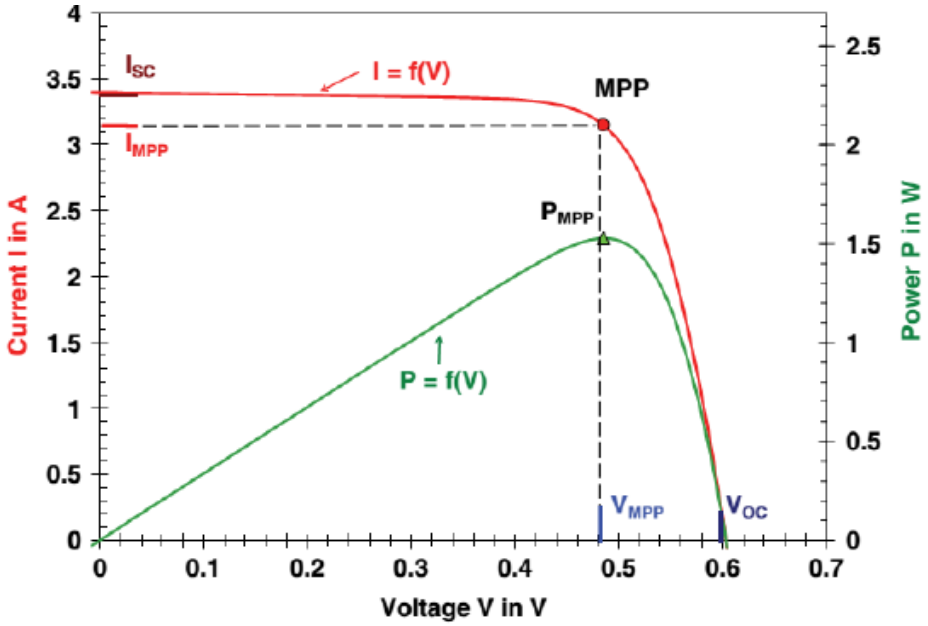


Figure 5. Characteristic I-V and P-V curves of a solar cell

From this curve, the characteristic parameters of solar devices can be determined and thus the correspondent Fill Factor and Efficiency can be calculated by Equation (1) and Equation (2) respectively.

- Fill Factor (FF): It is a measure of quality of the solar cell. Is determined by the correlation of the maximum power (P_{MAX}) and the theoretical power (P_T).

$$FF = \frac{P_{MAX}}{P_T} = \frac{V_{MP} \times I_{MP}}{V_{OC} \times I_{OC}} \qquad (1)$$

- Efficiency (η): It is obtained from the relationship between the maximum power generated by the solar cell (P_{MAX}) compared to the solar power input (P_{IN}). P_{IN} is taken as the product of the irradiance that strikes the device (G) with the surface area of the solar cell (Area).

$$\eta(\%) = \frac{P_{MAX}}{P_{IN}} = \frac{FF \times V_{oc} \times I_{sc}}{G \times Area} \times 100 \qquad (2)$$

2.1.1 Solar cell families

Solar cells technology can be classified into first, second and third generation (Panthi, Bajagain, An, & Jeong, 2021):

i) First generation: Mainly based on cells with silicon technology, either monocrystalline (sc-Si) or polycrystalline (mc-Si).

ii) Second generation: This generation of solar cells were introduced as a response to high material usage and cost of silicon solar cell. The maximum film thickness for this generation was brought down from a few nanometers to tens of micrometers as a measure to prevent the waste of materials. Examples of thin film or thin film technologies are amorphous-silicon, cadmium tellurium (CdTe) or cadmium selenide (CdSe).

iii) Third generation: Consist of novel technologies which are promising but not commercially proven yet. The goal is to have simultaneously efficient solar devices but less expensive so it can be used by more people, and to develop different final applications. Organic solar cells, dye-sensitized solar cells and perovskite solar cells make part of this category.

Silicon solar cells are the most commonly used technology. These silicon solar cells dominate 90% of the photovoltaic market due to the abundance of silicon (Si) as raw materials and its current commercial average efficiency is around 18%-22% (Office of Energy Efficiency & Renewable Energy, 2018).

Silicon cells present several disadvantages such as weak absorbance for long wavelengths, its opaqueness and therefore limited potential for applications and the fact that silicon layers cannot bend. On the other hand, the use of silicon as raw material implies the use of complicate and energy consuming processes for making it pure and thus adequate to make an efficient solar cell.

CdTe solar cells technology exhibits as main characteristic, an optimum band gap near 1,5 eV so that could deliver very high efficiencies as single junction device. Due to it, is presented as the only thin film technology in the first ten top producers in the world. The strong progress in efficiency in the last years was achieved by a new redesign of the structure, reaching a single solar cell efficiency of 22.1% and a module efficiency of 19% (Romeo & Artegiani, 2021).

Organic cells are a promising new generation of photovoltaic cells. They present several improvements over the silicon solar cells such as their lightness the absence of heavy metals and the fact that they are semi-transparent. Furthermore, one of the unique characteristics of this type of solar cell is the possibility of non-vacuum manufacturing of the entire solution from indium-tin oxide (ITO) substrates (Yang et al., 2021), which makes it much easier and cheaper to produce and allows obtaining an efficiency of 18.22% for this type of solar devices (Q. Liu et al., 2020)..

Dye-sensitized solar cells present similar advantages as organic solar cells beside being compatible with flexible substrates. Moreover, they are particularly interesting to work in low light conditions. These devices have achieved an efficiency of around 14% (Błaszczyk et al., 2021).

Perovskite solar cells have attracted a great deal of research, thanks to the impressive increases in efficiency that these devices have obtained in a very short time, from 3.9% in 2009 to 25.5% today.

Furthermore, with only ca. of 400 nm, PSCs have three orders of magnitude less than the monocrystalline silicon solar cells, which can be decisive in the development of great scale process (Mesquita, Andrade, & Mendes, 2018)

The next figure (Figure 6) shows the progress of the efficiency of the different types of solar examined over the years. As we can see from the graph, the efficiency of perovskites-based solar cells has suffered a boost during these last years until reaching one of the main positions comparing to the other materials.

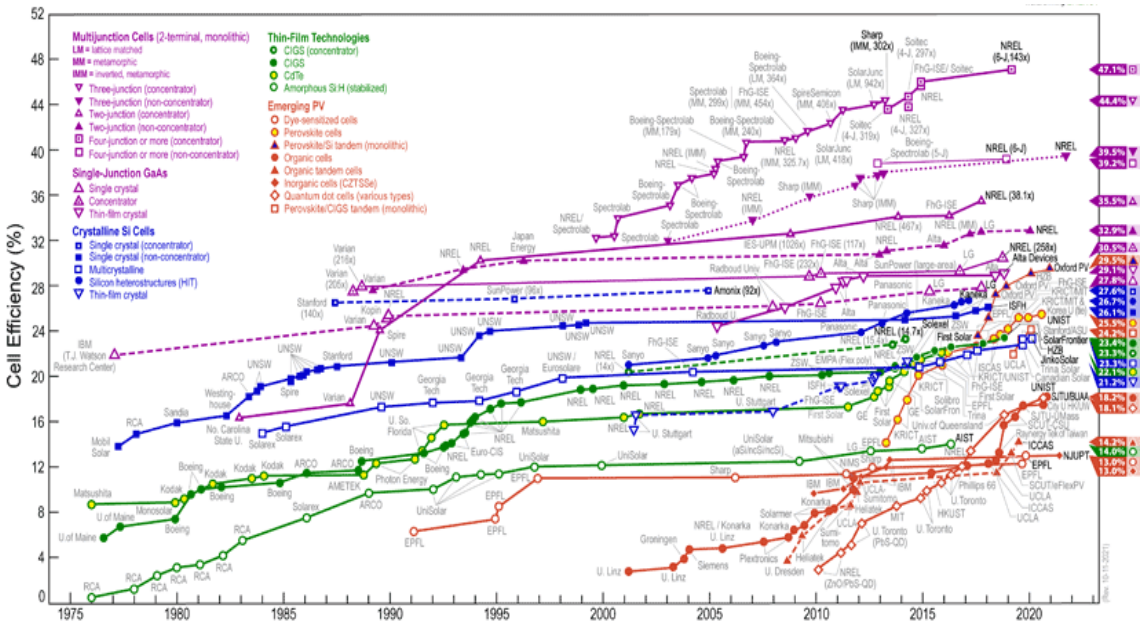


Figure 6. Best research-cell efficiency chart over time (Brittany L. Smith, 2020)

2.1.2 Perovskite-based solar cells

Organic-inorganic perovskites have an ABX_3 structure: A being an organic cation, (MA: $CH_3NH_3^+$,FA: $CH_3(NH_2)^{2+}$ or Cs^+); B a divalent metal greater than A: (Pb^{2+}; Sn^{2+}; Ge^{2+}) and X an anion (Cl^-, Br^-, I^-, BF_4^-, PF_6^-, SCN^-) or mixture of this several examples (Saliba et al., 2016). Perovskite generally adopts a cubic structure formed from sharing the corners $[BX_6]^{4-}$ of an octahedron. As shown in Figure 7, cation A must be small enough to fit in the voids of the octahedral units to preserve structural integrity (Grancini & Nazeeruddin, 2018)

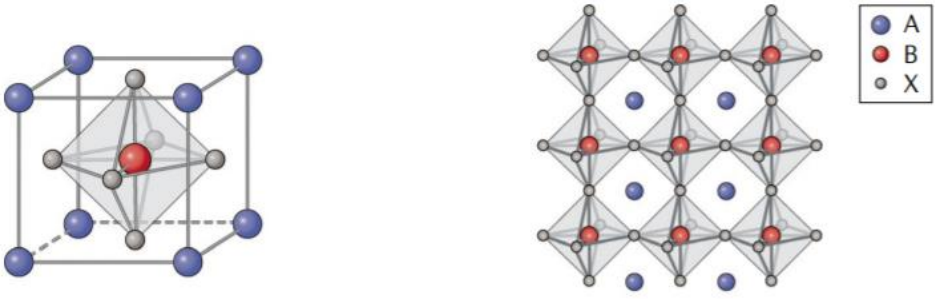


Figure 7. Simplified crystalline structure and an extended cubic structure of perovskite.

Devices prepared using perovskite as a light absorbing material works similarly to other types of solar cells. Thus, the photovoltaic operation of these devices contains three steps, as shown in Figure 8: the absorption of photons together with a generation of charge (1), the transport of said charge (2) and the extraction of the charge load (3) (Hussain et al., 2018). When light hits the perovskite, charge carriers (electrons and holes) are generated. After the electron is separated from the hole, it enters the electron transport layer (ETL) and then migrates to the anode (glass substrate coated with transparent conductive oxide, in the figure coded as FTO). At the same time, the hole is absorbed by the hole-transporting layer (HTL) and migrates to the cathode (gold or silver).

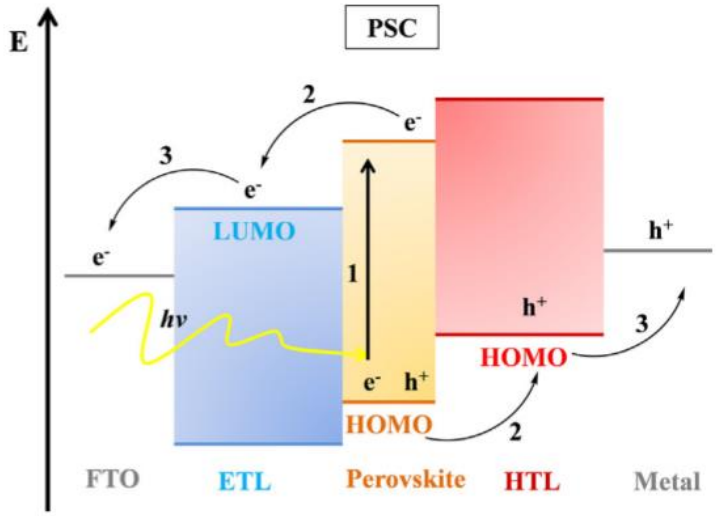


Figure 8. Simplified energy diagram of perovskite-based solar cells and diagram of their operation (Marinova et al., 2017)

Perovskite-based solar cells can present different types of structures depending on the dispositions of the different layers. These disposition sequences can be divided in N-I-P (regular) or P-I-N (inverted) structured cells. The difference between a regular and an inverted is that the regular structure has the electron transport layer (ETL) above the FTO layer, followed by the perovskite layer and the hole-transporting layer (HTL) whereas in the inverted structure, the HTL is right after the FTO layer, followed by the perovskite layer and the ETL. Despite the lower efficiencies obtained by P-I-N compared to N-I-P cells, these are more stable and thus cheaper to produce. Due to this fact, there are many research to apply this type of cell in the industry and even a perovskite cell efficiency (PCE) as high as 23.7 % was already achieved in an inverted single-junction PSC (Matteo Degani Qingzhi An, 2021).

Recently, three different common structures of PSCs have been developed: mesoporous PSC (N-I-P), regular planar PSC (N-I-P) and the inverted planar PSC (P-I-N). The different configurations are shown in figure 8.

The Mesoporous Perovskite Solar Cells (MPSCs) have gained more attention because their high power conversion efficiency (η) (Osman, Abdolkader, & Ahmed, 2021). A typical MPSC involves nanoscale pores in ETL scaffold, which follows the absorber layer covering the ETL and forming an intermixed layer.

Sequentially, the top electrode and the HTL are deposited above to complete the device. This extra step in the fabrication process originated by the mesoporous layer is undesirable for scaling the size of the device, and has question their required use for improving stability or getting higher efficiency (Zhen Li et al., 2018).

The Planar Perovskite solar cells (PPSCs) main difference from the intermixed layer in MPSCs architecture is their compact ETM layer. This structure gives the cell two interfaces: (ETL/ perovskite) and (perovskite /HTL) and a much more effective and rapid separation of the electron-hole pairs by HTL and ETL.

This planar P-I-N architecture (which is often built with a compact HTL) may be called an inverted planar structure if an inversion of the extraction layer is made when compared to the regular structure. Inverted structure devices have exhibited many advantages such as high stability and easy fabrication process(Crispin et al., 2006).

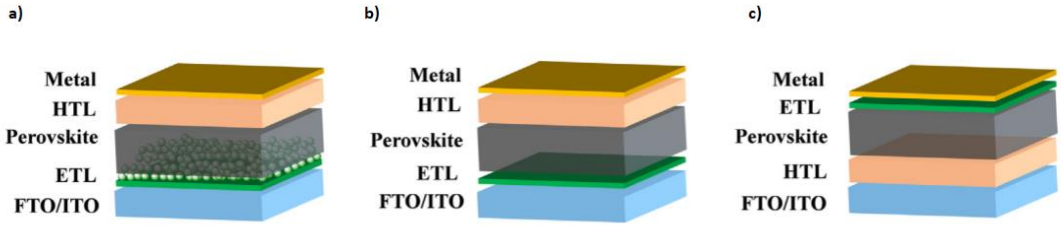


Figure 9. Simplified structures of the devices: a) regular mesoporous; b) regular planar; c) inverted planar (Osman et al., 2021)

The beneficial characteristics of PSC are, strong solar absorption in the visible spectrum, low recombination rates of non-radiating carriers, low exciton binding energy, and a tuneable bandgap of 1.1 to 2.3 eV (Green et al., 2014). In addition, PSC´s are very easy to manufacture, since they can be formed directly from a solution using techniques such as spin coating, dip coating, interdiffusion in two steps, chemical vapor deposition, spray pyrolysis, atomic layer deposition, ink jet printing and thermal evaporation.

The fact that there are several techniques available, makes PSC a very versatile photovoltaic technology, and allows its usage in substrates of different sizes and levels of flexibility. With these qualities in mind, many researchers see in the development of PSC technology an approach to more energy efficient cities in form of building-integrated photovoltaic (BIPV), where PV replaces the traditional building envelopes such as windows, roof and walls. With this substitution, BIPV cover materials protect the building interior from the external environment, generates power and offset the building construction costs.(Roy, Ghosh, Bhandari, Sundaram, & Mallick, 2020)

Another great advantage of PSC devices is its thickness, a key factor in the upscalling development of this technologies. PSCs only require 400 nm of layer to equal crystalline silicon solar panels efficiency, which have around 200 µm (almost three orders of magnitude more). (Mesquita et al., 2018)

Nevertheless, despite the numerous advantages presented by the PSCs, photovoltaic grade perovskites still lack long-term stability due to their sensitivity to high temperatures, moisture, and oxygen. The hydrolyzation and its consequent decomposition of the perovskite in atmospheric humidity, demands that the PSC has to be manufactured in a vacuum filled with nitrogen (Leguy et al., 2015).

These manufacturing issues, added to other difficulties such as the heavy encapsulation requirement due to presence of lead in most of the perovskite absorbers or the use of gold, increases their overall cost exponentially. This is a major obstacle for the PSC commercialization, especially in a market that is so dominated by silicon solar panels(Asif, Singh, & Alapatt, 2015).

However, the rapid succession of efficiency records in PSC as well as in PSM that can be observed in Figure 10 tend to optimism and the possible commercialization of the technology in a few years.

Information about the PSC panels designs and manufacturing process from these companies is rare, therefore, is important to carry out a thorough research with the available information to get a better idea of the economic background of the PSC.

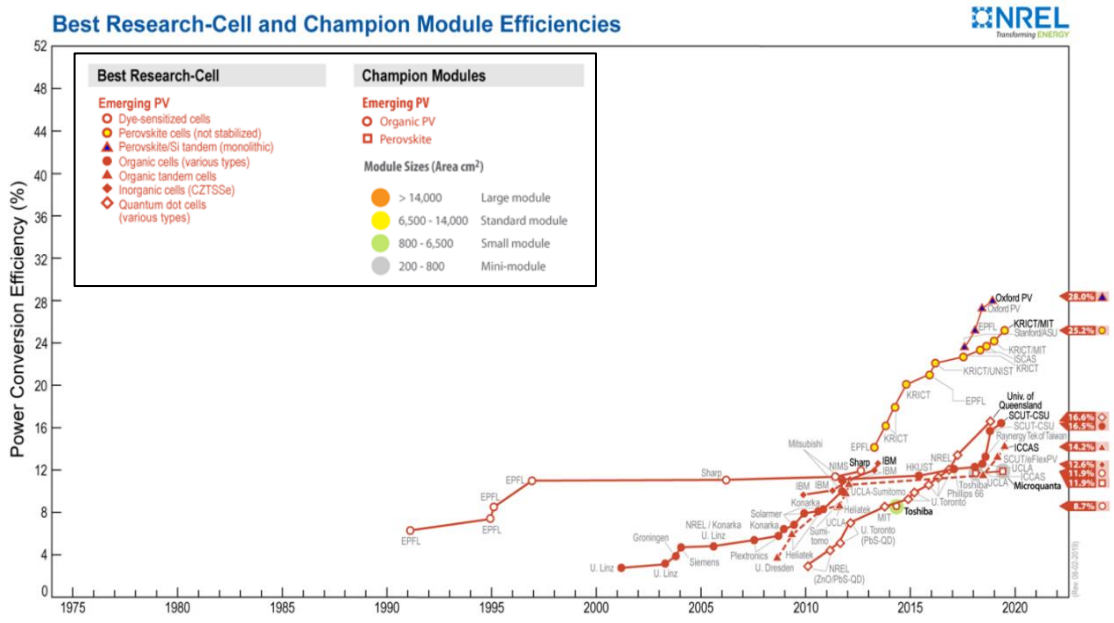


Figure 10. Efficiency progress for early-stage PV technologies chart (Brittany L. Smith, 2020)

2.2 Economic analysis of renewable energy generation systems

The assessment of the economic potential of renewable energy systems is a complex process, which requires a systemic approach. Furthermore, it must be based on a life cycle thinking (LCT) perspective, considering all the relevant life cycle of the technology under study, from the extraction of the raw materials, material production,

construction and operation of the renewable energy system, and final disposal/recycling. The LCT method is fundamental as allows the identification of all the potential impacts (environmental + social + economic) in all stages of a product or service life, taking into account, in an explicit way, the interconnect nature of existing supply chains and production (Mazzi, 2020).

One of the main goals of the economic analysis is the identification of the key cost driver that control de economic viability of the studied technology. This identification involves, as much as possible, the calculation of quantitative measures of the economic performance. Thus, specific indicators can be defined depending on the system, and the selection of a proper set should be base in criteria such as:

- easy to calculate using data directly available from the production process and/or from the literature;
- being independent as much as possible;
- taking into account the main economic aspects, in particular taking into account the time value of capital and the various types of costs;
- context in which the analysis is being done, for example if the energy generated will be sold or used locally;
- be consensual and widely used in practice, especially for renewable energy generation systems;
- easy to use, in particular in the comparison with renewable energy generation systems or to communicate with the relevant stakeholders, especially consumers either institutional (e.g., companies) or individual (e.g., residential).

Of the various economic indicators proposed and/or used in practice the following three indicators are most used in economic analysis studies (Song et al., 2017): the Levelized Cost of Energy (LCOE); the Energy Return on Energy Invested (EROI), and Energy Payback Time (EPBT). The first indicator directly relates the costs with the energy produced, considering the capital devaluation during the system expected lifetime. The remaining two indicators are a measure of the energy generated versus the energy needed to produce it, during the system lifetime. The indicators are described in detail in the following sub sections.

2.2.1 Levelized Cost of Energy (LCOE)

Levelized Cost of Electricity (LCOE) is an economic measure used to compare the lifespan costs of generating electricity across various generation technologies. It shows a cost-effective perspective as an average electricity price that must be earned by the generation source to break even (Song et al., 2017). It is a more objective and robust measure than the Internal Rate of Return (IRR) or Net Present Value (NPV), that require in their calculation a value for the energy price, in order to be able to estimate them (Delapedra-Silva, Ferreira, Cunha, & Kimura, 2022). Since that value can vary in time in unexpected ways, hence the predicted values of IRR and/or NPV assuming an average value may be incorrect and lead to unrealistic predictions.

Therefore, the calculation and comparison of LCOEs is one of the key aspects of the economic analysis in the energy sector, since it can in a more objective way different

technologies, allowing developers to identify which aspects represent the main cost issue. Also, it helps highlight opportunities for entrepreneurs to develop different scales of projects or supporting decisions to pursue projects on an economic basis (Missaoui, 2019).

LCOE can be defined by the following expression:

$$LCOE = \sum_{i=0}^{n} \frac{(C_i + M_i)/(1+r)^i}{E_i / (1+r)^i} \quad (3)$$

Where: C_i - capital investment (€); M_i - operational and maintenance expenditures (%); E_i - energy production (kW/h); r - discount rate; n - lifetime of the system; and i - the number of the year. Not include in the LCOE equation are the disposal costs, that may represent either a cost or a combined cost-plus revenue, as for some renewable energy system the materials used (e.g., metals) can be recovered and have a market value.

Most of times C_i corresponds to capital expenditure (CAPEX), equal to the sum of capital that a business uses to securing major physical goods or services to develop the companies' abilities to generate profits. In the case of energy projects, CAPEX includes costs such as: power-generation equipment, land costs, studies, or infrastructure (Vartiainen, Masson, Breyer, Moser, & Román Medina, 2019). For a PV system CAPEX is usually divided into three components: PV modules, inverters, and other balance of system (BoS), according to the following equations

$$CAPEX_{PV\ Total} = CAPEX_{PV\ Total} + CAPEX_{PV\ Inverters} + CAPEX_{PV\ Other\ BoS} \quad (4)$$

From an economic point of view, the CAPEX may represent a barrier to the investment, even though the project is economic feasible based on the value of LCOE. Depending on the situation, in many cases the buyers do not have enough capital to acquire the necessary parts and services necessary to generate the energy (Powell et al., 2015).

The term M_i is named Operating Expenditures (OPEX), as it represents the ongoing costs that a company must run its basic day to day operation. It is frequently identified as the expenses related to operations and maintenance (O&M). Investors in renewable energy usually distinguish two main types of O&M costs:

- Variable O&M costs (commonly expressed in USD cents / kWh produced): Variable generation costs are related to the generation of energy, such us maintenance, parts substitutions, energy/fuel needed to obtain the energy. This is usually one of the most interesting factors of renewable energy projects, since common variable O&M costs such as fuel costs or emission rights do not apply, increasing the long-term benefits (Vartiainen et al., 2019).
- Fixed O&M costs: They include the fixed maintenance of the technology used in the project plus the costs associated with personnel, (operational and administrative staff).

The value of the discount rate r depends in the particular conditions in which the investment and the system is being deployed, in particular national.

Its value is usually considered to be equal to the weighted average cost of capital (WACC), defined as the real discount rate of a given investment, taking into account both private funds/equity and other forms of financing, in particular share stock, bonds, and bank debt. It is a common used financial tool for decision making and investment appraisal, since it represents an appropriate benchmark rate to decide the acceptance or rejection of an investment that takes into account the specific risks of the economic sector as well other national or regional issues (Blasco-Ruiz, 2020).

WACC is determined by considering the relative weights of equity and debt using the following expression

$$WACC = \frac{D}{D+E}K_d + \frac{E}{D+E}K_e \quad (5)$$

where: D - total debt; E - total shareholder's equity, K_e - cost of equity, and K_d - cost of debt. The values of K_e and K_d are determined from the sector return rates of investments and average costs for a given economic sector, and estimates can be obtained from the literature (Roth, 2019).

2.2.2 Energy Return on Energy Invested (EROI) and Energy Payback Time (EPBT)

The energy return on invested (EROI) and the energy payback time (EPBT) are two useful metrics for examining the energy generation performance of energy generation devices.

The EROI is dimensionless metric defined as the ratio between the energy produced during the lifetime of the system to the energy needed to manufacture the system, including in the energy embedded in the extraction and production of the raw materials used in the system parts production and implementation. EPBT on the other hand, is the time that a device must operate to recover the energy used in its manufacturing, or the complete lifetime depending on the system boundary (Jennifer Collier, 2016).

EROI and EPBT are calculated using the following equations respectively (Bhandari, Collier, Ellingson, & Apul, 2015):

$$EROI = \frac{Lifetime\ energy\ output}{Embedded\ energy} = \frac{Lifetime(year)}{EPBT(year)} \quad (6)$$

$$EPBT(year) = \frac{E_{in}}{E_{out}} = \frac{Embedded\ (primary)\ energy\left(\frac{MJ}{m^2}\right)}{Annual\ (primary)\ energy\ generated\ by\ the\ system\left(\frac{MJ}{m^2 \cdot year}\right)} \quad (7)$$

Primary embedded energy is given by the direct energy processing and material embedded energy.

The former corresponds to the electricity used during the manufacturing of the device while the latter includes the energy spent during the raw material extraction and production of the various system parts.

2.2.3 Other relevant factors

Besides the metrics definition, there are other factors that influence the process economics. Among them, the Technology readiness levels (TRLs) are an evaluation method that, through a Technology Readiness Assessment (TRA), estimates the maturity of the technologies assessed. TRLs establishes the technology on a scale of 1 to 9 with 9 being the most developed technology due to the study of demonstrated technology capabilities and requirements in conjunction with program concepts.(Héder, 2017).

In 2014 were established the definitions of the TRL levels in the General Annexes of the European Commission with the purpose of setting boundaries between the funded projects of Horizon 2020, an EU framework program that took place between 2013 and 2020. Table 1 sets out these definitions together with their respective levels.(Commission, 2014)

Table 1- Description of the different technology readiness levels (TRLs)

Level	Definition
TRL 1	basic principles observed
TRL 2	technology concept formulated
TRL 3	experimental proof of concept
TRL 4	technology validated in laboratory
TRL 5	technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6	technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7	system prototype demonstration in operational environment
TRL 8	system complete and qualified
TRL 9	actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies or in space)

TRL principal purpose is to assist into making strategic and logical decisions concerning the transitioning and development activity of the technology, providing a collective understanding of technology status. Depending on the TRL level of a given technology the economic valuation may be more objective or not.

2.3 Economic evaluation of perovskite solar cells

Some studies can be found in the literature dealing with the economic evaluation of perovskite solar cells. Notwithstanding the current interest in this technology, the number of published studies is small, and in the following sub sections some of the most works are presented.

2.3.1 Perovskite Solar Module (PSM)

In recent years, there has been a significant effort to estimate the cost of producing perovskite solar modules. One of the first studies was the work of Chang et al. in 2017, that estimates a cost of US$300/m^2 for perovskite-on-glass modules (Chang et al., 2017). However, Chang's approaches were later found to be partially wrong, as he used impractical industrial processes and expensive materials such as Ag and Au. For this reason, the following scientific articles give much more optimistic results, which are shown in Table 2.

Table 2 - Comparison of manufacturing cost for perovskite single junction modules

Configuration	Module cost (US$/m^2)	Source
FTO/TiO_2 / meso-TiO_2/PbI_2, MAI (two step) /P3HT/Au (N-I-P structure)	300	(Chang et al., 2017)
FTO/TiO_2 / meso-TiO2/PbI_2, MAI (two step) /P3HT/Ag (N-I-P structure)	102	(Chang et al., 2017)
FTO/TiO_2 / meso-TiO_2/PbI_2, MAI (two step) /P3HT/Ag (N-I-P structure)*	90	(Chang et al., 2017)
ITO / ZnO / $CH_3NH_3PbI_3$ / NiO / Al (P-I-N structure)	31,7	(Song et al., 2017)
ITO / SnO_2 / Pb_2, MAI (one step) / NiO / Cu (N-I-P structure)	32,7	(Zongqi Li et al., 2018)
Low-cost mesoporous perovskite single junction module (N-I-P structure) **	38,8	(Cai et al., 2017)
High-end perovskite single junction module (P-I-N structure) **	29,2	(Cai et al., 2017)

**Advanced module with improved patterning and reduced waste*

*** No information available of the materials used*

2.3.2 LCOE values for Perovskite Solar Module (PSM)

As stated above, the levelized cost of energy (LCOE) can be used to compare different technologies and evaluate the competitiveness of the perovskite solar modules with the existing renewable energy generation systems.

The LCOE data for different renewable and conventional technologies provided by (Kost, 2021) together with the studies by (Song et al., 2017), (Zongqi Li et al., 2018),

and (Cai et al., 2017) are shown in Table 3. It must be considered that the multiple variables involved in the LCOE (geographic location, lifetime, degradation, etc.) and the extensive variability of configurations provided by the PSCs, makes difficult to make a completely reliable comparison between technologies.

Table 3 - LCOE values of perovskite solar modules, renewable energy technologies and conventional power plants

Energy technologies	Levelized cost of electricity [€cents/kWh]		Reference
	MIN	MAX	
Song PSC module	4.3	6.9	(Song et al., 2017)
Li PSC module	3.8	5.4	(Zongqi Li et al., 2018)
Cai PSC module	3	4.2	(Cai et al., 2017)
PV rooftop small	6	11	(Kost, 2021)
PV rooftop large	4.8	9.8	(Kost, 2021)
PV utility scale	3	5	(Kost, 2021)
Wind Onshore	4	8.1	(Kost, 2021)
Biogas	8.2	17	(Kost, 2021)
Coal	11	20	(Kost, 2021)
Natural Gas	11.8	28.9	(Kost, 2021)

3.Materials and methods

In this work a LCT approach is considered when performing the economic evaluation of a perovskite solar cell. In particular, besides the direct production costs other costs are considered, such as: materials, transportation, disposal at the end of the product or system lifetime, taxes, and interest.

In practice this is similar to do a Life Cycle Costing (LCC) study. Similarly, to the methodology of Life Cycle Assessment (LCA) has the different goal of assessing the environmental impact linked to a product or process during its life cycle, a LCC may follow the same sequence of steps defined by the LCA ISO standards ISO 14040 (International Organization for Standardization, 2006a) and 14044 (International Organization for Standardization, 2006b) In particular, the following four steps can be defined, as described below.

- Goal and system definition, which may involve making a description of the process or process under study, and the fundamental assumptions made in the work. Although not mandatory, most of the times a functional unit is defined, that corresponds to a representative product or process from where the economic performance can be assessed. Its definition must be representative of the system performance, usually being this a typical product.
- Inventory, in which the various costs terms are collected or calculated, and other relevant information is obtained.
- Economic indicators calculation.
- Results analysis, usually involving the identification of the key aspects and/or costs terms controlling the system economic performance. Proposals for improvement are usually suggested and their impact evaluated, especially how they can improve the economic performance.

In this chapter the main aspects and assumptions considered in this work are presented and supported, in particular those related to first three steps of the LCC methodology.

3.1 Overall objectives

This study principal goal is to analyze the economic viability of a PSC technology based on a mesoscopic architecture, using as functional unit a photovoltaic module made by four sub-modules composed by 3 individual cell each 3-PSC, being one of them presented in Figure 11. Such sub-modules have a N-I-P mesoscopic configuration with an area of 8,8 x 8 cm2 and a power of 182.4 mW. Moreover, the analysis aims was not to consider only the economic consequences, but rather make a more global evaluation of the system under study (Farjana, Mahmud, & Huda, 2021).



Figure 11 - Image of the 3-PSC module produced

According to the LCT perspective considered in this work, the following life cycle stages were considered: production and processing of raw materials, manufacture of the PSC and module, and utilization stage. The final disposal of the PSC cell, either recycling or landfill deposition, transportation steps, as well the waste treatment generated in process are not considered in this work.

In order to compare the perovskite solar cell technology with other conventional and renewable electricity generating technologies, the evaluation uses some common and consensual economic indicators used in the analysis of energy generation systems. In particular, the following three indicators were considered: Levelized cost of electricity (LCOE), the Energy Payback time (EPBT) or the Energy return on Energy Invested (EROI), as defined above in Equations (3), (6) and (7).

For the base case scenario, the study will consider the materials and production process currently implemented at laboratory scale, and Porto (41º2´N 8º59´W) as the geographic location in which the PSC module will be implemented. Following this assumption, Portuguese market conditions were raised, for example electricity costs in the calculation of power consumption for preparing the devices. As no information is available for the PSC lifetime and loss of efficiency, their values will be assumed based on literature information.

After obtaining the results of the base case, a parametric analysis will be done, in which the influence of the main parameters that have a significant impact in the PSC economic performance will be assessed. In particular, different geographical locations in the Iberian Peninsula with different climate conditions will be considered, and how the main parameters controlling the PSC performance influence its economic viability

A final objective is the definition of the conditions, defined as a function of the main PSC performance parameters and capital investment, that the PSC technology must achieve in order to have commercial prospective.

3.2 System description

The functional unit is a photovoltaic module consisting of four mesoporous 3-PSC sub-modules arranged in series, which involves connecting the positive terminal of each

panel to the negative terminal of the next panel in series, as illustrated in Figure 12. Thus, the current density is maintained while summing up their voltages. This configuration, even though it offers low reliability as all panels depend on each other, provides a higher voltage of the PV system.

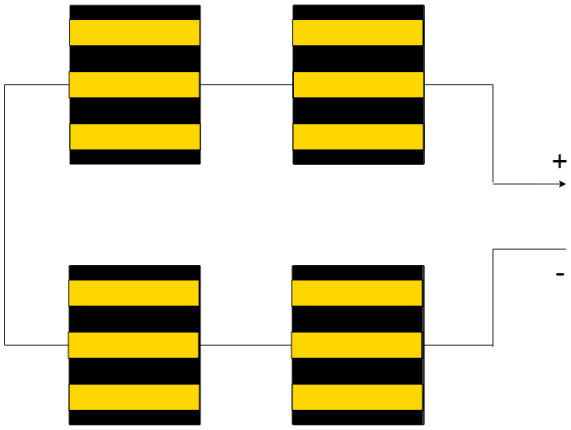


Figure 12. Disposition of the functional unit stated

Table 4 displays the main technical features of the PV module that was studied in this work. The arrangement of the PSC modules in the base case scenario has not been yet studied at the laboratory, therefore, some assumptions were assumed, regarding in particular the system active area and solar energy efficiency, as shown in Table 4.

The experimental data already obtained for the PSC cell supports that, for the current state of development, the technology has a TRL of 4, as the proof of concept was reached at a laboratory scale (Strazza et al., 2017). Yet, the PSC module is still far from industrial production and practical production, that involves the scale-up of the production process, and the results of this work will contribute to reach that global, that corresponds to a TRL of at least 7 or higher.

Table 4 - Technical features of the functional unit studied

Parameter	Value	Unit	Source
V_{oc}	12.28	V	(Ana Luís Carneiro, 2021)
J_{sc}	5.49	mA·cm^2	(Ana Luís Carneiro, 2021)
PMMP	2918.89	mW	(Ana Luís Carneiro, 2021)
Active area	105.6	cm^2	Calculated
Efficiency	16.26	%	(Stockhausen, Andrade, Ivanou, Stannowski, & Mendes, 2019)
FF	0.41		(Ana Luís Carneiro, 2021)

3.2.1 PSC fabrication

The assembling of the PSC sub-module is a bottom-up sequential process as described in (Choi et al., 2014). First, for 5 minutes the FTO layer was washed with deionized water and KOH saturated solution by sequential ultrasonication. The air-drying stage is then followed by the UV–ozone treatment over the substrate for a period of 15 minutes. A Versa laser printer engraves at 5 mm over the glass edge with the objective of electrically isolating the photoelectrode from the counter-electrode.

The successive step is the development of ETL, first through the deposition of the titanium dioxide (TiO2) blocking layer. To achieve that, it is necessary a heating plate at approximately 450 ºC where the FTO glass it is positioned while the solutions of acetylacetone in anhydrous isopropyl alcohol and titanium di-isopropoxide bis(acetylacetone) are spread with subsequent sintering over 45 minutes. Then, the substrates are transported to the glovebox once they have cooled down to room temperature. It will be there where, using the spin-coating technique (Lee, Teuscher, Miyasaka, Murakami, & Snaith, 2012) at 5000 rpm for a period of 10 seconds, an ethanol suspension of TiO2 paste is deposited on top of the blocking layer. This action is instantly followed by the drying of the substrates at a temperature of 100 ºC for 10 minutes. Soon after, using an oven at 500 ºC for 30 minutes, the film is completely annealed.

Then, using a precursor solution formed by lead iodide (PbI2), lead bromide (PbBr2) and two cations (formamidinium iodide in anhydrous N, N-dimethylformamide: dimethyl sulfoxide and methylammonium bromide (MABr)) the perovskite solution is developed. There is a third cation, cesium (Cs), which will be added to the to the initial solution after the total dissolution of all the elements by adding 5 % in volume of a cesium iodide. Once again, spin-coating will be used for the deposition of the layer in a two-step process: first at 1000 rpm for 10 seconds and then at 6000 rpm for 30 s.

As the entire process is conducted within a nitrogen-filled glove box, Figure 13 shows how chlorobenzene is dropped on top of the spinning substrate 15 seconds before it ends the second step of the process. Afterwards, the crystallization of the substrates begins when they are placed at 100 ºC for 40 minutes and once finished that time, the substrates were cooled down for a few minutes before proceeding to the HTL deposition.



Figure 13. Image of a spin-coated procedure in LEPABE

HTL deposition will be produced by using a solution containing FK209 (Dyenamo), lithium bis(trifluoromethanesulfonyl)imide (Li-TFSI, Acros Organic, 99 %) solution and chlorobenzene, 4-tert-butyl pyridine (TBP, Acros Organic, 96 %) in which the spiro-MeOTAD compound is dissolved. The resulting solution was spin-coated at a speed of 4000 rpm for 20 s in the perovskite layer at. Lastly, the gold deposition, done by thermal evaporation (M. Liu, Johnston, & Snaith, 2013) on top of the HTL layer. Temperatures between 100/120 ºC over a period of approximately two hours and a half are used to evaporate solid blocks of gold in vacuum.

3.3 Inventory analysis

To determine the associated cost and estimate a range of LCOE, EPBT and EROI values for perovskite solar modules a bottom-up cost model is developed. Two important concepts related to the creation of a cost model are the inputs and outputs. Inputs refer to what inflows into the system across the boundary while outputs consider what outflows from the system interior to the exterior (Frischknecht et al., 2015).

According to the definitions of economic indicators considered in this work, the main inventory items are the material and energy costs as the energy generated during the module lifetime. In the following two sub sections is described how the inventory was done for both types, describing the data sources, calculation procedures, and assumptions made.

3.3.1 Materials and Energy costs

The materials and energy costs inventory consists mainly of the materials needed to produce the PV module, including not only the materials that will constitute the PSC but also other auxiliary materials used, and the energy costs require by the production process (Sarialtin & Zafer, 2016). It is important to highlight that the price costs considered in this research are at laboratory-scale.

Table B 1 in Annex B presents the quantities of raw materials and values of energy consumed in each of the perovskite solar cell layers used to produce the 8.8 x 8 cm2 3-PSC sub-module used as base for the development of the functional unit studied. This material usage as the estimation of electricity consumption have been provided in a previous work (Ana Luís Carneiro, 2021). The values of the scribing and the UV-Ozone drying stage of the FTO glass were not considered in the inventory due to their low energy consumption when compared with the other inventory terms.

3.3.2 Energy production estimative

One of the main obstacles faced by any photovoltaic system project is how to obtain a reliable estimate of the energy generated by the PV system. This is due to the large number of variables and parameters that can influence it, such as: geographic location in particular latitude, climatic conditions, orientation limitations, among others. In this work the following equation (Celik et al., 2018) was used to estimate the energy generated in the solar cell in a year.

$$E_i = I_i \times PCE \times A \quad (8)$$

where $\boldsymbol{I_i}$ is the average yearly global irradiation at a given site, $\boldsymbol{PCE}$ is the power conversion efficiency (%), and $\boldsymbol{A}$ is the PSC module active area (m^2). The last two parameters were defined in Table 4, that presents the main technical features of the model device that was studied in this work. While the PSC sub-module was already produced and characterized at LEPABE, the arrangement of the PSC modules in the base case scenario has not been yet studied at the laboratory. Thus, some assumptions were assumed, regarding in particular the solar energy conversion

The value of $\boldsymbol{I_i}$ was estimated using the Photovoltaic Geographical Information System (PVGIS) webtool (Huld, Müller, & Gambardella, 2012). It provides a free and open web access to solar radiation and temperature data to deliver PV performance assessment tools for any worldwide location. More information on the irradiance data and the main bases of PVGIS is available in Annex D and Annex A respectively. In a nutshell, for a given geographic location, that can be defined in the tool, PVGIS determines the optimum tilt angle for the solar panel in order to achieve the maximum irradiance from the geographical site. From the monthly irradiation values an estimate of the average yearly total irradiation can be obtained and using equation 8 and estimate of average annual electricity production can be achieved. The monthly irradiation databases range from 2011 to 2016, ensuring that the natural climactic and cloud variability is minimized, and the average values are significant. Although PVGIS does not provide an estimate for the variability, from the values of the predicted yearly energy values predicted for Porto is expected that the irradiance variability to be below 10%.

3.4 Economic evaluation

In this work the Levelized Cost of Energy (LCOE), as defined by Equation (3) was selected as the main economic indicator, as it considers all the resources and physical assets required to supply a defined amount of energy. In its calculation some specific terms were not considered or are zero. For example, the fuel costs needed to obtain the generate the energy are assumed to be zero, as photovoltaic electricity generation does not require fuel. Also, the disposal costs, either landfill deposition or recycling, is not taken into account, as the technology is still under development it is unclear how the perovskite solar cells would be disposed of properly from an environmentally way.

The calculations for the EPBT and EROI terms comes was done by estimating of the embedded primary energy value using the EcoInvent V3.5 Lifecycle Inventory (LCI) database. In particular, the values of Cumulative Energy Demand (CED) (Frischknecht et al., 2015) reported in Annex C were used in the calculation of both indicators. As the values of CED are not available in the LCI database for all the compounds used for the assemble of the PSC studied, a cut off criteria was imposed in this work.

The materials that were used for the development of the CED were: Titanium di-isopropoxide bis(acetylacetone), Acetylacetone (< 99.5%), Anhydrous isopropyl alcohol (99.8%), Dimethylformamide, Chlorobenzene and Gold.

4. Results and discussion

In this section the results of this thesis are presented and analyzed. Firstly, the inventory costs of a 3-PSC sub-module are given, including the cost per functional unit and cost per square meter for the PSC; and the LCOE, EROI and EPBT are presented for the base scenario. Then, based on the results obtained, an analysis of various possible optimizations is done, in order to determine how can be improved the market potential of the PSC device. This involves a cost factors analysis and a parametric analysis of the parameters deemed more relevant from an economic point of view.

4.1 Inventory costs

The main costs to manufacture a 3-PSC sub-module are the electricity consumption and materials used to produce it. They are listed in Table 5.

Table 5 - Material and electricity costs to manufacture a 3-PSC module

PSC Layer	Input material / Energy process	Amount	Unit	Cost (€)
FTO Glass	Fluorine Tin Oxide Glass	38.7	g	-
	PT: electricity, production mix PT [Ultra-sonication]	2.04×10^{3}	kJ	0.08
Electron transporting layer	Titanium di-isopropoxide bis(acetylacetone)	3.00×10^{-4}	L	0.13
	Acetylacetone (< 99.5%)	1.95×10^{-7}	g	8.23×10^{-8}
	Anhydrous isopropyl alcohol (99.8%)	3.50×10^{-3}	L	0.35
	PT: electricity. production mix PT [Heating plate (450 C°. 45 min)]	7.35×10^{3}	kJ	0.30
Mesoporous layer	Ethanol	5.43×10^{-4}	L	0.10
	TiO2 (solid paste)	7.14×10^{-2}	g	0.23
	PT: electricity, production mix PT [spin coater, dry plate and oven (100 C°, 10 min)(500 C°, 30 minutes)]	9.20×10^{4}	kJ	3.83
Perovskite layer	Formamidinium iodite (FAI)	8.60×10^{-2}	g	0.28
	Lead Iodide (PbI2)	0.254	g	0.37
	Methylammonium bromide (MABr)	1.12×10^{-2}	g	0.02
	Lead bromide (PbBr2)	3.67×10^{-2}	g	0.47
	Dimethylformamide	4.00×10^{-4}	L	0.06
	Dimethyl sulfoxide	1.00×10^{-4}	L	0.08
	Cesium iodide (CsI) (5%)	1.44×10^{-7}	g	4.67×10^{-8}
	Chlorobenzene	1.20×10^{-3}	L	0.08
	PT: electricity, production mix PT [spin coater and dry plate (100 C°, 40 min)]	2.42×10^{3}	kJ	0.10
Hole transport layer	Spiro-MeOTAD	5.10×10^{-2}	g	8.31
	Chlorobenzene	5.58×10^{-4}	L	0.37
	4-tert-butyl pyridine	2.00×10^{-5}	L	0.20
	Lithium bis(trifluoromethanesulfonyl)imide	1.15×10^{-5}	L	0.28
	FK209 (Dyenamo) solution	5.00×10^{-6}	L	0.35

Table 5.1 - (Cont.) Material and electricity costs manufacture a the 3-PSC module

PSC Layer	Input material / Energy processes	Amount	Unit	Cost (€)
	PT: electricity, production mix PT [spin coater]	10	kJ	0.00041
Back electrode	Au	0.4	g	24.24
	PT: electricity, production mix PT [Thermal evaporation (100-120 C°, 150 min)]	2.07×10^4	kJ	0.86

From the values listed in the previous table, obtained from the data presented in the studies of (Ana Luís Carneiro, 2021), the overall energy consumed is 29.71 kWh. Table 6 presents the combined costs of a 3-PSC sub-module manufactured using the production process previously described in Section 3.2.2. The total cost per module is the sum of material and electricity costs, for the latter assumed a price of € 0.15 /kWh was assumed (IEA, 2020). Since the functional unit comprise four modules, the total cost of the unit is the cost per module multiplied by four.

Table 6 - Total costs for a 3-PSC module

	Amount	Unit
Material Cost per module	35.99	€
Electricity Cost per module	5.10	€
Total Cost per module	41.09	€
Functional unit cost	164.37	€
Module cost	583.69	€/ m^2

Figure 14 shows that the largest single item (67%) in the manufacturing costs is the back electrode/gold layer, in agreeing with the literature (Chang et al., 2017). In addition, considering the optimistic assumptions of no additional refinement (Woodhouse et al., 2013), and of a gold price of € 60.6 /g, the gold required to form a 80 nm layer would cost nearly € 400 of the € 583.69 that the production of one square meter of PSC module would cost. This material cost is by itself larger than the total fabrication cost of c-Si solar modules, which can be estimated from spot price data as approximately 60 €/m^2 (Brittany L. Smith, 2020). The other relevant term is the hole transport layer (HTL), that corresponds to 26%, being the relative importance of the remaining layers not significant. Thus, when trying to reduce the materials costs should focus in those two layers, in particular in reducing or even substituting gold by other cheaper material.

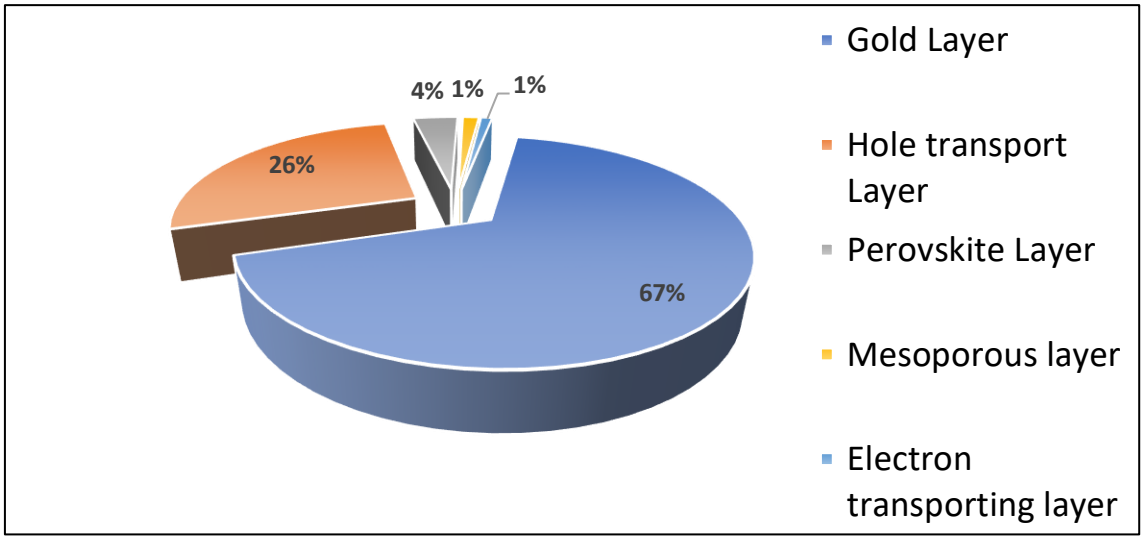


Figure 14 - Relative price cost distributed according to the layers of 3-PSC module

Figure 15 shows the relative energy consumption for each layer. The mesoporous layer uses the most energy, due to the high temperatures and long periods of time necessary for its production, mainly from the use of an oven to anneal the TiO2 film. The gold and perovskite layers represent the two other significant, being the remaining terms not relevant. Hence, as the largest share of energy consumption corresponds to the deposition of the mesoporous layer, this process should be improved or replaced in order to reduce cost of the functional unit.

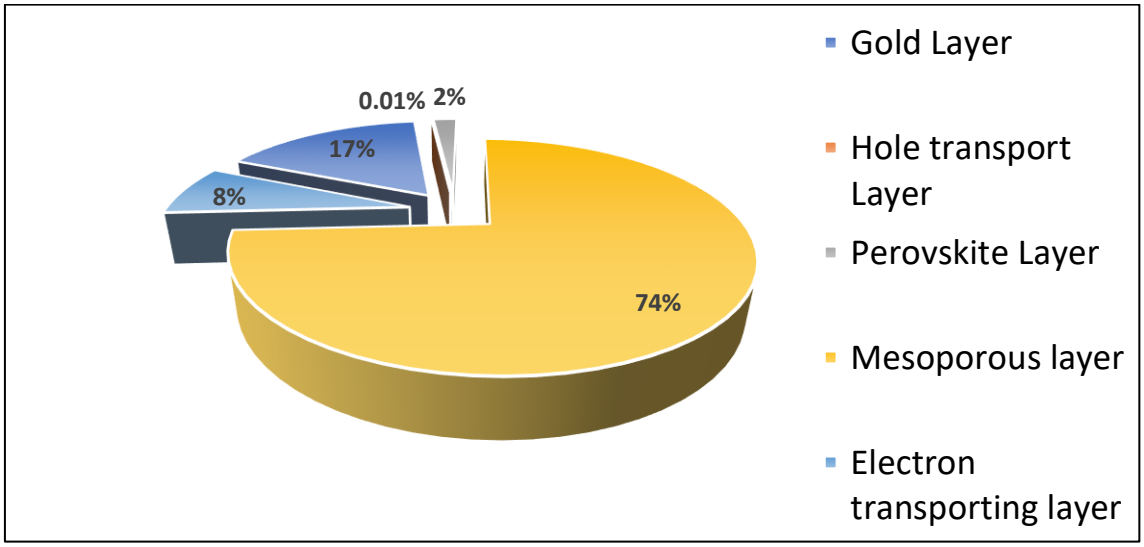


Figure 15 - Relative energy consumption distributed according to the layers of 3-PSC module

4.2 PSC base case: economic analysis

In this section the results of the economic analysis of the 3-PSC module are presented and discussed. Table 7 presents the data used with the base scenario, in particular the location information needed to use PVGIS, that was the Faculty of Engineering of the University of Porto, FEUP, located in Porto, north-western Portugal.

Table 7 - Main base case scenario values

Parameter	Value	Unit	Source
Location	[41.178, -8.597]	[Lat/Lon]	Map data ©2019 Google
Elevation	121	m	(Huld et al., 2012)
Active area	0.01056	m^2	[Calculated]
Solar panel efficiency	16.25	%	(Stockhausen et al., 2019)

Using PVGIS for the assumptions given in the previous table and using Equation (8), the following values are estimated: optimal tilt angle of 36 degrees, average yearly irradiation of 1855.35 kWh/m^2, and average yearly energy generation of 3.19 kWh. Despite the good irradiance conditions provided by the location of Porto and the optimistic efficiency proposed for our PSC module, the limited active area prevents from obtaining larger amounts of energy.

Table 8 lists the remaining assumptions needed to estimate the value of LCOE. Since the perovskite solar cell technology has a low value of TRL, 4, and therefore is not in the market, this work used information from the literature to obtain reliable values to quantify the parameters needed for the calculations.

Table 8 - Assumptions for the LCOE estimations

Parameter	Value	Unit	Source
Weighted Average Cost of Capital (WACC)	8.75	%	(Nadia Ameli, 2017)
System Lifespan	20	years	-
O&M Annual Costs	5	%	(Fu, James, & Woodhouse, 2015)
Inflation rate	1.37	%	(Nadia Ameli, 2017)
Solar panel yearly degration	0.5	%	(Jordan, Kurtz, VanSant, & Newmiller, 2016)

Based on the information of the previous table and the one obtained from the Ecoinvent LCI database (as per Table C 1 in Annex C) giving an material embedded energy estimated value of 102,38 kWh, it is possible to quantify the values of LCOE, EROI, and EPBT, which are presented in Table 9, using the methods described in chapter 3.3.2 and 3.4.

Table 9 - Economic analyses results for base case scenario

	Value	Unit
LCOE	8.67	€/kWh
EPBT	75.56	years
EROI	0.26	dimensionless

Comparing the value of LCOE obtained with the range of values of other technologies, shown in Figure 16, and the values estimated by other researchers to other types PSC

at laboratorial scale (Cai et al., 2017; Zongqi Li et al., 2018; Song, 2018), it can be concluded that the PSC module device developed for this work has a value of LCOE much higher. Hence, in the current state of development the PSC based on mesoporic architecture is not competitive.

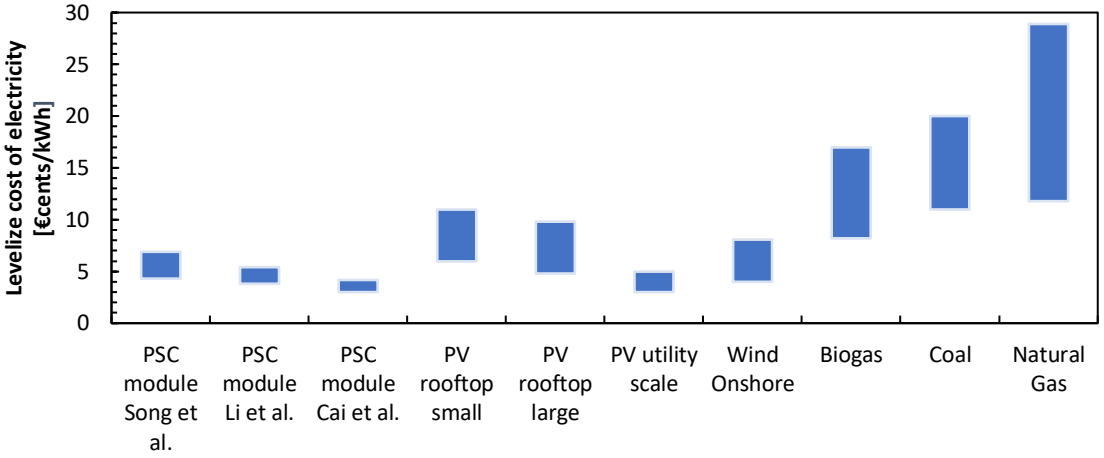


Figure 16. LCOE of perovskite solar modules, renewable energy technologies and conventional power plants (Kost, 2021)

Regarding EROI, the energy generated during the assumed lifetime of the functional unit is lower, 62.8 kWh, than the energy consumed only in its production, 118.84 kWh, an as EROI considers all the energy embedded in the materials during its production, a value lower than 1 is obtained, making the cell a net consumer of energy. This is due mainly to the very high value of CED of gold, a material that requires significant amounts of energy to be produced. Consequently, the value of EPBT is also very high.

From a technical point of view, the technology is at a TRL level of 4, therefore at the laboratory proof of concept stage. The use of lab grade chemicals, much more expensive that bulk chemicals, and a process not optimized in terms of energy consumption, support the conclusion that, to be market viable, the PSC production process must change, either by substituting materials and/or being more energy efficient. Also, a more efficient cell and/or with a longer lifetime can also be important factors, and they explored in the next sub section.

4.3 Parametric study

To identify which aspects researchers and developers should focus their efforts, a parametric study can be performed. Even though a full analysis should consider all three indicators, in this section only values of LCOE will calculated and discussed, as this indicator can be considered the more relevant from an economic point of view. From Equation (8) for LCOE, the following parameters are considered the most relevant: location, cell efficiency, WACC, yearly degradation rate, and inflation rate. A one at time (OAT) analysis will be done in this section, as it is easier to identify the real dependence of LCOE in a given parameter.

Concerning location, the geographic location of the PSC module has a strong influence in the values of the economic indicators, as the irradiation depends strongly in the

climatic conditions and latitude, leading to large variations in the energy generated. Considering the Iberian Peninsula, according to the Koppen climate classification ((Beck et al., 2018) three main climatic conditions may be defined, as seen in Figure 17.

Two zones correspond to Mediterranean climate: warm summer (Csb) and hot summer (Csa); and characterized by summers with very low precipitation, with Csa having in average more hours of insolation when compared to Csb. The other corresponds to an Oceanic climate (Cfb), where the temperatures and precipitation have smaller inter annual variations when compared to Mediterranean climates and the coldest month temperature average must be above -3 °C. Other climates exist in the Iberian Peninsula, but they are limited to mountainous areas most of them.

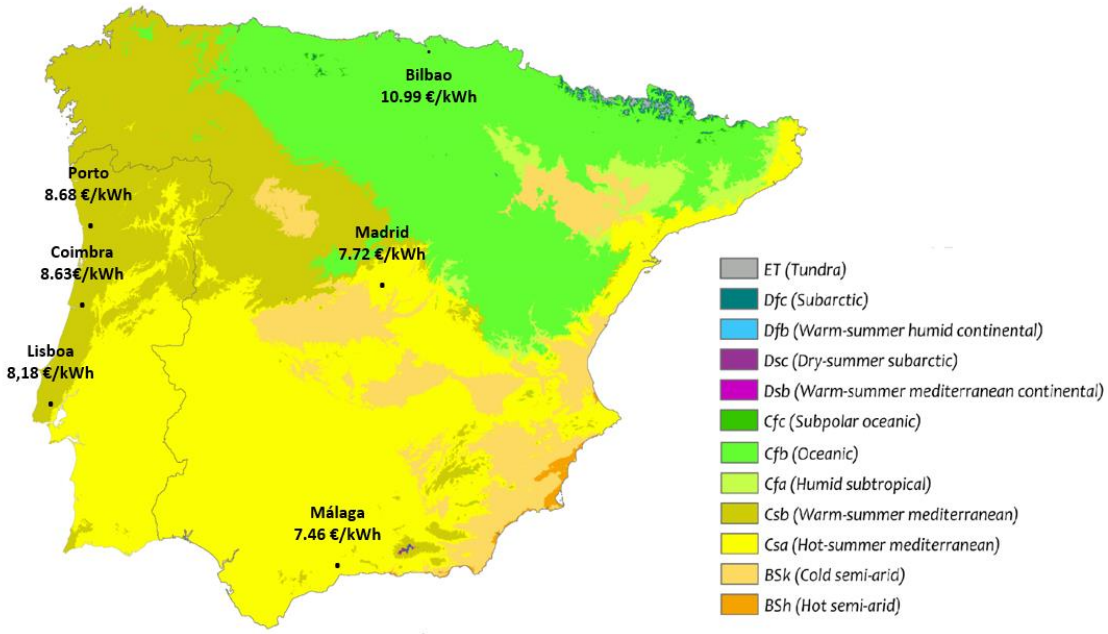


Figure 17 - Climate study of the Iberian Peninsula for the base case scenario

The Portuguese cities of Porto, Coimbra and Lisbon are the examples of the Warm-summer Mediterranean climate (Csb), while the Spanish cities of Malaga and Madrid represent the Hot-summer Mediterranean climate (Csa), and the city of Bilbao exemplifies the Oceanic climate (Cfb). They were selected in this work to highlight the effect of the climatic and geographic location in the PSC module performance.

Table 10 reports the energy generated by the functional unit in different cities, using the parameters listed in Table 8 for the calculation of the LCOE estimate values.

Table 10 - Geographic location study results of the base case scenario

Location	Coordinates [Latitude/Longitude]	Climate [Köpen classification]	Energy generation [kWh/year]	LCOE [€/kWh]
Porto	41º2´N 8º59´W	Csb	3.18	8.68
Coímbra	40º2´N 8º42´W	Csb	3.20	8.63
Lisboa	38º7´N 9º14´W	Csb	3.38	8.18
Málaga	36º7´N 4º41´W	Csa	3.71	7.46
Madrid	40º5´N 3º63´W	Csa	3.58	7.72
Bilbao	43º3´N 2º93´W	Cfb	2.52	10.99

The results show a considerable influence of the climatic conditions. As expected, Bilbao presents the worst economic results, since the PSC device only generate a total of 2.52 kWh/year, due to more cloudiness of the Oceanic climate when compared to Mediterranean climates. For the two variants of Mediterranean climates, two clusters are seen, being the values similar for the same variant. As expected, Csa performs better than Csb, as locations with a Csa climate have higher hours of insolation, thus leading to more energy generated and lower values of LCOE.

Hence, to further account for the effects of location only one for each climate condition was used for the remainder of this sub section: Malaga for Csa, Porto for Csb, and Bilbao for Cfb. Moreover, the values of LCOE obtained for the case base, to highlight how the changes in the parameters can improve the performance when compared to it.

Figure 18 presents the relationship between LCOE and the lifetime of the assembled PSC module. As expected, as the lifetime increases the value of LCOE lower, as more energy will be generated during the device operation, with a variation of 50% for the range of values considered. The results show a decrease in the impact of the studied variable in time, being the variations of LCOE small for values of the lifetime higher than 15 years but representing a decrease of approximately 15% in the value LCOE when the lifetime change from 10 to 15 years. Despite the rapid growth in the average lifespan of PSCs increasing from hours to approximately a year in less than a decade (Leijtens et al., 2017), stability problems are still common in perovskite technology so lifespan should be a variable to be considered in future research works. Compared with the case base, it can be seen that increasing the functional unit lifetime will have a small impact in the economic feasibility.

As can be seen in Figure 19 (the ordinate axis is the same of Figure 18 to ease up the comparison between figures) varying WACC from 0% to 15 % leads to variation of around 40% in the values of LCOE. Contrary to the case of lifetime, the variation is almost linear, having a slightly higher slope for Bilbao (Oceanic Climate) when compared to the other two locations that have Mediterranean climate. Therefore, for locations with climates similar to Bilbao or with lower total hours of insolation the value of WACC, or the interest rate applied to finance the acquisition of the equipment (corresponding to the CAPEX), can be a significant aspect to consider when deciding to acquire this type of solar cells.

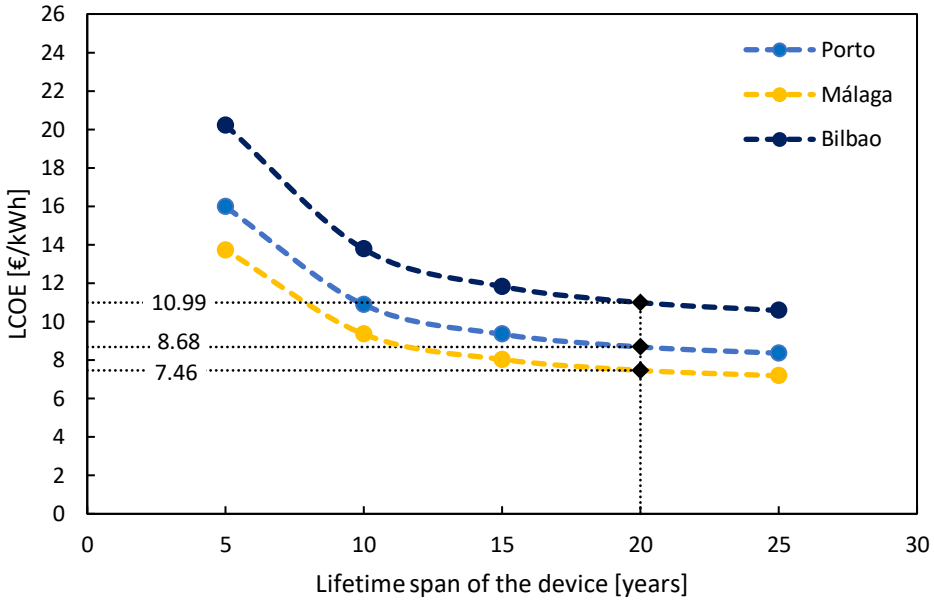


Figure 18 - Lifespan study for the base case scenario

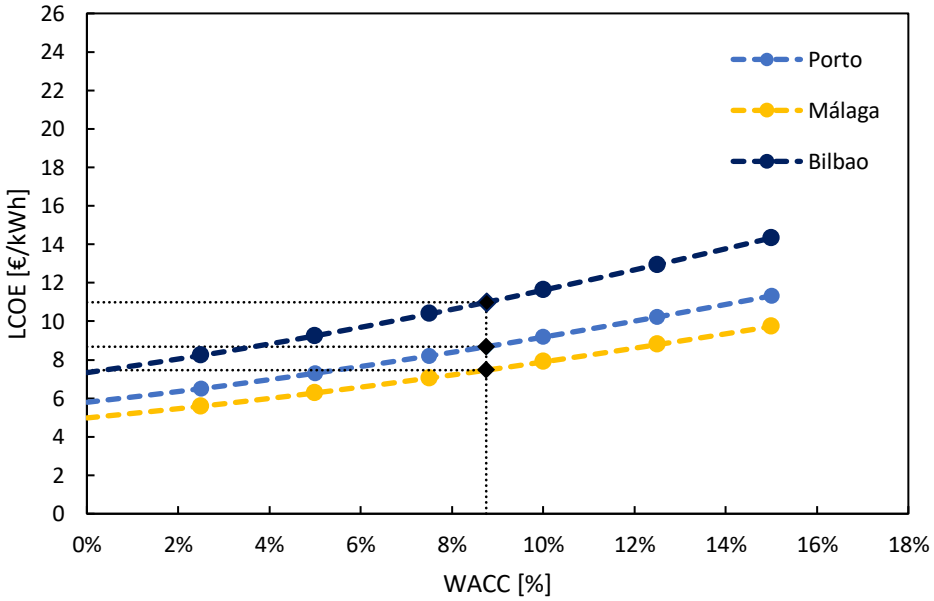


Figure 19 - WACC study for the base case scenario

Figure 20 shows the values of LCOE for the three locations as a function of the solar yearly degradation. The results show a smaller influence of this parameters, with a variation of around 20% for all range of values considered, with all locations sharing the same qualitative behavior. Only in the case that the yearly degradation of the solar panels is much higher than the values considered would the LCOE be affected by this variable in a significantly way.

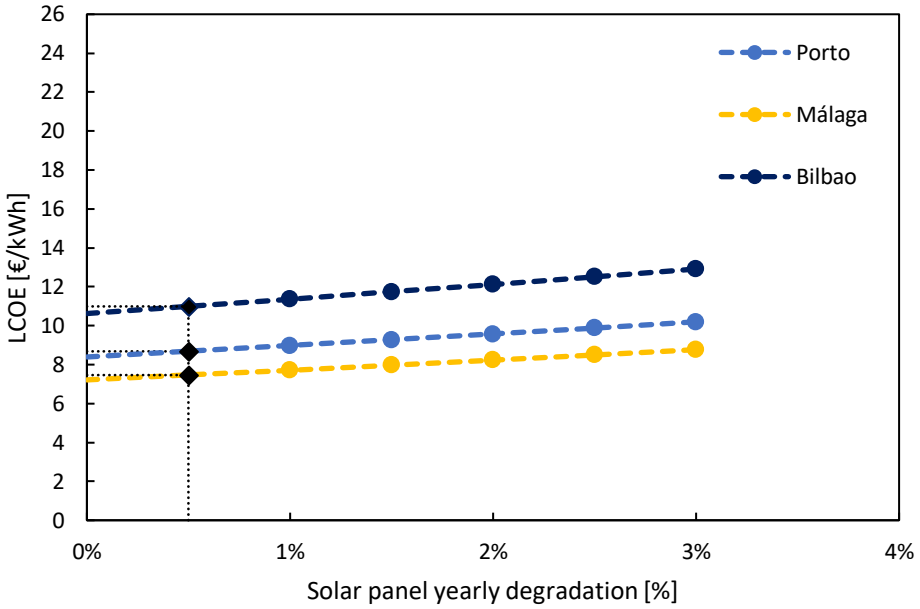


Figure 20 - Yearly degradation of the solar panel study of the base case scenario

Figure 21 presents the influence of inflation on the LCOE. It can be seen that the variations are small, about 20% for the all range of values. Being the inflation a quantitative estimate of decline of purchasing power of a given currency over time (Fernando, 2022) it would take the development of an extremely negative situation such as an Hyperinflation, with values higher than 50 %, to assume a real weight off the variable over the commercialization of perovskite technology.

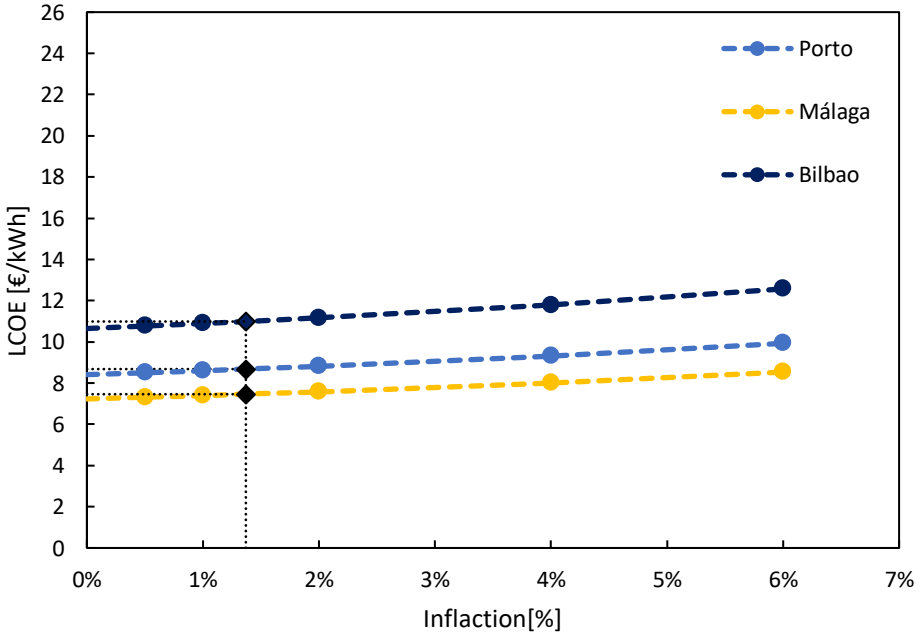


Figure 21 - Inflation study of the base case scenario

Finally, the efficiency of the solar cells in the values of LCOE is presented in in Figure 22, showing a strong dependence, with a reduction of 70% in the LCOE values for the

full range of values considered. For the base case scenario, an increase of 7% for the efficiency results in a reduction of approximately 30% over the original LCOE value proposed for the base case scenario. The results shows that research and development activities should focus in increasing the cell efficiency, as it is the factor with more impact in its economic performance.

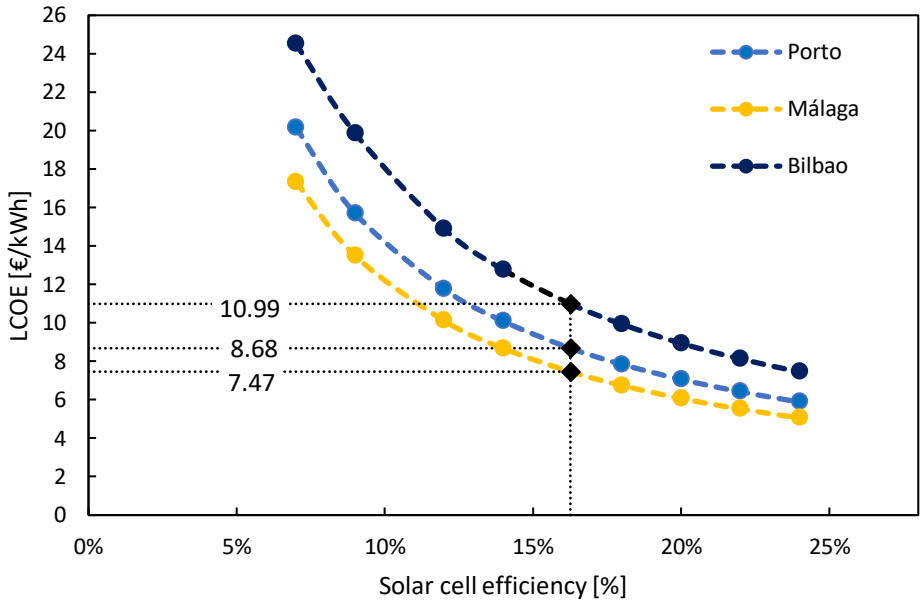


Figure 22 - PSC efficiency study of the base case scenario

In terms of LCOE estimates comparisons variations in solar yearly degradation and inflation have a relatively small effect on LCOE (about +/- 20 %). Therefore, the lifespan of the system, mainly related to the material properties, the solar cell efficiency, which affects directly to the yearly energy production of the system, and the WACC, that impacts the cost of capital, are the main variables in the LCOE estimates.

As the WACC value is outside the control of the cell manufacturers because it depends on the national or regional economic conditions and the risk perceptions in an economic sector, in the next section only the lifetime and the PSC efficiency will be considered when assessing in which conditions the functional unit would be economic feasible.

4.4 Economic viability study

The results of the previous section demonstrate that at the current state of development, the studied PSC is not economic viable. The main cost terms were identified, and what are the parameters that have the largest influence on the LCOE value, therefore, in which the research and development efforts should focus first.

In this section it is explored how the functional unit can be made economic viable, especially what need to be changed/improved. For this, a target LCOE value of € 0.15 /kWh. As done in chapter 4.1, that value was used as an estimate for the electricity price to calculate the energy costs, and so it is a good starting point to evaluate the

technology commercial potential. In order to reach this goal, a set of changes in the base case scenario are proposed and assessed.

One of the key aspects that need to be significantly reduce is the total material costs. As shown above, the module has a cost per square meter of € 580, ten times the cost of one square meter of silicon solar cells (Park, Grätzel, Miyasaka, Zhu, & Emery, 2016). The main factor is clearly the gold used in the back contact layer. Thus, the first logical step to bring the cost of PSC technology closer to its commercial alternatives is to replace partially of totally gold as a material used in the 3-PSC cell.

An interesting option is the utilization of carbon materials, as shown in Figure 23 (Cristina Teixeira, 2019), as they share some exceptional features with the gold such as their high oxidation stability or their non-toxicity (Werner et al., 2020). The use of carbon paper as back-contacts could improve the economic indicators for perovskite technology (Teixeira, Andrade, & Mendes, 2020). In the studies mentioned the utilization of three types of carbon papers as back-contacts is reported: carbon paper with no polytetrafluoroethylene (PTFE) treatment - CP1, a highly flexible and thin commercial carbon paper - CP2, and a carbon paper with a microporous layer coated with PEDOT PSS - CP3. To ensure a similar performance of the PSC module (losses lower than 10% when compared to the base case scenario), a thin layer of 5 nm of gold is added to the modified cell.

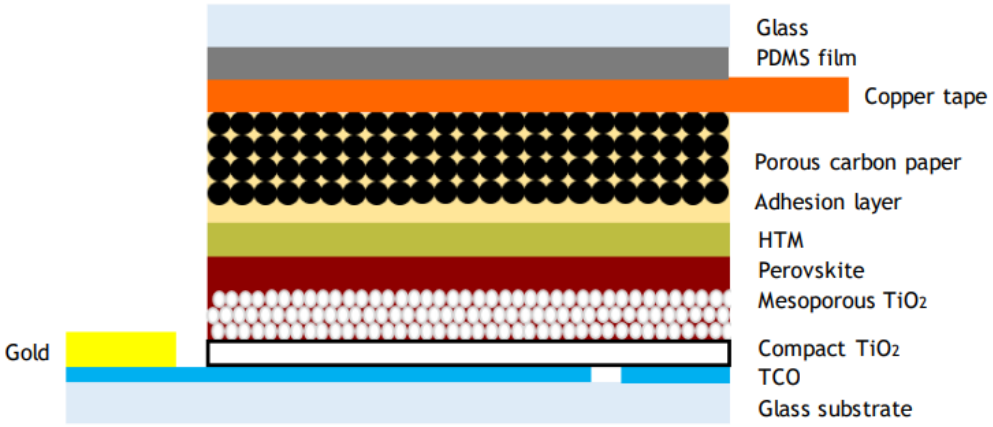


Figure 23 - Scheme of a PSC device with carbon paper as back-contact

Due to the impossibility to obtain reliable data of the energy consumption related to the deposition of the carbon paper back contacts, it was assumed that the carbon paper deposition is not different in energy consumption when compared to the gold deposition process. Therefore, the values of EROI and EPBT do not change due to replacement of gold only for carbon paper + gold, even though it is expected a significant reduction on the value of those indicators, as producing carbon paper will surely be less energy intensive than producing gold. However, no evaluation was done as no data was found concerning the CED of carbon paper production.

Other possible modification to decrease the production costs, and consequently the LCOE, consider the overall energy costs of the manufacturing process. As evidenced by

Figure 15 and the results presented in Table 5, the mesoporous layer has the higher energy demand in the perovskite solar cells production, with an energy cost superior to the target LCOE value. Therefore, changing the PSC design, in particular its architecture and/or layer structure, should be considered. In particular, changing the current N-I-P structure to a P-I-N structure would be a good measure, since the P-I-N structure don't have mesoporous layer. However, considering the values given in Table 5, other energy costs must be reduced to achieve the target LCOE value.

The scale-up to larger areas may reduce those terms, as the same amount of energy will be used to obtain those cells, thus reducing the energy cost per unit area. However, in the current state of development of the technology is not possible to estimate how much the costs will reduce.

Two scenarios were considered to determine if the proposed changes would help to achieve the LCOE targets presented above, in terms of material substitution. As done before, the remaining parameter are the same of the base case scenario, to better see the effects of the proposed changes.

> **Scenario 1: Reduction / Substitution of gold as back contact**: carbon paper (CP1) is used as back electrode plus an additional 5 nm gold layer.
> **Scenario 2: Scenario 1 + Change of the PSC structure**. Change of architecture from N-I-P to P-I-N, by means of semi qualitative analysis (no efficiency losses have been assumed).

The LCOE values obtained for each scenario and locations are presented in Table 11. In Scenario 1, the LCOE values decreased by 54.5 %, and for Scenario 2 the reduction was of approximately 72 %. Although achieving significant reductions, the proposed new scenarios are still far away from being feasible from a commercial point of view

Table 11 - Comparison between the LCOE values obtained for the proposed scenarios

	LCOE Values [€/kWh]		
	Base case scenario	**Scenario 1** Substitution of the gold as back contact	**Scenario 2** Scenario 1 + Disposal of the mesoporic structure
Porto	8.68	3.98	3.11
Málaga	7.46	3.42	2.67
Bilbao	10.99	5.04	3.93

In Figure 24 it is presented the influence of the PSC efficiency and lifespan in the LCOE values for the scenarios 1 and 2, considering the three locations. As expected, even for the highest values of efficiency and/or useful lifetime, the values of LCOE are much larger than the target value. This means that other material cost terms have to be reduced. A clear option involves the replacement of laboratory grade chemicals by cheaper lower purity compounds, that can still be used in practice without losing cell efficiency. However, at the current state of development it is not possible to make decisions for which chemicals will be possible the proposed substitution.

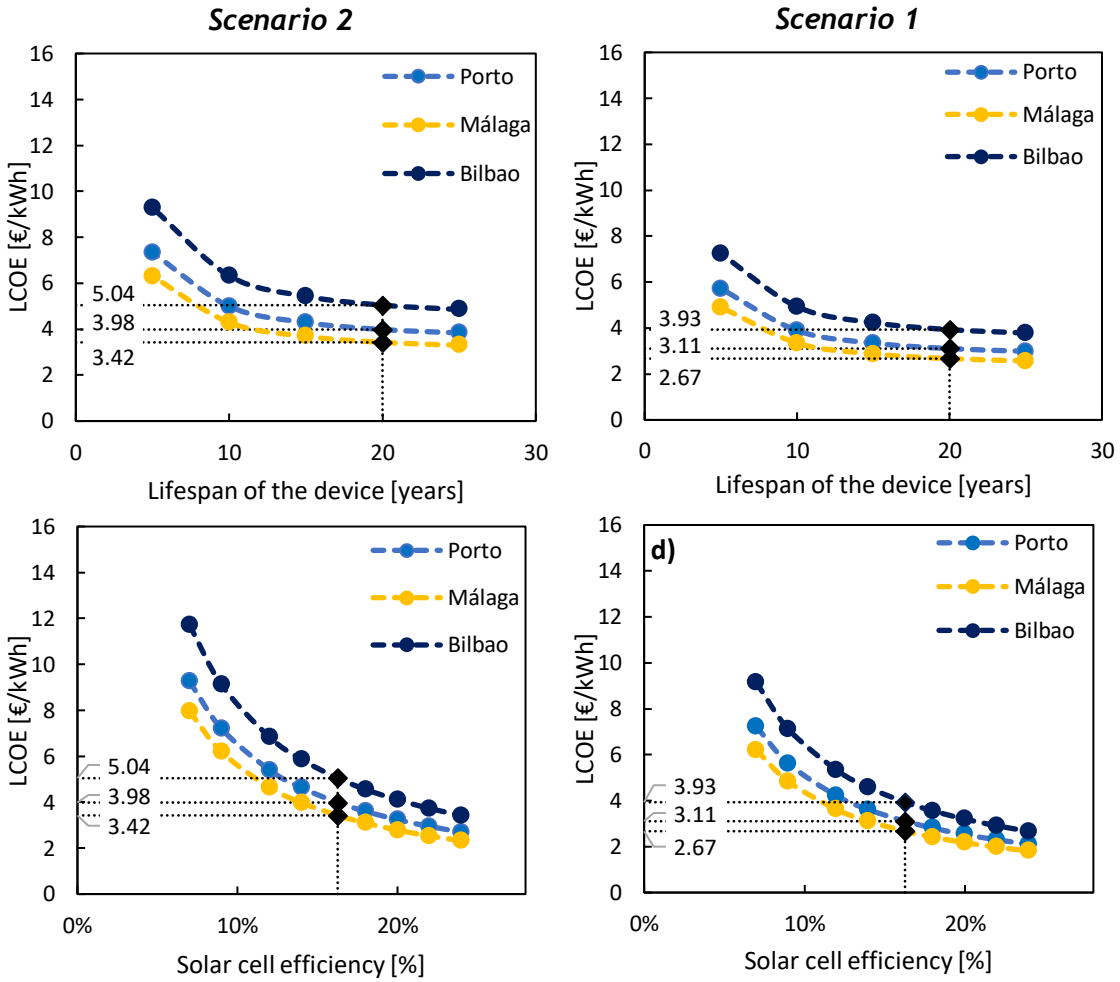


Figure 24 - PSC efficiency and lifespan studies for Scenario 1 and Scenario 2

Figure presents the potential of reduction of the LCOE by combining scenarios 1 and 2. It can be seen that by combining the two reductions of the LCOE, a value of more than 70% is reached over the original values. Yet, to reach the target value more development efforts must be considered.

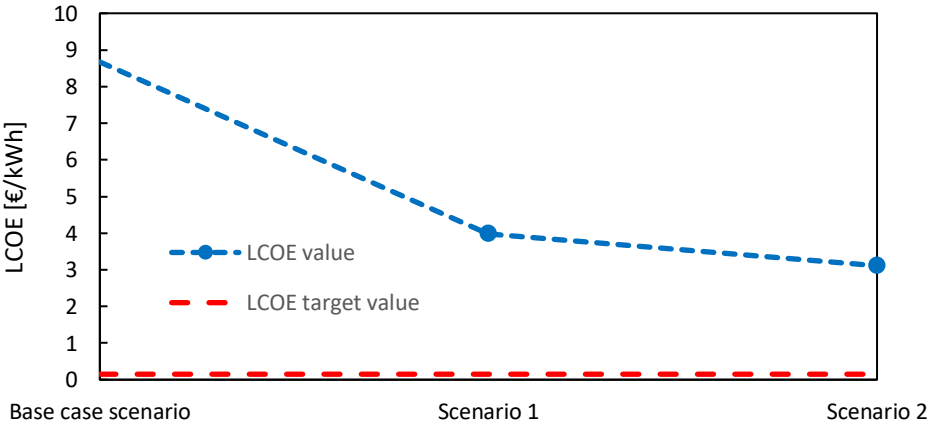


Figure 25- Exposure of the LCOE values through the changes proposed in the section economic viability study

As stated before, the material and energy costs of the production of a PSC cell are a measure of the capital cost, CAPEX, needed to produce one 3-PSC sub-module. As the capital cost is main term of the LCOE, and the maintenance costs are defined a small percentage of CAPEX, its limit value can be estimated in order to verify the target value of 0.15 €/kWh, developing Scenario 3. To be commercially viable the CAPEX must be lower than that limit value, and the development activities must reduce to this value. In Table 12 the limit value is compared with the values obtained for scenarios 1 and 2, with the parameter values considered for the case base scenario. It can be seen that significant reductions are still necessary to reach the target LCOE.

Table 12 - Comparison between the Capital investment values obtained for the proposed scenarios

	Base case scenario	**Scenario 1** Substitution of the gold as back contact	**Scenario 2** Scenario 1 + Disposal of the mesoporic structure	**Scenario 3** The LCOE is set in 0.15 €/kWh
Capital Investment [€]	164.37	75.45	58.81	2.84

Figure presents the influence of the PSC efficiency and lifespan in the values of capital investment needed to reach the target LCOE value, corresponding to scenario 3, for the three locations considered in this work. As expected, the values predicted for Malaga are greater, as the larger amount of energy generated at that location compensate increases of the capital value when compared to the other locations. For similar reasons, Bilbao has the lower limit values. Regarding the influence of the parameters, a linear dependence is observed for the solar efficiency, with the largest slope for Malaga. For the lifespan, although increasing its value increases the LCOE limit value, for values larger than 20 years the variation is small. Moreover, comparing the overall variation for both parameters, it is more significant for the cell efficiency, showing that a focus should be given to improve it.

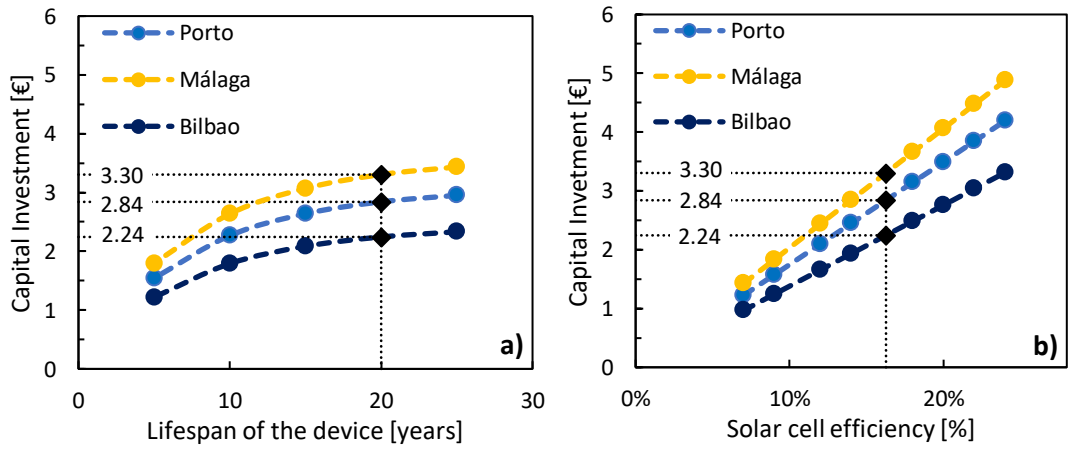


Figure 26 - Capital investment values for Scenario 3

Also, the variations are larger for Malaga and smaller to Bilbao for the two parameters, demonstrating the importance of the climatic conditions in the economic performance. sent the relation of the efficiency and lifespan variables have with the capital investment in scenario 3. This is aimed to estimate what range of scientific improvements over the PSCs are necessary to establish that the perovskite technology has reach the commercial feasibility point.

It is important to highlight that, though the results of scenario 3 illustrate the large gap that exists between the use of current perovskite technology and its commercialization, these estimates should be evaluated with care. The methodology used for the economic evaluation did not consider some key aspects, such as: larger scale up simulation, industrially updated costs, engineering-optimized processes, architecture structure, among others; that may have a significant impact on the process economics.

5. Conclusions

The objective of this study was to evaluate the economic performance perovskite solar cells. Despite being a promising solar technology with numerous significant improvements during the last studies, when it comes to practical level applications, issues about their stability and reproducibility show up, decreasing its commercial potential.

For those reason, in this work it was conducted an economic study based on a experimental perovskite solar cell based on an mesoporous architecture with an active area of 105.6 cm^2 which was produced from four 3-PSC sub-modules. The evaluation was done considering three economic indicators: LCOE, EROI and EPBT. The data was obtained from the experimental solar cell as well from the literature and the LCI database Ecoinvent V3.5.

The results show that the values of LCOE are still too high when compared with other energy generation technologies, in particular renewable based, being the values almost one hundred times higher than those that corresponding to previous developed PSC studies. This is the result of large material costs, due to the utilization of gold and laboratory grade reagents in the production process, which results in very high capital costs. Moreover, the energy costs are also relevant, showing that the production must be optimized from an energy point of view.

The parametric study showed that the main parameters influencing the economic performance are the climatic conditions, the cell efficiency, the cell lifetime, and the WACC. The analysis of the climates in the Iberian Peninsula showed that those with higher irradiance exposure, such as Hot-summer Mediterranean climate or Warm-summer Mediterranean climate produces more energy comparing to Oceanic climate, which tend to feature cloudier conditions with precipitation. Parameters such as inflation and yearly degradation are not very relevant.

Two proposals to improve/lower the value of LCOE were considered and evaluated: replacing of gold as back-contact´s layer by carbon layer with a nanometer scale layer of gold and changing the cell architecture from a N-I-P structure to a P-I-N structure. Although both scenarios achieve significant improvements, with LCOE reductions of around 54.5 % for only gold substitution and 72 % for the combined options, they are still too far from the established goal of 0.15 €/kWh. Thus, a third scenario was defined in which the capital cost was determined in order to fulfill the target value. The analysis concluded that higher values of capital cost are obtained for warmer climates, allowing greater flexibility over PSC production process and the cell efficiency is the most relevant factor.

Further work includes the experimental analysis of the proposed scenarios to determine if the estimated results are in agreement with those achieved in the laboratory, and the scaling up of the PSC cells. Also, a more complete parametric analysis of the parameters influencing the cell performance, and an uncertainty analysis should be done.

Assessment of the work done

5.1 Objectives Achieved

This master thesis has as main goal the economic evaluation of Perovskite Solar Cells technology through the use of calculation common economic instruments such as the LCOE, EROI and EPBT and the development of cost-effective evaluations. The aimed objectives were reached as the variables with greater impact over the PSC commercial feasibility were classified and evaluated. Different proceeding approaches were analyzed as well to establish a series of parameter values which will serve as guidance for future works.

5.2 Other Work Carried Out

An abstract based on the work developed within this master thesis was submitted to the 5th edition of Energy & Environment: Bringing together Economics and Engineering conference (ICEE 2022) reporting the economic and commercialization evaluation of Perovskite Solar Cells. Being this abstract was accepted for oral presentation in ICEE 2022.

5.3 Final Assessment

Personally, I consider that the endless possibilities regarding the development of perovskite solar cells makes their complete understanding extremely difficult. Therefore, the conclusion of the master thesis has left me with a bittersweet feeling since the obtained estimates have not been commercially optimistic but have proven their potential for future research The fact of having had constant communication and incredible support from my supervisors - for whom I will always be grateful - has not prevented me from sometimes feeling lost in the face of the mental challenges involved in developing a dissertation of these characteristics. This work has represented my first contact with economic evaluation, a topic that I really wanted to explore and that through the development of this master thesis has helped me to strengthen my conviction that I would like to work in this sector in the future. The introduction in the photovoltaic sector has also been a pleasant surprise, allowing me to study and research about extremely interesting topics, such as the appearance of potential new technologies or understand the technical principles with which solar panels are ruled.

Finally, even if there are many strategies to continue the economic evaluation of this technology, I am convinced that this work may serve as basis for future works, in particular applied to new architectures. Inverted perovskite solar cells should be then studied since this arrangement might be even more interesting for commercial applications due to its improved stability, as well as reduced costs in terms of energy and raw materials.

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Annex A - Description and use of PVGIS

As described in section 3.5, the amount of average daily irradiance obtained in the different locations studied was estimated using the Photovoltaic Geographical Information System (PVGIS) free access webtool. PVGIS was an instrument developed by the JRC – Joint Research Institute of the European Union a European Commission's science and knowledge service that carry out researches to provide independent scientific advice and support to EU policy.

The link of the presentation of the European entity can be accessed through the following link https://ec.europa.eu/jrc/en and the webtool used in this study can be found here https://ec.europa.eu/jrc/en/pvgis

Using webtool requires the definition of the following information:

- Geographic location, for which webtool makes Google Maps embedded directly in the app. Company location information was obtained from your website.
- Define the solar radiation database, which considers the geographical coordinates of the selected location, and the average weather conditions in this. The database initially defined by the webtool was used (PVGIS-SARAH)
- Month of the chosen data to be downloaded and desired timetable with the choice between UTC time and Local time options
- The slope [°] and Azimuth [°], normally assumed to be south facing, which is the most appropriate, although the possible orientation depends on the characteristics of the place where the panels are installed.

Figure 1 shows a snapshot of the PVGIS webtool data entry table, as well as it is possible to define the geographic location of the study site (in this case of the department of chemical engineering of FEUP).

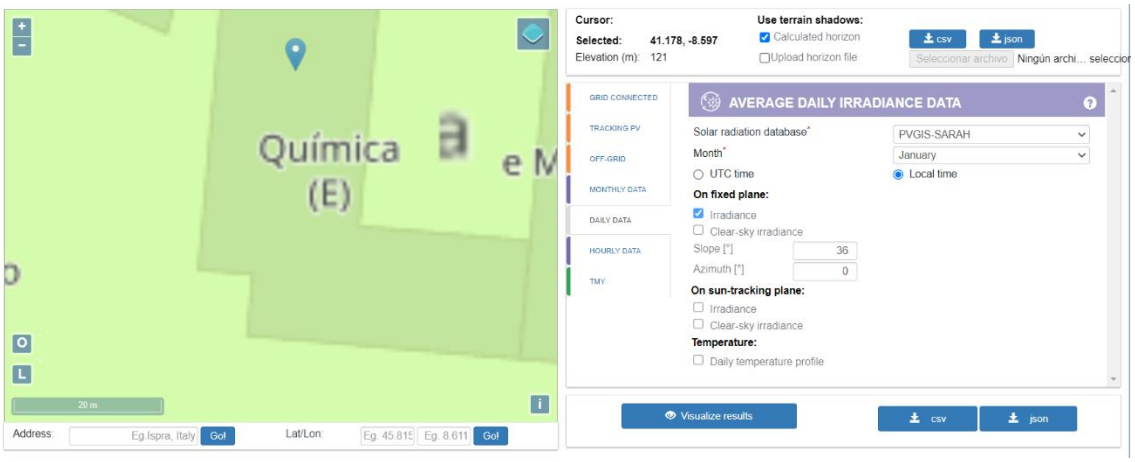


Figure A 1- PVGIS webtool data entry table.

Then just click on the "Visualize results" button, and you get the results that are shown in Figure 2. The results can be exported to a csv file, which can be opened in Excel, for further treatment of the obtained results.

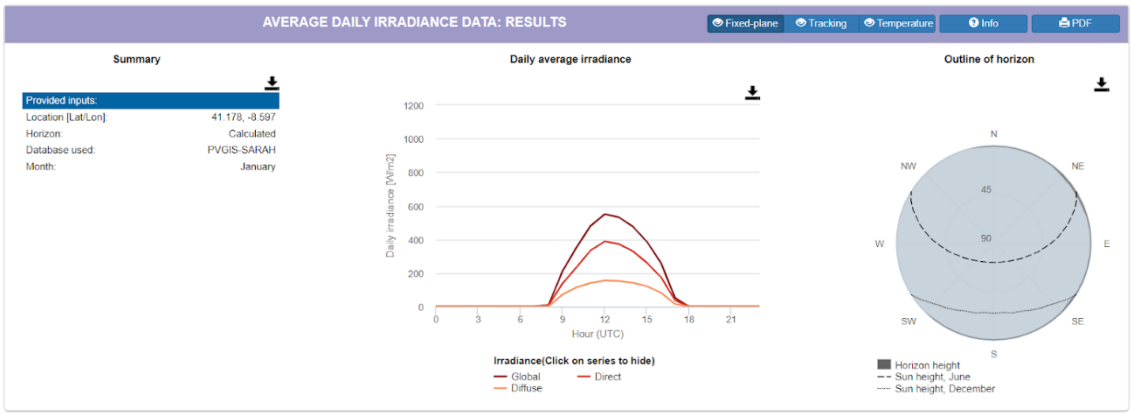


Figure A 2 - PVGIS webtool results table for location and data considered

Annex B – Life cycle inventory

Table B 1 - Material and energy inventory of manufacturing a 3-PSC module. I stand for material input and P for the process energy requirement

Input material		Amount	Unit
FTO Glass			
I	Fluorine Tin Oxide Glass	38.7	g
P	PT: electricity, production mix PT [Drying* with uv-ozone*, scribing and ultra-sonication]	2,04 x 10^{3}	kJ
Electron trasporting layer			
I	Titanium di-isopropoxide bis(acetylacetone) (75% wt)	3.00 x 10^{-4}	L
I	Acetylacetone (< 99.5%)	1.95 x 10^{-7}	g
I	Anhydrous isopropyl alcohol (99.8%)	3.50 x 10^{-3}	L
P	PT: electricity, production mix PT [Heating plate (450 C°, 45 min)]	7.35 x 10^{3}	kJ
Mesoporous layer			
I	Ethanol	5.43 x 10^{-4}	L
I	TiO2 (solid paste)	7.14 x 10^{-2}	g
P	PT: electricity, production mix PT [spin coater, dry plate and oven (100 C°, 10 min)(500 C°, 30 minutes)]	9.20 x 10^{4}	kJ
Perovskite layer			
I	Formamidinium iodite (FAI)	8.60 x 10^{-2}	g
I	Lead Iodide (PbI2)	0.25	g
I	Methylammonium bromide (MABr)	1.12 x 10^{-2}	g
I	Lead bromide (PbBr2)	3.67 x 10^{-2}	g
I	Dimethylformamide	4.00 x 10^{-4}	L
I	Dimethyl sulfoxide	1.00 x 10^{-4}	L
I	Cesium iodide (CsI) (5%)	1.44 x 10^{-7}	g
I	Chlorobenzene	1.20 x 10^{-3}	L
P	PT: electricity, production mix PT [spin coater and dry plate (100 C°, 40 min)]	2.42 x 10^{3}	kJ
Hole transport layer			
I	Spiro-MeOTAD	5.10 x 10^{-2}	g
I	Chlorobenzene	5.58 x 10^{-4}	L
I	4-tert-butyl pyridine	2.00 x 10^{-5}	L

Table B 1 – (Cont.) Material and energy inventory of manufacturing a 3-PSC module

Input materials		Amount	Unit
I	Lithium bis(trifluoromethanesulfonyl)imide	1.15×10^{-5}	L
I	FK209 (Dyenamo) solution	5.00×10^{-6}	L
P	PT: electricity, production mix PT [spin coater]	10	kJ
Back electrode			
I	Au	0.40	g
P	PT: electricity, production mix PT [Thermal evaporation (100-120 C°, 150 min)]	2.07×10^{4}	kJ

Annex C – Cumulative energy demand (CED)

Table C 1 – Estimate values of the cumulative energy demand impact for the manufacturing a 3-PSC module

		cumulative energy demand biomass	cumulative energy demand fossil	cumulative energy demand geothermal	cumulative energy demand nuclear	cumulative energy demand primary forest	cumulative energy demand solar	cumulative energy demand water	cumulative energy demand wind	
		rewenable energy resources, biomass	non-rewenable energy resources, fossil	rewenable energy resources, geothermal, converted	non-rewenable energy resources, nuclear	non-rewenable energy resources, primary forest	rewenable energy resources, solar, converted	rewenable energy resources, potential, converted	rewenable energy resources, kinetic (in wind), converted	TOTAL
Material	**Unit**					**MJ-Eq**				
Gold production		3330.4	194240	271.93	21105	16.08	3.19	8577.10	1613.10	229156.80
Titanium di-isopropoxide production		1.88	75.17	0.10	5.86	2.02	2.31×10^{-3}	3.06	0.52	86.58
Acetylacetone production	**kg**	0.28	43.99	2.43×10^{-3}	2.32×10^{-4}	1.06×10^{-4}	1.19	0.15	0.02	45.62
Anhydrous isopropyl alcohol production		0.28	6.62	0.01	1.85	2.40×10^{-4}	4.71×10^{-4}	0.36	0.05	64.16
Dimethylformamide production		0.44	75.90	0.04	2.26	7.31×10^{-4}	6.31×10^{-4}	1.20	0.18	80.03
Chlorobenzene production		0.57	71.27	0.03	3.41	6.71×10^{-4}	1.63×10^{-3}	1.06	0.17	76.52

Annex D – Irradiation for the different geographic locations

Table D 1 – Irradiation estimate values for the city of Porto

Porto		Irradiation data (kWh/m^2)											
		Months											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Years	2011	96.87	123.83	140.09	194.07	211.4	206.85	208.19	189.54	185.92	176.02	103.27	104.06
	2012	139.77	172.69	191.48	143.37	180.46	175.25	213.81	206.09	181.65	121.71	99.72	77.99
	2013	79.07	115.63	113.02	177.92	202.57	191.95	202.86	227.86	186.46	122.56	117.87	105.81
	2014	71.54	79.92	153.94	152.46	212.17	182.71	201.89	200.35	159.1	136.34	77.93	115.78
	2015	120.06	107.2	168.72	164.79	205.63	199.35	214.88	186.99	186.56	124.96	127.64	100.71
	2016	60.41	92.88	147.02	170.92	166.4	197.9	226.92	207.55	177.92	134.91	93.54	116.42
Average monthly irradiation		94.62	115.36	152.38	167.26	196.44	192.34	211.43	203.06	179.60	136.08	103.33	103.46
Average yearly irradiation		1855.35	kWh/m^2										

Table D 2 - Irradiation estimate values for the city of Coimbra

Coimbra		Irradiation data (kWh/m^2)											
		Months											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Years	2011	104.65	128.49	143.24	187.44	191.41	209.96	207.06	184.3	187.44	175.98	106.45	118,72
	2012	144.98	179.29	178.91	123.44	178.93	174.25	214.18	210.71	182.8	136.24	99.87	92,85
	2013	86.12	118.52	107.04	172.11	189.92	184.06	212.68	225.84	190.82	120.04	125.65	112,33
	2014	77.26	83.95	151.95	146.46	205.93	181.69	190.05	209.41	154.35	141.48	77.4	119,18
	2015	129.54	113.27	166.7	162.2	209.92	193.54	216.07	195.74	177.53	126.21	137.28	109,68
	2016	60.68	98.8	151.44	175.73	170.2	198.83	222.77	206.74	175.03	139.17	97.49	115
Average monthly irradiation		100,54	120.39	149.88	161.23	191.05	190.39	210.47	205.46	178.00	139.85	107.36	111.29
Average yearly irradiation		1865,90	kWh/m^2										

Table D 3 - Irradiation estimate values for the city of Lisboa

Lisboa		Irradiation data (kWh/m^2)											
		Months											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Years	2011	96.26	130.75	164.02	190.78	201.59	212.9	225.16	204.88	202.91	183.68	106.57	121.33
	2012	147.78	181.76	179.45	138.13	194.55	203.82	234.41	229.6	195.77	141.57	96.29	94.78
	2013	91.48	128.65	123.91	194.19	204.98	200.07	209.48	236.8	192.81	137.18	128.32	112.74
	2014	78.89	95.3	155.19	164.02	215.16	205.34	223.16	227.51	169.99	144.48	82.94	119.23
	2015	125.68	119.39	187.78	171.76	227.07	212.46	227.64	218.06	197.82	120.58	134.38	87.44
	2016	79.8	110.67	164.95	178.67	172.39	196.67	204.5	201.81	179.51	144.56	101.09	126.1
Average monthly irradiation		94.62	103.32	127.75	162.55	172.93	202.62	205.21	220.73	219.78	189.80	145.34	108.27
Average yearly irradiation		1968.56	kWh/m^2										

Table D 4 - Irradiation estimate values for the city of Madrid

Madrid		Irradiation data (kWh/m^2)											
		Months											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Years	2011	119.31	152.91	143.07	194.4	203.15	214.81	237.24	225.17	212.45	194.08	99.73	141.32
	2012	158.89	175.09	203.93	158.1	207.26	213.52	243.33	232.2	192.43	156.66	97.93	107.25
	2013	117.74	124.27	132.72	175.82	195.5	205.23	228.53	233.67	201.45	161.97	130.28	137.12
	2014	93.39	107.31	178.72	198.84	215.49	217.1	227.53	236.9	187.79	169.15	107.93	141.6
	2015	150.12	132.25	171.39	188.02	223.32	215.63	232.7	226.25	202.26	145.02	142.45	131.8
	2016	77.3	111.63	148.77	166.95	180.28	210.9	229.38	232.57	198.52	160.53	113.81	114.51
Average monthly irradiation		119.46	133.91	163.10	180.36	204.17	212.87	233.12	231.13	199.15	164.57	115.36	128.93
Average yearly irradiation		2086.11	kWh/m^2										

Table D 5 - Irradiation estimate values for the city of Málaga

Málaga		Irradiation data (kWh/m^2)											
		Months											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Years	2011	127.04	167.46	159.15	171.09	187	199.56	223.16	218.6	206.51	183.62	137.16	158,92
	2012	165.76	183.83	198.11	182.87	213.47	213.77	227.01	216.98	181.11	154.31	105.36	138,12
	2013	153.08	154.25	133.09	184.34	192.88	209.12	224.85	227.11	191.22	182.19	157.06	146,21
	2014	138.07	129.92	195.26	199.09	218.68	204.37	228.05	229.49	179.65	184.74	125.85	140,85
	2015	163.44	147.93	180.84	174.8	213.13	207.64	224.85	206.71	193.85	146.69	167.64	135,39
	2016	124.81	126.43	186.56	172.38	191.81	220.1	221.89	230.59	212.95	176.65	128.86	144,83
Average monthly irradiation		145.37	151.64	175.50	180.76	202.83	209.09	224.97	221.58	194.22	171.37	136.99	144.05
Average yearly irradiation		2158.36	kWh/m^2										

Table D 6 - Irradiation estimate values for the city of Bilbao

Bilbao		Irradiation data (kWh/m^2)											
		Months											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Years	2011	71.32	98.88	122.95	160.2	160.81	146.14	153.1	155.94	153.91	140.63	92.67	67,78
	2012	74.17	79.78	165.81	89.37	171.27	141.69	168.25	168.24	137.07	114.81	81.87	72,08
	2013	72.49	64.03	112.85	128.57	105.5	127.98	182.48	153.45	127.51	98.85	39.67	96,14
	2014	58.23	82.1	128.89	140.73	152.11	166.56	153.33	151.52	155.11	141.31	71.27	59,68
	2015	80.01	52.54	101.32	150.16	133.58	155.91	153.76	170.14	133.54	113.36	94.66	106,07
	2016	57.27	75.93	122.82	159.97	192.31	172.95	180.3	191.24	146.65	131.98	74.79	82,68
Average monthly irradiation		68.92	75.54	125.77	138.17	152.60	151.87	165.20	165.09	142.30	123.49	75.82	80.74
Average yearly irradiation		1465.51	kWh/m^2										