Socioeconomic study of the use of solar photovoltaic technology to optimize the use of electricity in a company

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Thesis to obtain the Master of Science Degree in

Electrical and Computer Engineering

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December 2019
Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.
Declaração

Declaro que o presente documento é um trabalho original da minha autoria e que cumpre todos os requisitos do Código de Conduta e Boas Práticas da Universidade de Lisboa.
To my mum and dad, who have always been by my side to support me in every possible way. To my family and friends, who supported me through this journey and gave me several advices when needed.

And at last but not least to my supervisor, who gave me all the guidance for this dissertation.
Acknowledgments

I would like to thank Professor João Torres for his expert advice and encouragement throughout this project, as well as Professor Carlos Ferreira Fernandes.

I would like to thank Mr. Brito, responsible for the North Tower, for giving me the authorization to access some important data for this thesis.

Also I would like to thank my colleagues, friends and family for their wonderful collaboration. You supported me greatly and were always willing to help me.

And at last but not least, my special thanks go to Instituto Superior Técnico, this college that welcomed me during these arduous 5 years, where I learned so much and grew personally, intellectually and professionally.
Resumo

Nesta dissertação serão enumerados diversos aspectos sócio-económicos, tanto vantajosos como desvantajosos, da utilização de energias renováveis, mais concretamente da utilização da energia solar para produção de electricidade num edifício de grandes dimensões, como é o caso geral de uma empresa.

Posteriormente será dimensionado um sistema fotovoltaico autónomo, num empresa através da aplicação de painéis solares nas janelas do edifício, ou seja, através do uso do vidro das janelas como captor da energia solar para produzir electricidade.

Para além do dimensionamento do sistema solar fotovoltaico, será também considerada a instalação de turbinas eólicas no topo da torre, como alternativa ao uso de baterias para alimentar o edifício durante a noite.

Palavras-chave: sistema fotovoltaico, empresa, autónomo, energia solar
Abstract

In this dissertation is going to be listed many socioeconomic aspects, both advantageous and disadvantageous, of the renewable energy utilization, more specifically of the solar energy utilization for electricity production in a large building, such as a company.

Then, is going to be designed an autonomous photovoltaic system, in a building, through the application of solar panels in the windows of the building, that is, through the use of the windows as solar energy captors to produce electricity.

In addition to sizing the solar photovoltaic system, it will also be considered the installation of wind turbines on the top of the tower as an alternative to using batteries to power the building at night.

Keywords: photovoltaic system, company, autonomous, solar energy
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<th>Description</th>
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<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>APA</td>
<td>Agência Portuguesa do Ambiente</td>
</tr>
<tr>
<td>AVT</td>
<td>Average Visible Transmittance</td>
</tr>
<tr>
<td>BiPV</td>
<td>Building integrated Photovoltaics</td>
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<tr>
<td>BoS</td>
<td>Balance of System</td>
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<tr>
<td>CRM</td>
<td>Capacitive Renumeration Mechanisms</td>
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<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DSSC</td>
<td>Dye-Sensitized Solar Cell</td>
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<tr>
<td>EAF</td>
<td>Electric Air Furnace</td>
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<tr>
<td>ED</td>
<td>Energy Dependence</td>
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<tr>
<td>EPD</td>
<td>Electrophoretic Deposition</td>
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<td>EWEA</td>
<td>European Wind Energy Association</td>
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<td>EXP</td>
<td>Exports</td>
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<tr>
<td>FF</td>
<td>Fill Factor</td>
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<tr>
<td>FiP</td>
<td>Feed-in-Premium</td>
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<td>FiT</td>
<td>Feed-in-Tariff</td>
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<tr>
<td>GHG</td>
<td>Greenhouse Gases</td>
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<tr>
<td>GHI</td>
<td>Global Horizontal Irradiation</td>
</tr>
<tr>
<td>GIC</td>
<td>Gross Inland Energy Consumption</td>
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<tr>
<td>GWP</td>
<td>Global Warming Potential</td>
</tr>
<tr>
<td>HAWT</td>
<td>Horizontal Axis Wind Turbine</td>
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<tr>
<td>IEA</td>
<td>International Energy Agency</td>
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Chapter 1

Introduction

Energy is the foundation of modern economies and the central need for modern life. It is a prerequisite for economic growth, improving living conditions and alleviating poverty. Therefore, access to energy is considered an important development goal.

Obstacles such as high energy costs, inaccessible energy grid infrastructure and disperse population makes providing access to a majority of the world’s population in developing countries a daunting task.

According to a new report produced by the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), the United Nations Statistics Division (UNSD), the World Bank and the World Health Organization (WHO), 840 million people are without access to electricity globally, out of which majority of people live in remote and isolated rural areas. To make the scenario more difficult, people are sparsely populated in these places. Out of many other reasons for not being electrified are very low power demand and economic burden to the government to build infrastructure, etc. Thus, renewable energy technologies offer a unique opportunity to provide affordable and sustainable energy to millions of people.

Sustainable energy is defined as “energy produced and used in ways that simultaneously support human development over the long-term in all its social, economic, and environmental dimensions” (United Nations Development Programme (UNDP) 2000). Economic accessibility, sustainability, and adaptability are the main factors justifying the use of renewable energy technologies to produce electricity. This and the awareness of climate change explains why globally investment in renewable energy sources for energy supply has grown continuously during the past decades and it is expected that these will increase considerably in subsequent decades as global demand for energy increases.

In 2016, renewable energy sources supplied 17.5% of the world’s primary energy supply [1].
The fact that expanded provision and use of energy services strongly associated with economic
development reveals how important energy is an essential factor in socio-economic development. It is
believed therefore that modern standard of welfare, education and health cannot be maintained without
sufficient energy [2].

But the multiple benefits of renewable energy go beyond their contribution to climate change mitigat-
ion or favourable effects on health because of the improved air quality. Many local economies can be
strengthened through the potentials of new business fields, job creation and productivity gains, whereas
others might suffer economic slowdown due to declining demand for their industrial production.

Still, country-specific co-benefits assessments are often lacking. This is mainly because assessment
methodologies are not adapted to specific country conditions and corresponding resource and data
availabilities.

As the technologies mature and the markets expand, it is likely that initial costs will decrease through
achieving economies of scale. Through the initiative Sustainable Energy for All (SE4All), the United
Nations aims for universal access to modern energy services and a doubling of the renewable energy
share in the global energy mix by 2030. This multi-stakeholder partnership brings together public, pri-
vate and civil sectors to mobilize resources for renewable energy deployment and electricity access
programs (SE4All, 2016). However, the investment to reach the goals of the SE4All initiative are difficult
to achieve. Current annual investments in global energy access efforts are estimated at United States
Dollars (USD) 13.1 billion, while the required annual amount is estimated at (USD) 49 billion in order
to achieve universal energy access by 2030 and another major obstacle to extensive use of renewable
technologies is their inability to compete with the conventional fuels except in niche markets [3].

1.1 Motivation

Nowadays the use of fossil fuels for electricity production has very negative aspects, so it is tried to
replace this source by renewable sources, as is the case of solar energy.

Within the negative aspects of the use of fossil fuels stand out their regeneration and their contribution
to pollute the environment.

Global emissions are reaching record levels and show no sign of peaking. The last four years were
the four hottest on record, and winter temperatures in the Arctic have risen by 3°C since 1990. Sea
levels are rising, coral reefs are dying, and we are starting to see the life-threatening impact of climate
change on health, through air pollution, heatwaves and risks to food security. The impacts of climate
change are being felt everywhere and are having very real consequences on people’s lives. Climate
change is disrupting national economies, costing us dearly today and even more tomorrow.

The fossil name comes from the time it takes for its formation, several million years. The regeneration
of this fuels is a big problem, because once finished they will only exist again after a long time. The
global economy is dependent on these natural resources, hence the variance of the oil price, since it is
expected to end in a few decades, which greatly influences the financial crisis now experienced.

The use of these resources had naturally big impacts in the man evolution, in social level, techno-
logical, economic and a serious consequence for our environment. These fuels contaminate the air with their combustion, thus damaging public health and increasing global warming. This temperature increase will bring catastrophic consequences if nothing is done otherwise.

This is where the importance of renewable energies comes in and why they have to be further developed than it has already been. These sources are and will be the key to reduce these major problems.

1.2 Topic Overview

The International Energy Agency explains the following:

"Renewable energy is derived from natural processes that are replenished constantly. In its various forms, it derives directly from the sun, or from heat generated deep within the earth. Included in the definition is electricity and heat generated from solar, wind, ocean, hydropower, biomass, geothermal resources, and biofuels and hydrogen derived from renewable resources."

Today we primarily use fossil fuels to heat and power our homes and fuel our cars. It's convenient to use coal, oil, and natural gas for meeting our energy needs, but we have a limited supply of these fuels on the Earth. We're using them much more rapidly than they are being created. Eventually, they will run out [4]. Even if we had an unlimited supply of fossil fuels, using renewable energy is better for the environment. We often call renewable energy technologies "clean" or "green" because they produce few if any pollutants. Burning fossil fuels, however, sends greenhouse gases into the atmosphere, trapping the sun's heat and contributing to global warming. If this trend continues, sea levels will rise, and scientists predict that floods, heat waves, droughts, and other extreme weather conditions could occur more often. Air pollution contributes to many diseases in humans. Acid rain from sulfur dioxide and nitrogen oxides harms plants and fish. Nitrogen oxides also contribute to smog.

On the other hand, renewable energy will help us develop energy independence and security. Replacing some of our petroleum with fuels made from plant matter, for example, could save money, such as health costs and reduce premature mortalities due to pollution.

Renewable energy is plentiful, and the technologies are improving all the time.

1.3 Objectives

The main objectives of this thesis are the following:

- To make the building energetically autonomous, using for such an integrated system of solar photovoltaic technology;
- Check the system behavior;
- Size the system and select the most suitable equipment;
- Analyse the investment (Return?/ How many years?);
• Comment possible system impacts on the user’s lifestyle.

1.4 Thesis Outline

1. Introduction

• Gives the definition of energy and also presents the huge need for renewable energy use today given the various negative effects of fossil fuel use.

2. State-of-the-art

• It is presented a little of the history of photovoltaic panels;
• It is presented some negative and positive socio-impacts of the use of the solar energy;
• The huge need of the population to consume electricity is also discussed;
• The consequences of using fossil fuels as a primary source of energy are conferred;
• Some consequences of the use of photovoltaic panels are also mentioned, such as the emission of gases during their manufacturing;
• Due to these serious consequences, it is shown some of the development that is currently being done and it is intended to be made in the future of solar panels;
• It is granted the definition of BIPV;
• And finally it is given some information about the wind turbines as possible substitutes for solar panels on certain occasions.

3. Sizing of the project

• The irradiance, temperature and energy consumption data in the chosen building are observed, in order to correctly size the project;
• The constituent technologies of the system are chosen;
• Different solutions of solar panels to cover the facades and the top of the chosen building are sized;
• It is made an economic study of the presented solutions;
• And finally, the use of wind turbines to replace solar panels on the top of the building is also studied.

4. Conclusions

• In the end, it is summarized all that was studied in this thesis and how the results obtained influence socially and economically the use of electricity in the chosen company but also in our society today;
• In addition to this, the future work to be done is also shown.
Chapter 2

State-of-the-art

In this chapter and as its name implies, the various themes already developed and studied today will be addressed in order to introduce and better understand what will be scaled in the next chapter.

2.1 Presentation of Photovoltaics

The sun serves as a giant nuclear furnace in space, constantly bathing our planet with free energy supply. The average amount of solar energy arriving at the top of the atmosphere is 1330 watts per square meter. About half of this energy is absorbed by the atmosphere [5].

The design of a solar energy conversion system needs exact knowledge regarding the availability of global solar radiation. Sunshine hours are measured at many locations around the world, while global radiation is measured at selected locations only. Obviously to ensure that this energy is usable in the night time hours, an adequate storage system must exist which is capable of accumulating this energy efficiently.

Among various solar energy technologies of sustainable energy sources, photovoltaic (PV) appears quite attractive for electricity generation, because it is noiseless, no carbon dioxide emission during operation, scale flexibility and rather simple operation and maintenance [6].

The photovoltaic effect is not new to the scientific community. In fact, it was first observed by Edmond Becquerel in 1839. In 1877, the first photovoltaic device was put in place with 0,5% efficiency. Since then, many scientific developments have allowed PV to be economically and technically viable solution for many applications, from satellites to remote telecommunication systems and pocket calculators. These are called autonomous systems, since they produce electricity for one specific need, with no other input needed. Such systems are composed of photovoltaic cells wired in series or parallel to form modules [7]. The sun radiation absorbed by the cell is converted into electricity. This electricity is send to an inverter, where DC is turned into AC. Batteries are used to store some energy and thus ensure the availability of electricity when there is no sun. A charge controller is also required, because it ensures that batteries are not overloaded or totally unloaded.

A photovoltaic cell is a device that converts sunlight into electricity using semiconductor materials.
The photovoltaic cells offer an existing potential for capturing solar energy in a way that will provide clean, versatile and renewable energy. Solar energy is provided as free, needs no fuel and produces no waste or pollution. Also, it is abundant, achievable in many parts of the world and cheap while the others are limited.

PV technologies can be divided into three main groups:

- Crystalline silicon cells (1st generation): They appear for the first time in 1954; they dominate the market, with a 90% market share worldwide. Is used in all kinds of medium to big terrestrial applications;

- Thin film cells (2nd generation): They appear for the first time in 1972; responding to the need of reducing silicon consumption, thin film cells are also lighter, allowing new applications in facade buildings;

- New solar cells concepts based on some existing materials (3rd generation): they promise higher efficiencies and lower costs, but are still at an early development stage [7].

2.2 In the world

Nowadays, in our world, the supply, conversion, transport and the use of energy is dominated by the fossil fuels.

The electricity from photovoltaic cells can be used for a wide range of applications, from power supplies for small consumer products to large power stations feeding electricity into the grid.

The following figure shows the world PV market demand currently.

![Demand Outlook in Global PV Market](image)

Figure 2.1: PV market demand in Jan 2019
The International Energy Agency (IEA) envisaged solar power accounting for 11% of global electricity production by 2050 and solar electricity contributes about 20% of the world’s energy supply by 2050 and over 60% by 2100. It is clear that electrical generation with PV cells will play an important role in future of the energy. PV systems developments will increase and focusing more and more on the PV industry that is poised for exponentially decrease their cost. This development will make it major in few years.

2.2.1 Economics and Markets

Recent global investments in the clean energy sector have exceeded those in conventional or fossil fuel based power generation technologies. In the early days of photovoltaics, some 50 years ago, the energy required to produce a PV panel was more than the energy the panel could produce during its lifetime. During the last decade, however, due to improvements in the efficiency of the panels and manufacturing methods, the payback times were reduced to 3-5 years, depending on the sunshine available at the installation site. However, the goal is to lower the price of technology even more.

Cost reductions will be achieved through the following measures: 1) higher conversion efficiency; 2) less material consumption; 3) application of cheaper materials; 4) innovations in manufacture; 5) mass production and 6) optimised system technology. The world is currently working on these fronts:

- Due to a very strong increase in the demand for PV systems, industrial have reacted, and in the coming three to four years, new factories will bring more silicon to the market, produced by more cost-effective methods. Or, on the other hand, the amount of silicon needed for producing cells can decrease due to some technological improvements. These two factors will help bringing the prices down in the short term;

- Conversion efficiency has been increasing very consistently since the first cells were produced.

The rapid development of photovoltaic industry and the continuous reduction of photovoltaic cost gradually establish a sustainable development of energy system.

More recent studies show, relatively to global PV market, that:

- Germany was the first to reach 1 GW of cumulative PV installed capacity. But today China leads with 174 GW of solar capacity installed, followed by the USA with 63 GW, Japan with 60 GW and finally Germany in fourth place with 46 GW;

- Major solar installation has been in regions with relatively less solar resources (Europe and China) while potential in high resource regions (Africa and Middle East) remains untapped;

- Costs for solar power are falling rapidly – “grid parity” has been achieved in many countries, while new markets for the solar industry are opening in emerging and developing nations. Grid parity occurs when an alternative energy source can generate power at a levelized cost of electricity (LCOE) that is less than or equal to the price of power from the electricity grid. Policy and regulatory incentives, oversupply of installation components, and advancements in technology are driving down the reduction in cost;
• Government incentives for the solar energy sector are being gradually scaled back in mature solar markets. There is now a need for a new electricity market design and for novel methods of financing solar projects in the absence of government support;

• Technology is constantly improving, and new technologies such as Perovskite\(^1\) cells are approaching commercialisation. Advancements are also opening solar energy new applications;

• In order to prevent environmental damage from solar PV, there is a need for strict and consistent regulation on processes over the entire life-cycle of infrastructure. Disposal and recycling must be considered as more modules reach the end of their lifespan.

Relatively to efficiencies of the solar cells:

• The record lab cell efficiency is 26.7% for mono-crystalline and 22.3% for multi-crystalline silicon wafer-based technology. The highest lab efficiency in thin film technology is 22.9% for CGIS and 21% for CdTe solar cells;

• In the last 10 years, the efficiency of average commercial wafer-based silicon modules increased from about 12% to 17%. At the same time, CdTe module efficiency increased from 9% to 16%;

• In the laboratory, best performing modules are based on mono-crystalline silicon with 24.4% efficiency. Record efficiencies demonstrate the potential for further efficiency increases at the production level;

• In the lab, high concentration multi-junction solar cells achieve an efficiency of up to 46% today. With concentrator technology, module efficiencies of up to 38.9% have been reached \[8\].

Taking into account these previous points, it can be concluded that there is a need to expand international collaboration in PV research, development, capacity building and financing to accelerate learning and avoid duplicating efforts. Implement effective and cost efficient PV incentive schemes that are transitional and decrease over time so as to foster innovation and technological improvement.

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\(^1\) Perovskite cells include perovskite (crystal) structured compounds that are simple to manufacture and are expected to be relatively inexpensive to produce. They have experienced a step rate of efficiency improvement in laboratories over the past few years.
Cost of technology

The cost of different technologies depends on the material used in the production of the cells and also on the maximum power achieved by them. The capital cost of a PV system is composed of the PV module cost and the Balance of System (BoS) cost. The cost of the PV module – the interconnected array of PV cells – is primarily determined by raw material (polysilicon) costs; while the BoS cost includes items such as the cost of the structural system, the electrical system costs, and the soft costs of system development (e.g. customer acquisition, permitting, labour costs for installation). The cost of the battery or other storage system, if any, in the case of off-grid application also needs to be added [9].

<table>
<thead>
<tr>
<th>Component</th>
<th>Costs</th>
</tr>
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<tbody>
<tr>
<td>Semiconductor</td>
<td>Capital and equipment cost + raw materials (e.g. silicon, saw slurry, saw wire) + utilities + maintenance and labour + manufacturer margin</td>
</tr>
<tr>
<td>Cells</td>
<td>capital and equipment + raw materials (metallization, dopants) + utilities + maintenance and labour + manufacturer margin</td>
</tr>
<tr>
<td>Modules</td>
<td>capital and equipment + raw materials (glass, ethylene vinyl acetate (EVA), metal frame, junction box) + utilities + maintenance and labour + margin + shipping + retailer margin</td>
</tr>
<tr>
<td>Inverter</td>
<td>capital and equipment + raw materials (magnetic, board, enclosures) + power electronics + utilities + maintenance and labour + manufacturer margin</td>
</tr>
<tr>
<td>Balance of system/Installation</td>
<td>Mounting + hardware + wiring + design + installation</td>
</tr>
</tbody>
</table>

Table 2.1: Breakdown of solar PV cost components
Risks

Reduction in solar prices is good news from the beneficiary's point of view. However, substantial and swift reduction is a major risk for investors. This is because energy generation cost of a system implemented later than earlier ones will always be lower. If the time difference between implementation of new and earlier systems is very small, then the beneficiary may become inclined towards dismantling the earlier system and installation of a newer one. This will pose a huge risk for investors of projects implemented earlier.

Investment in solar energy is also at risk from swift changes from policy and regulation, particularly in light of steeply falling costs of implementation and rising deployment. As these trends were difficult to predict, policymakers have been forced to modify or prematurely phase out initiatives supporting solar in a bid to save costs.

Socio-economics

As described in the previous section, solar energy is becoming increasingly affordable, thanks to the dramatic fall in component prices and the cost of installation and operation, both at utility and distributed level. Nonetheless, with the relatively high upfront costs characteristic of solar and other renewable energies, there remains the need for governments to monitor and guide the uptake of solar energy applications in many parts of the world, by utilising a wide range of policy instruments currently available. Policy frameworks must be well designed to minimise capital costs of implementation for developers and regulatory risk for investors.

Countries are increasingly recognising the potential of solar energy to provide sustainable energy, and this is reflected in the growth in the number of targets and support policies enacted by governments. By 2015, 164 countries had renewable energy targets in place; around 45 of them had targets specific to solar energy – across power generation and heating and cooling. Developing and emerging economies have led the expansion in policy targets in recent years [9].

The world’s most established solar markets have all benefited or are currently benefiting from both supply-side and demand-side drivers. For utility-scale solar, subsidies such as feed-in-tariffs (FiTs) and feed-in-premiums (FiPs) have been particularly successful in Europe, Australia and the United States. In the USA, utilities sign long-term power purchase agreements (PPAs) with developers, securing income streams for the power plant. Some governments also provide investment or production tax credits to boost solar development. For distributed systems, FiTs and net metering have been successful measures.

FiT is a regulatory instrument that guarantees an investor buy back price at which the power purchaser (distribution utility in most cases) will buy power that is being fed to the grid directly. This tariff or buy back price is calculated considering the overall investments in the renewable/solar Project along with regulated return on the investment. FiT is always prescribed for a fixed tenor.

The growth in the solar market has also led to changes in policy and market design affecting other energy sources. For example, in some European markets (UK, Germany, France, Italy, Belgium) and
parts of the USA, the rapid growth of solar and wind-powered electricity on the grid and the inherent variability of their output, has contributed towards the establishment of, or desire to establish, variant Capacity Renumeration Mechanisms (CRMs) in these markets, where conventional generators are paid to ensure security of electricity supply and stability of the grid. The incentive for capacity payments is two-fold. Firstly, they are designed to ensure that sufficient capacity is available at all times. Also, the extra income would help alleviate the struggle of existing conventional plants to cover their operational costs; which has been experienced in Germany, where the penetration of renewables has significantly reduced the number of operating hours of conventional generators and driven down wholesale electricity prices. On the other hand, critics claim that CRMs will have negative effects on free competition and the potential integration of multiple energy markets.

There is a lack of knowledge about the social and political impacts of solar panels. Most of the research has been dealing with the technical and economic aspects of the evaluation. Hence research is based on limited assumptions which are made after comparing the solar with the impacts from electrical devices. Furthermore estimations are based on laboratories tests – they can differ from the consequences in the real world. Although the benefits are clear, the market – and not policies – mostly decides about adopting solar PV successfully. From an experience on subsidies in the EU rooftop market we can learn that this kind of market cannot sustain in the long term. Not only that solar has reached competitiveness with the coal, oil, gas and other carbon generating resources but also it needs no water for energy generation. Finally by implementing solar energy many international conflicts for oil and water can disappear and save the enormous military costs. Hence by redirecting in investments from military use to solar energy can also significantly mitigate climate change [10].
## Table 2.2: Social and economic impacts of solar PV

<table>
<thead>
<tr>
<th>Impacts</th>
<th>Positive</th>
<th>Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land use and landscape</td>
<td>Decreased land use compared to conventional energy resources; Reuse of degraded sites; Use of unused sites (such as in deserts); Multi-purpose and integrated use on existing developments or buildings (like rooftops, facades).</td>
<td>Unavailable land/high competition with other land uses (such as agriculture); Degradation of vegetation and soil erosion; Higher up-front costs; Visual/landscape experience; Microclimatic change; Glare risk by reflection.</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>Reduced transmission lines/grids; Energy supply for decentralized, low density off-grid areas, also in developing countries.</td>
<td>Requirement for energy storage for continuous supply.</td>
</tr>
<tr>
<td>Political</td>
<td>National energy independent from import; Lower military expenses (less conflicts in the oil rich countries).</td>
<td>Economically detrimental subsidies such as uncontrolled and miscalculated feed-in-tariff mechanisms.</td>
</tr>
<tr>
<td>Energy market</td>
<td>Diversification; Deregulation;</td>
<td>Intermittent supply issues.</td>
</tr>
<tr>
<td>Industry, Education</td>
<td>Jobs creation; Higher development and education level.</td>
<td>Health hazards and risks during manufacturing phase.</td>
</tr>
<tr>
<td>Public and marketing</td>
<td>Increased environmental consciousness; Improved image.</td>
<td>None</td>
</tr>
</tbody>
</table>

Then some of the topics in the table will be developed. Relatively to jobs creation, the solar industry has shown an expansion in employment. In 2014, nearly 3.3 million people worldwide were employed by the solar energy sector, with the solar PV sector accounting for 2.5 million jobs. But the vast majority of jobs are in Asia, especially as the manufacturing of solar equipment and the major demand centers for solar energy move eastwards. Job growth has been particularly strong in the operations and maintenance sector, needed to support the burgeoning secondary solar PV market [9].

Our world is facing the pressure of continuously increasing food demand (due to rise in population and increase in average income), supplemented by lower agriculture yield. Land requirement is increasingly a premium in many countries of the world. Solar PV technology, through rooftop PV segment, provides a very huge social benefit by not using land but spare rooftops. It is normally argued that most of the land used for solar plant installations are generally non-fertile; however, this argument ignores the possibility of innovations in agriculture technologies that could find out ways to use non-fertile land for production of some crops. A solar plant has a life of around 25 years which is too long a horizon for ignoring innovations in agriculture technologies.
2.3 In the Europe

Since 1990 and maybe even before, Europe has intended to quickly rise the proportion of native energy employing zero-carbon resources, establishing new industries, banking on clean technologies and confronting the energy framework with a more distributed energy model. Solar energy consumption is getting among the European countries but this increase is not sufficient to demand electricity. Road maps are an important tool for future planning for energy demand developments. To do so, expert meetings and workshops are organised to simulate communication and discussion within European PV community. The preparation of the road map is an interactive and ongoing process. It points out major research areas for the short and long term, including cross fertilisation with other R&D fields. It will cover marketing, product and standardisation aspects, environmental issues as well as the issue of human resources for PV.

2.3.1 In Portugal

Portugal is strongly dependent on foreign countries in what concerns to fossil fuels, but is also a country with plenty of natural resources, allowing the development and use of renewable energies. One of the most important resources in Portugal is its high solar radiation, especially when compared with the northern European countries, such as Germany. However, the development of solar energy in Germany is much more advanced than in Portugal, making it one of the leading nations in terms of implementation and production of solar energy systems [11].

Consumption in Portugal

Portugal was the fourth country of the European Union with a higher incorporation of renewable electricity in 2015 (44,6%) after Denmark (50,2%), Austria (62,6%), and Sweden (72,1%). The Portuguese renewable annual electricity production has increased almost fourfold since 2005 and reached 33,3 TWh in 2016, relying mostly on hydro (16,9 TWh) and wind (12,5 TWh) sources, together representing 88% of the total renewable power production [12].

To check the energy dependence of Portugal is used a parameter, Energy Dependence (ED), that characterizes the extent to which an economy relies upon imports to meet its energy needs. The indicator is calculated as net imports of primary energy (IMP) imports minus exports (EXP) divided by the sum of gross inland energy consumption (GIC) with international maritime bunker (IMB).

\[
ED(\%) = \frac{IMP - EXP}{GIC + IMB} \times 100
\] (2.1)

Portugal had the seventh highest energy dependence among EU-19 and EU-28 countries in 2015. None of the EU-19 countries had a negative energy dependence, all depending on primary energy imports to satisfy their energetic needs.
The national energy strategy settled strategic policies, approved in 2005 by the Portuguese Government, such as the energy market liberalization, the promotion of energy from renewable sources, and of technologies with better efficiencies. As a result, the use of oil declined (i.e. 14.6%) in the following decade, replaced by natural gas and energy from renewable sources, whose values increased by 4% and 9% respectively, while the use of coal practically remained constant in the same period. Still, fossil fuels represented 78% of the consumed primary energy in 2015, a value slightly above EU-19 (72%) and EU-28 (73%) group countries, whose patterns are nearly identical. The remaining 22% of primary energy was exclusively based on renewable sources, making Portugal the fifth country with the highest share of energy from renewables amongst the EU-28 countries.

Relatively to the non renewable sources, Portugal does not have indigenous oil reserves with economic viability, although regular onshore and offshore exploration activities have been carried out since 1940. Therefore, all oil consumed by the country is imported.

After national coal production ceased in 1994, Portugal dependence on imported coal to secure its energy needs increased. Portugal imported 4.5 million of tons of coal from Colombia (88,1%), the USA (6,6%), South Africa (3,5%) and Ukraine (1,8%) in 2014.

The natural gas resources in Portugal are non-existent. The supplies are received through a pipeline, while the remaining part, liquefied, is transported to Portugal in ships that unload at the Sines terminal. On the southern part of the country, only a negligible quantity is imported using tanker trucks exclusively from Spain. The most important supplier is Algeria, with a share ranging between 45-52%, while Qatar and Nigeria were the major suppliers of liquefied natural gas (LNG).

Not long ago in Portugal, more specifically in April 2019 during the Easter week, there was a strike by drivers of dangerous substances, such as fossil fuels. This strike made that thousands of petrol and diesel stations, around the country, stayed without sufficient fuel to supply all vehicles. Some of the stations even ran out of fuel. This has caused an enormous chaos, because the population, in general, depends on their vehicles to survive. Apart from the huge queues of cars every day on all the stations, many planes, buses and even trains have stopped making their usual routes and with this, for example, the regular food supply in supermarkets has ceased, etc. That is, if this strike continued for much longer, Portugal would stop. So, in this example, one sees the excessive and worrisome dependence that this
country still has on fossil fuels.

In Portugal, the renewable energies boosting took place mainly in the 21st century and, for the last 3 years, the country has experienced a period of strong development in solar energy. Behind this boosting and strong development are, for sure, the influence of European Union energy policies, the national plans for energy efficiency, specific legislation to encourage the renewable energies use and specific programs supporting solar energy exploration, among other important reasons.

More than half of the energy from renewable sources produced in Portugal comes from biomass. The amount of energy produced from biomass remained nearly constant along the 2005-2015 decade, while the production of electricity tripled, reaching a share of 38% of the total energy from renewable sources produced in 2015. The most established renewable energy sources (RES) for electricity production in Portugal are hydro and wind, both totaling over 90% of the installed capacity. Biomass is the third RES with a higher installed capacity, followed closely (in recent years) by photovoltaic, which remarkably increased from 3 MW to 451 MW in the 2005-2015 decade. During this period, the wind energy installed capacity increased almost 400% and was by far the type of RES with the highest absolute variation (i.e., 3971 MW).

**CO₂ sources and availability**

A significant percentage of global GreenHouse Gas (GHG) emissions are from fossil fuels used in the production of electricity. The latest official portuguese report on GHG emissions (APA, 2017) indicates that net emissions of GHG in Portugal in 2015 are 1.58% lower than 1990 levels. GHG emissions from energy and industrial processes have increased 18% and account for 80% of total emissions in Portugal [13].

The CO₂ emissions are essentially divided into two categories: the most relevant class is related to CO₂ generated from the combustion of fuels for energy production (ca. 90% of all CO₂ emitted in 2015) and the other to CO₂ produced in industrial processes. Given 2015 GHG sequestration levels, the total GHG emissions in Portugal will need to be reduced until 2050. To meet these goals, Portugal faces the challenge of reducing its GHG emissions by 87% in the next 35 years. The energy sector, and the power sector in particular, will play a major role in this path towards lower GHG emissions [13].

In the absence of additional measures to promote decarbonization in Portugal, an increase in the use of renewable energy of up to 34% of final energy consumption is cost-effective; together with the cost-effective adoption of electric-vehicles absent any policy intervention, the increased share for renewable energy and the adoption of electric vehicles contribute to a significant decarbonization of the energy system in 2050 (a 38% reduction in GHG emissions relative to 1990 levels).

**Possible Solution**

Portugal is one of the European countries with better solar conditions but is certainly not one of the countries that has been taking the best advantage of it. Portugal has the best yearly solar radiation in the whole Europe (Cyprus is the only exception, as said before), with values reaching 70% more than
those of Germany. That means a huge advantage for the country, as the electricity produced in Portugal can cost 40% less than in the European giant. Adding to this fact, many others make it important for Portugal to efficiently explore the opportunities that PV can offer.

The first and more obvious ones are environmental (as said many times above in this thesis): the use of an endogenous, universal and free resource to produce greenhouse gases free electricity can help the environment, but also improve the equilibrium of the national electric mix and its behavior during peak hours. The increase in grid liability, the decrease in the production variability and losses during transportation, and the reduction of use of the bigger power plants are also factors that can benefit the electricity production frame. As for architecture, the Building-integrated Photovoltaic (BiPV) solutions can replace other facade materials, help on the buildings thermal efficiency, reduce maintenance costs and even provide positive aesthetic effects (color variations, transparency effects, and no reflection surfaces). In a macro point of view, it is also relevant to state the advantage of diversifying the energy sources and decreasing the need for imports, and of the huge impact that this technology may have in the future for less developed countries. In short, PV can benefit the industry and the economy (with long term effects), the security of energy supply (medium term), and the environment (long term).

The country has a very high potential for solar power generation due to its geographical position, which influences the intensity and the rate of incoming sunlight, and to its climate conditions, which positively affect the amount of incoming solar radiation. Located in the subtropical zone of the northern hemisphere, between latitudes 37° and 42°, in the range of contact between the Atlantic ocean and the European continent, Portugal presents insulation values of 1800-3200 hours of sunshine and 1386 W/m² of solar radiation. Within RES PV emerges as the technology with the greatest potential for development and exploitation in Portugal. This potential is due to the high availability of resources (sunlight) and to the residual expression of this technology as part of RES and its contribution to the national production, approximately 1.6% in 2013 [14].

For today’s usage it is important to use more recent data when assessing radiation availability at a given site, provided long enough recent series are available. These data that is going to be talked about next have been recorded by IPMA - Portuguese Institute for Sea and Atmosphere (Instituto Português do Mar e da Atmosfera) - during the period 2001-2015.

In order to obtain reliable results it was necessary to perform quality data analysis and gap filling, after the pre-analysis, the annual values of GHI and its variability were determined. The applied criteria were:

- Years that lack more that 5% of the total records are not considered for analysis;
- For days that lack more than two records for more than two hours, between sunrise and sunset are rejected and daily GHI availability for those days is estimated through the mean daily value of the same period for the other years of the data series;
- For days that lack less than two hours, the corresponding gaps are interpolated from the values of the neighboring hours;

3Global Horizontal Irradiation - total amount of solar energy incident on a horizontal surface
• GHI average annual availability was determined by averaging the annual averages of GHI;

• GHI annual variability was determined through the standard deviation of the annual averages of GHI [15].

GHI availability is higher from North to South due to the latitude effect and the higher average cloudiness in the North region of Portugal. On the other hand, GHI availability also increases from West to East, especially in the North and Center regions most probably due to the frequent formation of fogs in seaside (because of earth-sea interactions).

The average annual values of GHI availability and its variability are important for the definition of sites for the implementation of solar plants, i.e. medium to large scale solar plants. Alentejo and Algarve, South of Portugal, are the most suitable areas for the implementation of solar energy projects, because these regions have high GHI annual availability and lower variability. Typically, in order for solar energy to work efficiently and supply energy to a building, a very large amount of space is required, in the form of rooftops or land, in order to install solar panels; these solar panel space requirements are a large impediment to practical usage. This drawback drove researchers to come up with transparent solar cells (TSCs), which solves the problem by turning any sheet of glass into a photovoltaic solar cell. These cells provide power by absorbing and utilizing unwanted light energy through windows in buildings and automobiles, which leads to an efficient use of architectural space.

2.3.2 Conventional PV manufacturing

Conventional PV (silicon based) manufacturing processes have roots in the electronics industry, many chemicals are found in solar PV, including lead, brominated flame retardants, cadmium and chromium. The manufacturing of solar cells involves several toxic, flammable and explosive chemicals. Many of those components suppose a health hazard to workers involved in manufacturing of solar cells. Solar panels are often in competition with agriculture and can cause soil erosion. The disposal of electronic products is becoming an escalating environmental and health problem in many countries. Recycling of PV panel is currently not economically viable because waste volumes generated are too small [10].

Most of the PV manufacturers do not produce all components by themselves: materials like glass, aluminium and copper are produced in conventional processes by traditional manufacturers. These processes are well developed – efficiency improvements in manufacturing are hard to achieve. By contrast, silicon production is a rather new branch. Hence prospects for reduction of energy need for manufacturing solar cells are clear. Metallurgical grade silicon (MGS) is produced in an electric air furnace (EAF). During this process silicon is reduced by carbon in a fused salt electrolysis. Thereby a purity of silicon of 98 to 99.5% can be achieved. As solar cells require a purity of at least 1 part per billion, further processing is necessary. In order to achieve the required purity the MGS must be converted to either electronic grade silicon (EGS) or upgraded metallurgical grade silicon (UMGS). UMGS is directly processed from MSG bypassing the process of silane production. As results process has lower efficiencies due to lower purity. In order to produce UMGS the liquid phase epitaxy, segregation or solving silicon in aluminium
is used. Due to the reason that high material losses arise from milling the wafers, other methods were developed. Some of them are pulling methods, tearing with a thin layer of silver and using laser.

As outlined in the above the main manufacturing processes are driven by electricity. That is why the environmental effects strongly depend on the energy mix the modules are produced in. Assuming that the energy used for manufacturing was 100% renewable, there would be no environmental impact apart from few hazardous materials which are used during the production. In order to rate the environmental effects it is important to consider the exhaustion of raw material, energy needed, global warming, acidification and waste.

Purification of silicon hazardous material such as silane might be required. Additionally, other toxic chemicals, e.g. diborane and phosphine, are necessary for doping the silicon. Only small quantities which are diluted in inert gas are used for this process. As these materials are commonly used in the microelectronic industry, a well-established control and monitoring exists. Nevertheless, silane and phosphine are inflammable gases, the latter is even highly toxic. During regular operation of the manufacturing processes these gases are not dangerous, but in case of any accident or leakage dangerous emissions of the aforementioned gases can happen. Using zinc should be avoided as this contributes to the exhaustion of raw materials as well as to the solid waste. Regular materials like aluminium and copper are associated with the standard industrial hazards. Although PV modules might be transported across long distances, only 0.1% to 1% of the emissions arise from transportation. To sum up, during production the following hazardous materials are emitted, silica dust, silanes, diborane, phosphine and solvents.

<table>
<thead>
<tr>
<th>Emissions (kg/kWp)</th>
<th>$SO_2$</th>
<th>$NO_X$</th>
<th>Particles</th>
<th>$CO_2$</th>
<th>$CH_4$</th>
<th>$N_2O$</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV module 1995/1998</td>
<td>5-5,5</td>
<td>4,5-5,3</td>
<td>No info</td>
<td>2,7-3,8</td>
<td>No info</td>
<td>No info</td>
<td>-</td>
</tr>
<tr>
<td>Entire PV system 1998</td>
<td>1,9</td>
<td>1,8</td>
<td>0,11</td>
<td>971000</td>
<td>1,6</td>
<td>0,0031</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2.3: Emissions from photovoltaic module and system

This table shows the emissions from PV module manufacturing and an entire PV system. The data is about 15 years old; therefore there must have been improvements in the manufacturing processes. The local electricity mix, i.e. the electricity sources used for manufacturing the modules, influence the primary energy needed as well as the $CO_2$ equivalent emitted per kWh produced. Differences occur especially in the production of silicon.

In this context, production of silicon significantly affects the carbon footprint.

**PV recycling**

Recycling of PV modules is a very complex process because the modules consist of many different materials. If the materials from PV modules are separated with certain purity, most of the materials get
recycled in standardized way. Examples are glass, copper, aluminium as well as other metals. In con-
trast, processes for reclaiming solar silicon and solar cells are mainly still in Research and Development
phase. First, all sorts of materials used in the PV module have to be detected; otherwise no efficient
recycling is possible. The recycling process depends on the type of PV module, i.e., not one process fits
to all, but different recycling processes for crystalline, thin film, amorphous and organic PV modules.

Environmental impacts of recycling and energy payback time

Following scenarios were analysed to compare the environmental impact of recycling of PV modules:

- High value recycling: recovery of silicon and all valuable substances;
- Simplified process: crushing, incineration of plastic materials in MWI, disposal of inorganic com-
  ponents;
- Incineration of modules without prior material separation.

The main variables affecting human health are:

- Toxicological properties of materials (toxic, carcinogenic or flammable);
- Degree of concentration;
- Frequency and length of exposures;
- Ability of receptor to absorb the compound;
- Individual sensibility of human bodies.

Primary health concern of Si-based panels might affect manufacturer and residents nearby via ac-
cidental use of toxic gases and solvents (such as arsine and phosphine) or simple inhalation of fumes
(from diverse acids such as HF and $HNO_3$, alkalis, dopant gases and vapors like $POCl_3$). The dispos-
able chemicals used during the manufacturing can have negative effects on public health. Yet they aim
to have lower affects by reducing disposal and replacing harmful chemicals with friendly alternatives.

2.4 The future of solar panels

"Imagine a world where we could generate electricity using the surface of our windows, smartphones,
our car’s sun roof or the glass roof of our office building. What sounds like a far-away dream, is on its
way to become reality thanks to transparent solar panels." [16]

Sun light is available for free everywhere, but the guarantee of using this light for solar power is
restricted to solar farms and rooftop panels. Recently, transparent solar cells caught the attention of
scientists due to their variety of possible applications in our daily lives. Transparent solar cells (TSC)
are already in use for these applications in some countries, while others are for the far future, once
their efficiency is improved. Transparent solar cells can transform crowded cities from exclusively power
consumers into power plants. BiPV is the nearest application for transparent solar cells. If all the buildings with 90% glass on their surface used transparent solar cells printed on the surface of the glass, the solar cells have the potential to power more than 40% of that building’s energy consumption.

Some companies have implemented transparent solar cells with reasonable efficiency but not enough to compete with silicon solar panels. However, this invention has a high potential of turning every glass surface in the advanced world into a solar panel. Researchers are now working to improve the efficiency of TSC without sacrificing transparency; this is expected to be achieved in the next 5 years [17].

To design a solar cell suitable for windows, we have to think outside the box. When we put a solar panel on a roof, we want it to absorb as much sunlight as possible, so that it can generate the maximum amount of power. For a window, there is inevitably a trade-off between absorbing light to turn into electricity and transmitting light so we can still see through the window. When thinking about a cell that could be fitted to a window, one of the key parameters is known as the average visible transmittance (AVT). The is the percentage of visible light (as opposed to other wavelengths, like infrared or ultraviolet (UV)) hitting the window that travels through it and emerges on the other side. Of course, we don’t want the solar window to absorb so much light that we can longer see out of it. Nor do we want it to let so much light through that it hardly generates any solar power. So scientists have been trying to find a happy medium between high electrical efficiency and a high AVT [18].

2.4.1 Defining BIPV

Our world is facing the pressure of continuously increasing food demand (due to rise in population and increase in average income), supplemented by lower agriculture yield. Land requirement is increasingly a premium in many countries of the world. Solar PV technology, through rooftop PV segment, provides a very huge social benefit by not using land but spare rooftops. It is normally argued that most of the land used for solar plant installations are generally non-fertile; however, this argument ignores the possibility of innovations in agriculture technologies that could find out ways to use non-fertile land for production of some crops. A solar plant has a life of around 25 years which is too long a horizon for ignoring innovations in agriculture technologies and it is here that enters the concept of Building-integrated photovoltaics (BIPV).

As briefly explained above, BIPV refers to the concept of integrating photovoltaic elements into the building envelope, establishing a symbiotic relationship between the architectural design, structure and multi functional properties of the building materials and the generation of renewable energy. The PV modules thus replace conventional construction materials, such as glass, taking over the function that these would otherwise perform whilst also including the additional function of energy production. Although this idea is not a new concept, it has until recently not been widely adopted due to the extensive planning and architectural challenges and an inertia in the building trade [19]. BIPV can be used in all parts of the building envelope, though roof surfaces are currently the preferred area for installing PV elements due to their advantageous irradiation values. However facades, windows and other structures often offer greater potential. The ratio of facade surface area to roof surface area increases with the
building height and also, the available roof area is often reduced due to the installation of facilities and superstructures, meaning BiPV facades are of particular value in high-density urban centres.

BiPV offers the potential to make micro renewable energy generation costs competitive with fossil fuels. By substituting conventional building envelope construction materials for solar PV modules, the additional installed cost of the PV energy generation element is marginal within the total build and in some cases cheaper on a square meter basis. Add on the multi functional benefits afforded by PV glass and the additional costs can become non-existent [19]. For these reasons, it is believed that the future for PV is BiPV.

2.4.2 Building Integrated Photovoltaics

With regards to the aesthetics of the building, a PV module should have a homogeneous appearance and either blend discretely into the overall design or dominantly shape it.

The appearance of the PV module is essentially determined by the type of technology used in the PV cell and by the design possibilities offered by the selection of materials used in the module [19].

The PV market, as an innovative and rapidly growing industry, offers a widening range of different technologies.

There are approximately nine technologies that apply to the fabrication of transparent solar cells, and they are a focal point of current research due to market demand and the potential applications of transparent solar cells (TSC).

The fully transparent solar panel may by definition not absorb visible sunlight. However, researchers at Michigan State University used organic salts that absorb specific invisible wavelengths of light, such as ultraviolet light. This light is then transformed, and the material of the panel moves it to its edges, where stripes of photovoltaic solar cells convert it into electricity. The efficiency of the fully transparent solar panels is currently about 1% with an estimated potential of 5%.

However, solar panel efficiency does not mean everything. In practice it only means that the less efficient panel needs to be larger than the more efficient one in order to produce the same amount of electricity. As transparent solar panels can be integrated into windows in buildings, it means that the lower efficiency is overcompensated by the potential areas of employment [16]. The best transparency achieved currently is less than 80%, the technologies that achieved more than 20% transmittance with at least 1% efficiency are elaborated in chronological order below.

Thin film photovoltaics (TPV’s)

TPV is basically a thin film that has a thickness ranging from a few nanometers to tens of micrometers of active material deposited on glass in different ways. Thin film technology reduces the cost of solar cells by conserving the materials used in fabricating the cell; it is easy to deposit thin films on many different substrates, from rigid to flexible and from insulators to metals, which allows for new applications. Thin film solar cell (TFSC) is fabricated by combining material layers that are usually used to make solar cells, but as thin films, which reduces the cost of the solar cell’s materials, by depositing the optimal amount...
of material that allows the solar cell to function properly. The properties of these materials are different from each other, and the overall performance of the cell is affected by each layer [17].

The resulting coating is then subdivided into individual thin linear cells; these cells are broken up by metallic or transparent lines. The size of the modules is predetermined by the size of the carrier plate and is therefore difficult to divide into smaller segments.

Semi-transparency can be achieved in some thin-film panels by selective removal of the PV module material layers using laser ablation. This creates a pattern in the panel and allows light to pass through the gaps. By nature of removing the active material, there is a proportional reduction in power. Various levels of clarity can be achieved with finer patterning and more ablation. The approach undertaken by some companies is to utilise a variety of thin-film materials to offer direct functionality. These include amorphous silicon (a-Si), micro-morph (a-Si/µc-Si) and Cadmium Telluride (CdTe).

- Amorphous silicon (a-Si) - this technology utilises the equivalent powdered silicon in very small quantities. This is vacuum deposited along with transparent, conductive oxides on both glass surfaces with the active PV material between as a semiconductor. The glass is then laminated together as a sandwich to create a uniquely translucent module.

- Micromorph (a-Si/µc-Si) - this technology consists of a multi junction structure of two layers of amorphous silicon and microcrystalline silicon. The a-Si absorbs in the blue light spectrum and the µc-Si absorbs in the red, with the result that the panel performance per square meter is improved significantly. The appearance of the opaque panels is black, while the transparent version appears colourless.

- Cadmium Telluride (CdTe) - This technology offers significant performance improvements over a-Si and even micromorph panels. Absorbing light across the spectrum, the colourless transparency is achieved through laser ablation to deliver a fine pixelated effect.

Near-Infrared transparent solar cell

Most research is directed towards making thin layers to achieve some amount of transparency and focus on absorbing the visible spectrum; this results in producing cells with an average transparency of less than 30% in order to maintain reasonable efficiency. In 2011, Richard Lupnt's research group took a different direction by changing the molecules of the dye in order to absorb ultraviolet and near-infrared (NIR) wavelengths (650-850 nm), instead on focusing on the active layer’s thickness to achieve a transparent solar cell. A hetero-junction organic PV (OPV) is transparent to visible light with a transmission of more than 65% and will absorb in the near-infrared spectrum with an efficiency of 1.3% [17].

Polymer solar cell (PSC)

To obtain an ideal TPV, the absorbing materials must harvest all the light in the UV and near infrared (NIR) regions and allow for visible light to pass through. There are some materials with these properties, such as carbon nanotubes and graphene, which are transparent conducting materials. It is inefficient to
only use these materials to build a TPV. Thus, it is suggested to combine a transparent polymer solar cell with a transparent conducting material, such as silver nanowires (AgNWs) combined with a transparent polymeric PV cell, which is non-transparent for UV and NIR light but transparent to visible light.

Visibly transparent polymer solar cells (PSCs) are another TPV technology that involves a polymer that can harvest near-infrared light and allow visible light to pass. The efficiency is 4%, and the transparency at 550 nm wavelength is 66% [17].

**Transparent luminescent solar concentrator (TLSC)**

TLSC is based on organic salts, and these take a totally different direction to realize a solar cell design with a different structure, which combines efficiency with transparency. NIR fluorescent transparent dyes are used in order to capture UV and NIR light, convert them into visible light, and then guide it to the edge of the glass where the solar cell is placed. The transparency exhibited by TLSC is 86%, and the efficiency is 0.4%.

**Perovskite solar cell**

Researchers focus on improving the semi-transparent nature of organic solar cells by utilizing an absorbing material that has a lower band gap than the photons, which means it will allow for visible light through and absorb near infrared light. By improving the transparency, efficiency is affected. This led to trying to find a transparent material that improves the efficiency of the cell, such as methyl ammonium lead halide perovskite. Perovskites are abundant organic materials that have good electric properties suitable for solar cells, such as a high absorption coefficient, high carrier mobility, direct band gap, and high stability. Most solar cells with perovskite crystal structure can achieve a power conversion efficiency of over 13%, which makes perovskite a good alternative to Dye-Sensitized Solar Cell (DSSC).

**Electrophoretic deposition (EPD)**

Electrophoretic deposition is another method for obtaining thin films. This method can be easily applied in two steps to deposit a thin film on glass. First, particles are deposited on glass by applying direct voltage across two electrodes, which creates an electric field. One of the electrodes acts as a cathode and the other as an anode, and they are immersed in a solvent that contains the particles. In the second step, the synthesized particles will gather and deposit on one of the electrodes, forming a thin layer of titanium dioxide.

**Comparison between different Transparent solar cell technologies**

As mentioned many times before in this thesis, the transparent solar cell is applicable in more than 5 applications used in our daily lives, such as buildings, car windows, trains, cells phones, laptops, etc. However, the process for realizing this technology is faced with a group of four obstacles and challenges, starting from synthesizing the transparent material to provide the required transparency of a normal window, while at the same time maintaining high efficiency.
The first and main obstacle is the selection of materials that allow the transmission of the visible wavelength of the absorbed light, while at the same time allowing for the absorption of photons that lie in the invisible section of the wavelength. It is difficult to find such materials because the main characteristic of solar cells is to absorb light and not let it through.

The second obstacle is the fabrication process used to prepare the materials needed to build the TSC, which must have high transmission with good efficiency.

The third obstacle is the architecture of the TSC and the substrate used to protect the cell.

The final challenge is the cost of the fabrication and materials, which must result in building a cheaper solar cell.

To overcome the challenges highlighted above, there has been ongoing research studies in more than ten directions; some are focused on finding alternative materials that can obtain an acceptable transparency for specific applications, while others are focused on UV absorption and NIR while transmitting visible light. Moreover, research was engaged in finding new structures that would be translucent yet supply a good amount of electricity. In general, 80% of the solutions are still under development or at the pre-commercializing stage.

<table>
<thead>
<tr>
<th>Name of solar cell</th>
<th>Year</th>
<th>T4(%)</th>
<th>( J_{sc} ) (mA.cm(^{-2} ))</th>
<th>( V_{OC} ) (V)</th>
<th>FF7</th>
<th>( \eta ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screen printing DSSC</td>
<td>2007</td>
<td>60</td>
<td>16,25</td>
<td>0,779</td>
<td>0,73</td>
<td>9,2</td>
</tr>
<tr>
<td>Near-infrared OPV</td>
<td>2011</td>
<td>55±3</td>
<td>4,7±0,3</td>
<td>0,62±0,02</td>
<td>0,55±0,03</td>
<td>1,7±0,1</td>
</tr>
<tr>
<td>Polymer solar cell</td>
<td>2012</td>
<td>66</td>
<td>9,3</td>
<td>0,77</td>
<td>56,2</td>
<td>4,02</td>
</tr>
<tr>
<td>Transparent luminescent solar concentrator (TLSC)</td>
<td>2014</td>
<td>86±1</td>
<td>1,2±0,1</td>
<td>0,5±0,01</td>
<td>0,66±0,02</td>
<td>0,4±0,03</td>
</tr>
<tr>
<td>Perovskite</td>
<td>2014</td>
<td>30</td>
<td>10,30</td>
<td>1,074</td>
<td>57,9</td>
<td>6,4</td>
</tr>
<tr>
<td>Tandem transparent Perovskite</td>
<td>2014</td>
<td>77 peak(^6)</td>
<td>17,5</td>
<td>1,025</td>
<td>0,71</td>
<td>12,7</td>
</tr>
<tr>
<td>Electrophoretic Technique</td>
<td>2015</td>
<td>55</td>
<td>14,83</td>
<td>0,68</td>
<td>0,71</td>
<td>7,1</td>
</tr>
<tr>
<td>Dip-coater</td>
<td>2015</td>
<td>~70</td>
<td>16,17</td>
<td>0,738</td>
<td>0,688</td>
<td>8,22</td>
</tr>
<tr>
<td>Quantum Dot Solar cell</td>
<td>2016</td>
<td>22,74</td>
<td>12,83</td>
<td>0,58</td>
<td>0,52</td>
<td>3,88</td>
</tr>
</tbody>
</table>

Table 2.4: Comparisons between different TSC based on process

\(^4\) Transmission rate percentage of the light through the solar cell
\(^5\) Current short circuit in one \( cm^2 \) active area of the solar cell
\(^6\) Voltage open circuit in one \( cm^2 \) active area of the solar cell
\(^7\) Fill factor which equal to the maximum power divided by the theoretical power (These power values are present in the data sheet of the corresponding solar cells)
\(^8\) The efficiency percentage of the solar cell
\(^9\) The peak of the transmission at 800 nm wavelength
<table>
<thead>
<tr>
<th>Name of solar cell</th>
<th>Advantages</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screen printing DSSC</td>
<td>Law complexity in terms of manufacturing process and final design. Can be produced at industrial scale; Materials used to build the solar cell are organics like titanium and abundant; Cost of manufacturing is almost half price of silicon based solar cell; Efficient usage of architectural space; Manufacturing process is environmentally friendly; Have a homogeneous appearance; Shading and high temperatures do not have any major effect on performance.</td>
<td>Low reliability, live time quality, and power output dropping rate need to be tested and improved; Not practical for large-scale deployments where higher-cost and higher-efficiencies cells are essential; Liquid electrolyte is not stable at variable temperatures.</td>
</tr>
<tr>
<td>Near-infrared NPV</td>
<td>Organic semiconductor, environmentally friendly; High transmission more than 55%.</td>
<td>The architecture of the device is more complex compared with DSSC; Low efficiency not more than 1.7%; Low supporting resources; Not ready for industrial.</td>
</tr>
<tr>
<td>Polymer solar cell</td>
<td>Flexibility; Low material cost compared with silicon; Environmentally friendly; Flexible and lightweight; Low band gap; Easy manufacturing for industrial request using Roll-to-Roll technique.</td>
<td>Low efficiency; Low stability; Short operational lifespan.</td>
</tr>
<tr>
<td>Transparent luminescent solar concentrator (TLSC)</td>
<td>Improve energy harvesting efficiency; Increase electronic device autonomy; Reduce the traditional PV module cost.</td>
<td>In case in complexity and manufacturing stamps; Low efficiency less than 1%.</td>
</tr>
<tr>
<td>Perovskite</td>
<td>Close to the market; Environmentally friendly; Can be made flexible in shape; Doesn’t require high temperature processes; Uniform perovskite layers; High efficiency.</td>
<td>Low transmission; Most material used are scarce elements like tellurium (as rare as gold), indium and gallium; Liquid electrolyte has the temperature stability problems; Expensive compounds; Highly volatile; Low stability. Rapid degradation.</td>
</tr>
<tr>
<td>Electrophoretic technique</td>
<td>The transparency can be increased with the use of nanotubes without affecting the efficiency; Manufacturing cost reduce with the reduction in the waste of active material used.</td>
<td>Complicated process that includes chemicals and need to be standardized for transparent solar cell; The its difficult to control the homogeneity; It can be used for laboratory scale however mass-production is complicated; Reports supported this process are few compare to other process.</td>
</tr>
<tr>
<td>Quantum dot solar cell</td>
<td>Capable of absorbing photovoltaic waves from infrared region of the spectrum; Low complexity in manufacturing and installing; Better stability than DSSC.</td>
<td>Low transmission; Quantum dots are inorganic.</td>
</tr>
</tbody>
</table>

Table 2.5: Advantages and disadvantages of TSC technologies
In general, when comparing all these technologies in terms of maturity and closeness to market, 80% of these technologies are still under development and need more improvements in order to be compatible with market PVs. In addition, these studies are limited to transparent solar cells, not transparent solar panels. The only available technology that provides solar panels is the semi-transparent solar cell, which can provide 20-40% AVT, with an efficiency that is not more than 8%. However, some of these technologies are closer than other technologies to the market, such as polymer, perovskite and transparent luminescent solar concentrator (TLSC). These technologies can be found in developed countries around the world, such as Heliatek in Germany, one of the leading countries in the world in the manufacture of organic solar films. These developed countries and others such as China, Japan and Switzerland are leading to research on transparent solar cells, and great improvements are expected to happen in the coming 10 years that will help solve the problems facing the world with regards to transparent solar cells.

Efficiency and transparency are not the only parameters that decide which technology would be better to implement; cost is an important factor that markets care about. The cost of each technology is divided into 3 types. The first cost is that of the materials used to produce the solar cell. The second cost is that of the process of manufacturing the solar cell, and the third cost is that of system installation. For the third cost, the cost of system installation is difficult to estimate at this stage because this technology has not yet reached a level of maturity. However, this cost varies based on applications and the efficiency required for supplying these applications with energy; it can be expected that TSC would be economical in regard to installation and installation spaces via architectural layout design optimization. Some technologies such as TLSC reduce the installation cost by easily coating existing glass by depositing the active layer on the inner surfaces of double-paned windows, along with standard low-emitting or solar control coatings. Moreover, the cost of the material is economical compared with the cost of silicon. Most of the materials used to make the active layers in TSC are cheap and abundant, such as titanium and perovskite. For example, producing TSC using screen printing does not need highly complex machines that are normally used in the fabrication of conventional systems. Moreover, using existing glass and window frames reduces the manufacturing cost by almost 50% compared with a conventional PV system.

Current work in this technology is concerned with the scale of the solar cell; however, it is projected that in the coming 10 years, this technology would scale up to the transparent solar panel size. The idea is challenging, but the benefits are significant. Nevertheless, these Technologies still have challenges and disadvantages that researchers are trying to overcome. One of these challenges is stability. Most organic solar cells degrade when exposed to oxygen or water vapour. This is one of the reasons that organic solar cells in the market do not have a lifetime warranty such as silicon PVs. In addition, electrolytes are affected by temperature changes, as they may freeze at low temperatures, and the sealing of the panels becomes a difficult task when the liquid expands at higher temperatures. Another major challenge that most of these technologies are facing is the low efficiency. The idea of TSC is very unique; however, it is very challenging to combine high transparency with high efficiency, and most of these technologies have low efficiency. To apply TSC and produce it for the market, its efficiency must
be compatible with traditional solar cell efficiency. This implies that most of the technologies are not yet ready to be commercialized. Although most of the material used to build TSCs are abundant, this is not the case for perovskite solar cells, which use scarce elements such as tellurium (as rare as gold), indium and gallium for the active layers in TSC. Lastly, despite the complexity of manufacturing, the TSC is reduced in some solar cells such as DSSC; however, it has been increased in others, such as TLSC, which added more steps to the manufacturing process. All these technologies must be tested under different conditions, such as snow, dirt on the window and temperature changes. Further experimentation must be done in different weather conditions and environmental impacts to increase the possibility for TSC to be compatible with traditional PVs.

2.5 Wind turbines

A short introduction to wind turbines will be made as these devices will be considered as an alternative to installing solar panels on the rooftop. Building rooftops can be an excellent location for wind turbines, both because the electric power generation is close to the user and because they allow to take advantages of faster winds while reducing the cost of support towers. The identification of the turbines position must however be preceded by a thorough analysis of available winds, because turbulence or areas of calm, generated by surrounding buildings or different obstacles located on the roofs (air conditioning systems, antennas), could lead to an energy production significantly lower than expected [20].

Wind energy technologies can be classified into two categories:

- Macro wind turbines that are installed for large-scale energy generation such as wind farms and;
- Micro wind turbines used for local electricity production.

Micro wind turbines are suitable for application at the building scale and are called ‘building-integrated wind turbines’. The main components of a wind turbine include blades, rotor, gearbox and generator. Small wind turbines were originally designed with a horizontal axis, also known as HAWTs. To reduce the need for a high tower, and for aesthetic reasons, vertical axis wind turbines (VAWTs) become increasingly popular for integrated building applications. Furthermore, VAWTs are also quieter (resulting in less noise nuisance) than HAWTs during operation [21].

HAWT is the most commonly used design configuration in wind turbines with rotors similar to that of aircraft rotors. When the rotating axis of the blades is parallel to the wind stream, the turbine is called horizontal axis wind turbine (HAWT). HAWT captures kinetic wind energy with a propeller type rotor and their rotational axis is parallel to the direction of the wind. These types of wind turbines are typically used under streamline wind conditions where a constant stream and direction of wind is available in order to capture the maximum wind energy. HAWTs are not effective where the wind is turbulent, so they generally located in areas where there is a constant directional airflow.

VAWT is probably the oldest type of windmills in which the axis of the drive shaft is perpendicular to the ground. It is a type of windmill where the main rotor shaft runs vertically, as opposed to the horizontal axis wind turbine. The blades of the VAWTs rotate with respect to their vertical axes that are
perpendicular to the ground. VAWT designs are sometimes loosely categorized as lift or drag based designs. They can capture wind from any direction and their heavy machinery is at ground level. Since the machinery is set on the ground, it simplifies the wind tower design and construction and reduces the turbine cost consequently. Unlike HAWTs, VAWTs are typically used in areas with turbulent wind flow such as coastlines, rooftops, cityspaces, etc.

Wind turbines can be grid-connected or off-grid. Off-grid systems require battery storage to store surplus electricity, thereby providing a more stable electricity supply. Their application is most suitable for rural and remote areas, such as remote villages and small isolated islands, where grid power is not available. Conventionally, grid-connected systems require power converters to convert the generated DC electricity to AC electricity to be compatible with power grid and AC-electricity-based appliances. As technologies improve, modern wind turbines can also directly generate AC power [21].

Recent developments in building integrated wind turbine technologies involve improving reliability, improving efficiency at low wind speeds and lowering capital cost. Wind turbine blades are now designed with lightweight materials and aerodynamic principles, so that they are sensitive to small air movements. Furthermore, the use of permanent magnet generators, based on rare earth permanent magnets, results in lightweight and compact systems that allow low cut-in wind speeds. In this way, electricity can be generated with wind speeds as low as a few metres per second.

To be more attractive for integrating into buildings, micro wind turbines are also being designed to be more visually attractive, without compromising their performance. Another objective is to reduce or even eliminate noise associated with blade rotation and gearbox/generator noise. This can be achieved by using low-noise blade designs, vibration isolators to reduce sound and sound absorbing materials around the gearbox and generator. Lastly, simplifying wind turbine components also adds to the attractiveness of wind turbine application and reduces maintenance costs. To lower the product costs, advanced blade manufacturing methods, such as injection moulding, compression moulding and reaction injection moulding, are being applied to reduce labour and increase manufacturing quality [21].

In terms of applications, development of wind home systems (WHSs), based on the idea of solar home systems is a growing trend. A typical wind home system comprises a micro wind turbine, a battery, and various DC electrical appliances [21].

### 2.5.1 Feasibility of technology and operational necessities

Wind turbines are often installed at locations with frequent windy conditions. Prior to installation of a wind turbine, it is important to collect wind data in the immediate vicinity of a building or installation site. Based on the wind data, a suitable type of wind turbine and suitable location can be determined to maximise the electricity generation. One important criterion is to match ambient wind conditions with a wind turbine’s cut-in wind speed, rated wind speed and cut-out wind speed [21].

Prior to installation of wind turbines, especially in a large number, on an existing building rooftop, it is important to ensure the roof structure is strong enough to hold the additional loads. These include the weight of wind turbines and vibration from wind turbine operation. Vibration absorbent technology
should be applied in order to prevent damage to building structure and to reduce interior noise in the building. As wind turbines are usually installed on the high point of the building, prevention measure from lighting damage should be in place. Accessibility for maintenance should also be planned for [21].

Research and development is the initial step for large-scale implementation of building integrated wind turbines in a region that has no precedent for wind turbine application. In particular, what is required is local wind mapping to understand wind speed, frequency, and wind directions at various heights and various settings. This data is crucial to determine the feasibility and the suitable types of wind turbines to be implemented in a particular area. If the feasibility study shows positive results, with a feasible return on investment, supporting policies and financial mechanisms should be in place to make building integrated wind turbines commercially viable for large-scale adoption by building owners, developers and related professionals and trades. Supporting policies should include but are not limited to the following:

- Reducing or removing subsidies for fossil-fuel-based electricity supply;
- Reducing or removing import tariffs on wind turbine components;
- Clearly identifying power grid expansion plans (for rural and remote areas) and communicating these plans clearly to the public. This is necessary for building developers to calculate payback period in the decision making process to invest and implement wind turbine off-grid systems including wind home systems;
- Setting up smart grid and incentivising feed-in tariff (in urbanised areas) as a platform to promote wind turbines for on-grid use.

In addition to the above incentivising policies, local building and construction authorities should regulate the installation of building integrated wind turbines in the following aspects:

- Structure safety;
- Noise pollution control;
- Grid connection;
- Urban-scape design guidelines.

Another important factor for large-scale implementation of building integrated wind turbines is capacity building, especially in the following areas:

- Technical knowledge to compute, simulate and deploy appropriate types of wind turbines at appropriate locations to maximise their performance and aesthetic integration with buildings and urban-scape;
- Installation skills and techniques for local workforce;
- Maintenance procedures for building owners and facility management personnel;
- Manufacture of micro wind turbines and related components. In this way, the products are locally available with low embodied carbon, and at the same time the local green economy is supported with new jobs creation and income sources.
2.5.2 Status of the technology and its future market potential

As a general observation, the market penetration for wind turbines in the regions near the equator is low, due to the small range of temperature change year round – a natural phenomenon that results in lower wind speed in comparison to regions further away from the equator [21].

For micro wind turbines, the initial markets were villages and developments on off-shore islands and remote rural areas. In these areas, the cost of installing micro wind turbines can usually be justified when compared to the high infrastructure cost to extend the power grid or building a power plant. Micro wind turbine grid-connected systems have also found a foothold in residential and commercial buildings in urbanised areas. The European Wind Energy Association anticipated this market sector to expand rapidly, thanks to the trend of higher energy prices and increasing demand for on-site power generation [21].

2.5.3 Financial requirements and costs

Financial requirements for the implementation of building integrated wind turbines include investment and maintenance costs. Investment cost covers not only the products and their installation, but also feasibility studies and system design related activities. One of the most critical activities is to analyse (for existing buildings) and predict (for new buildings during design stage) the wind conditions on and around the building to determine the feasibility and location for installation [21].

The cost components of wind turbines vary in a wide range, depending on the type, capacity rating, and local availability. Return on investment depends greatly on the actual wind conditions and performance onsite, and partially on the incentive level of feed-in tariff and local electricity pricing [21].

2.5.4 How the technology could contribute to socio-economic development and environmental protection

Wind power is a key component of renewable energy utilisation. Implementation of building integrated wind turbines contributes positively to the environment as a climate change mitigation option. Wind turbine technologies, used in wind home systems in particular, contribute to social development by improving the quality of life to villagers in remote islands and rural areas, similar to that of solar home systems. These benefits include:

- Better environmental health and reducing fire hazards by avoiding use of kerosene for lighting;
- Making information and entertainment accessible through the use of radio and television.

Building integrated wind turbines offer opportunities for local economic development, including:

- Less financial burden to households due to lower electrical costs;
- Opportunities for households/building owners to sell surplus electricity back to the grid;
- New skills and job opportunities for the local workforce;
• Mechanism to grow the local green economy.
Chapter 3

Sizing of the project

In this section is going to be designed an autonomous photovoltaic system, in a building, through the application of solar panels in the windows of the building, that is, through the use of the windows as producers of electricity through solar energy. As seen before, using the windows as solar panels has the big advantage that is using as much space as possible to produce more electricity. In this case, the building chosen is the North Tower of Instituto Superior Técnico, in Lisbon, Portugal.

For a better understanding of the structure of this chapter a flowchart will be presented.
Figure 3.1: Flowchart of the structure of the chapter of Sizing of the project
3.1 The building in study - North Tower

The work was completed in 1995 and is marked by a volume on a building that works as a base, and is thus high, presenting the facade on a curtain facade system, adopting the Exterior Glass Casting (EGC) solution type. This block, part of the campus Alameda, has approximately a superficial area of $7036 \text{ m}^2$.

The Tower has 19 windows along its width and 17 windows along its height. Each window has approximately 164 cm of width and 215 cm of height. With this, the top of the tower has an approximate area of $971 \text{ m}^2$ and each facade has an approximate area of $1139 \text{ m}^2$, which makes an approximate lateral surface area of $4556 \text{ m}^2$. In these facilities students have amphitheaters equipped with audio-visual aids, classrooms and laboratories, as well as a set of additional infrastructures including computer rooms, study rooms, library, and a prototyping and calibration unit, in a total of 303 spaces. In terms of the orientation of its facades, as shown in 3.3, four facades can be found in the same building: the north (facade 1), the south (facade 3), the east facade (facade 2) and the west facade (facade 4) [22].

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Figure 3.2: North Tower, Instituto Superior Técnico [22]

Figure 3.3: North Tower top view, via Google maps [22]
The windows applied to the curtain facade system are double, the types applied in the facade area above the parapets and in the spaces between floors up to the height of the parapet are different. Thus, above the parapet the outer glass is tempered and the inside laminated and below the parapet both windows, of the double glazing, tempered.
3.1.1 Irradiance

Based on the equation of the sun’s position in the sky throughout the year, the maximum amount of solar insulation on a surface at a particular tilt angle can be calculated as a function of latitude, longitude and day of the year. The power incident on a PV module depends not only on the power contained in the sunlight, but also on the angle between the module and the sun. When the absorbing surface and the sunlight are perpendicular to each other, the power density on the surface is equal to that of the sunlight (in other words, the power density will always be at its maximum when the PV module is perpendicular to the sun). However, as the angle between the sun and a fixed surface is continually changing, the power density on a fixed PV module is less than that of the incident sunlight. The amount of solar radiation incident on a titled module surface is the component of the incident solar radiation which is perpendicular to the module surface. The following figure shows how to calculate the radiation incident on a titled surface ($S_{\text{module}}$) given either the solar radiation measured on horizontal surface ($S_{\text{horiz}}$) or the solar radiation measured perpendicular to the sun ($S_{\text{incident}}$).

![Figure 3.4: Position of the panel relatively to the horizontal plane](image)

The equations relating $S_{\text{module}}$, $S_{\text{horiz}}$ and $S_{\text{incident}}$ are:

$$S_{\text{horizontal}} = S_{\text{incident}} \sin(\alpha)$$  \hspace{1cm} (3.1)

$$S_{\text{module}} = S_{\text{incident}} \sin(\alpha + \beta)$$  \hspace{1cm} (3.2)

where $\alpha$ is the elevation angle; and $\beta$ is the tilt angle of the module measured from the horizontal. The elevation angle has been previously given as:

$$\alpha = 90 - \phi + \delta$$  \hspace{1cm} (3.3)

where $\phi$ is the latitude; and $\delta$ is the declination angle previously given as:

$$\delta = 23, 45'' \sin \left( \frac{360}{365} (284 + d) \right)$$  \hspace{1cm} (3.4)

where $d$ is the day of the year. From these equations a relationship between $S_{\text{module}}$ and $S_{\text{horiz}}$ can
be determined as:

\[ S_{\text{module}} = \frac{S_{\text{horizontal}} \sin(\alpha + \beta)}{\sin(\alpha)} \tag{3.5} \]

The tilt angle has a major impact on the solar radiation incident on a surface. For a fixed tilt angle, the maximum power over the course of a year is obtained when the tilt angle is equal to the latitude of the location. However, steeper tilt angles are optimized for large winter loads, while lower tilt angles use a greater fraction of light in the summer. The incident power is the solar radiation perpendicular to the sun’s rays and is what would be received by a module that perfectly tracks the sun. Power on Horizontal is the solar radiation striking the ground and is what would be received for a module lying flat on the ground. These values should be regarded as maximum possible values at the particular location as they do not include the effects of cloud cover. The module is assumed to be facing south in the northern hemisphere and north in the south hemisphere. For some angles, the light is incident from the near of the module and in these cases the module power drops to 0. The number of hours the sun is shining each day, that is the number of hours between sunrise and sunset each day. In latitudes above 67° the sun shines for 24 hours during part of the year. Surprisingly, when averaged over the year, the sun shines an average of 12 hours per day everywhere in the world. In the northern latitudes the average intensity is lower than at the Southern latitudes.

The equations to generate the plots of irradiance are given below. These equations are calculated in solar time, and not in local time. The number of sun hours is simply the time between sunrise:

\[ \text{sunrise} = 12 - \frac{1}{15^\circ} \cos^{-1} \left( \frac{-\sin(\varphi)\sin(\delta)}{\cos(\varphi)\cos(\delta)} \right) \tag{3.6} \]

And sunset:

\[ \text{sunset} = 12 + \frac{1}{15^\circ} \cos^{-1} \left( \frac{-\sin(\varphi)\sin(\delta)}{\cos(\varphi)\cos(\delta)} \right) \tag{3.7} \]

The direct component of the solar radiation is determined from the air mass:

\[ I_D = 1,353 \times 0,7^{AM0.678} \tag{3.8} \]

The airmass can be determined from the Air Mass formula:

\[ AM = \frac{1}{\cos(\theta)} \tag{3.9} \]

The azimuth angle and the elevation angle at solar noon are the two key angles which are used to orient photovoltaic modules. However, to calculate the sun’s position throughout the day, both the elevation angle and the azimuth angle must be calculated throughout the day. These angles are calculated using “solar time”. In conventional time keeping, regions of the Earth are divided into certain time zones. However, in these time zones, noon does not necessarily correspond to the time when the sun is highest in the sky. Similarly, sunrise is defined as the stage when the sun rises in one part of the time zone.
However, due to the distance covered in a single time zone, the time at which the sun actually clears the horizon in one part of the time zone may be quite different to the “defined” sunrise (or what is officially recognized as the time of sunrise). Such conventions are necessary otherwise a house one block away from another would actually be different in time by several seconds. Solar time, on the other hand is unique to each particular longitude. Consequently, to calculate the sun’s position, first the local solar time is found and then the elevation and azimuth angles are calculated.

Irradiance and Temperature data in the Tower

So, taking into account the previous explanation of irradiance and the North Tower coordinates, that are:

- Latitude = 38.73758208°;
- Longitude = -9.13859305°.

It was possible to study the irradiance and the temperature throughout the year in the considered coordinates, using the following website: re.jrc.ac.europa.eu. Here it was checked that August was the month with higher values of average temperature and irradiance, and that January was the month with lower values. Thus, it was considered that August would be a good sample to represent the summer and January would be a good sample to represent the winter. Also, it was taken into account the fact that the facades have non-uniform illumination throughout the day due to their different slope orientation (orientation of the surface, if looking north it will be 0°, if looking south it will be 180° and it varies between 0 and 360 degrees) and the slope tilt (inclination of the surface with respect to the horizontal, 0° is flat, 90° is completely vertical and it varies between 0 and 90 degrees). With this, each facade has a slope tilt of 90°, but as it was seen previously the slope orientation is different. Facade 1 has a slope orientation of 0°, facade 2 has a slope orientation of 90°, facade 3 has a slope orientation of 180° and facade 4 has a slope orientation of 270°. Relatively to the top of the Tower, this one has a slope tilt of 0°. Thus, the solar radiation values in each facade and in the top of the tower are different.

Although it was verified on the previous website that August and January are the months with the highest values of irradiance in general, it was not possible to withdraw the irradiance values from each facade since there is no specific section on this website to insert the slope orientation. With this, the website mentioned above was only used to observe the months with the highest and lowest values. Thus, it was resorted to another source to withdraw the data, where it was possible to place all the needed specifications. However it was only possible to withdraw the data by day and not by month, so the data presented below are daily data of each month considered. In addition, it was taken into account the fact that despite August is the month of summer with higher values of temperature and irradiance, in this month Instituto Superior Técnico closes, so the north tower also does not work. Thus, for the summer month was considered June, in which the values of temperature and irradiance are already high and also it is in this month that the tower presents the greatest energy consumptions.

For the samples, it was considered the days of greater consumption of the Tower because it is in these days that the solar panels will need to produce more energy.
It should be mentioned that the daily values of irradiance, in every considered month, are always around the same. So these daily data will be considered as the average of the whole month.

Figure 3.5: Average daily irradiance in January in each facade and in the top of the tower.

Figure 3.6: Average daily temperature in January
3.1.2 Energy consumption

It is also necessary to study the energy consumption of the tower during the summer and during the winter, in order to calculate the correct number of technologies to make the tower completely autonomous energetically. The following data was acquired from the website: https://energist.tecnico.ulisboa.pt/. Because it was difficult to withdraw the data during a month, it was considered as samples for the winter, the day with greater consumption in January.

Regarding the data during the summer, although August is the month with the highest values of irradiance and temperature, it was verified that the days of greatest consumption were in June, as mentioned before. So, the following day will be considered as sample: June 19th, the summer day with the highest consumption.
It should be noted that the data from these days are considered as mean values of the energy consumption over the years in the North Tower.

3.2 Basic Structure of an autonomous solar energy system

An autonomous solar system is a photovoltaic solar power plant which is not connected to the grid. The extraction of the maximum power from solar panels called MPPT technique (Maximum Power Point Tracking) provides an effective method to solve the optimization problem. PV arrays represent the essential power conversion unit of a photovoltaic system. The output characteristics of PV array depend on the irradiation, the temperature and output voltage of PV array.
Photovoltaic generator

The principle operation of a photovoltaic generator is based on the photovoltaic effect of semiconductor PN junction. When exposed to sunshine, a DC current is generated; this current varies linearly with the solar radiation. The current-voltage characteristic depends on the irradiation and temperature conditions on the surface of the photovoltaic cell. The maximum operating point must always be followed to ensure that the PV generator has reached its maximum power output in real-time to maximize permanently the transferred energy.

DC/DC Converters

A photovoltaic generator (PV) Works in optimum conditions; it must have an adaptable converter. This adaptation is achieved by searching automatically the maximum power point (MPP) of the PV generator. The converter may be a DC/DC “Boost” or “Buck” according to applications.

MPPT Controller

One of the most commonly used MPPT strategies is the perturb and observation method, the working principle is simple, we disturb the system power by acting on the control signal “PWM”, and observe the direction of the output power variation. Indeed, the MPPT controller adjusts the voltage across the photovoltaic source by using a DC-DC boost converter, and measures the output power. After that, it varies the voltage across the PV by changing the PWM duty cycle and takes a second power measurement. If the power increases, the maximum power is not yet reached so we must choose the new control signal by changing the PWM duty cycle in some direction. Therefore, we need to adjust the voltage in the positive direction until the power will not increase, that’s mean that the variation rate will be null.

Controlling the charge state

The state’s control technique battery ‘SOC’ is the most convenient and most commonly used. It consists of measuring and calculating the arriving and leaving quantities of electricity during charging and discharging in terms of ampere-hours. This technique is called the coulomb metric measurement. The
chosen model assumes that the battery charge status ‘SOC’ is the ratio of the amount of electricity received or returned by the battery and the capacity of the battery (Ah).

**Photovoltaic inverter**

The inverter consists of two H-bridge cells connected in series which are fed by independent voltage sources. The outputs of the H-bridge cells are connected in series such that the synthesized voltage output is the sum of all of the individual cell outputs. This inverter converts the DC voltage into AC voltage.

### 3.2.1 The chosen technologies

The first step is to choose the most suitable panels to implement in the tower, depending on what has been studied so far. The ideal would be to implement panels with solar cells that had the following characteristics:

- Manufacturing price low;
- Abundant cell constituent materials in order to be produced at industrial scale;
- Low complexity in terms of manufacturing process and final design;
- The materials used to build the solar cell have to be organics;
- Manufacturing process has to be environmentally friendly;
- Shading and high temperatures should not have any major effect on performance;
- Durability;
- High efficiency with a good transparency;
- Cheap cell materials;

But since there is not yet a cell with all these characteristics, it will be chosen other existing options that present a large part of the points listed above. Thus, it will be considered three different solutions of amorphous silicon panels, one cheaper, one intermediate and one more expensive to coat the tower facades. Also, it will be considered a different solution of crystalline PV glass after the study with the amorphous silicon is performed. For the cheaper one of the solutions of amorphous silicon it was chosen the PS-C transparent panel from **Polysolar**, for the intermediate one it was chosen the PS-M-NX panel from **Polysolar** and for the more expensive one it was chosen the panel with the biggest dimensions from **Onyx**. For the solution of crystalline silicon, it was chosen the PS-PC-SE glass panel with different levels of transparency from **Polysolar**.

To coat the top of the tower, it will be considered the PS-MC-SE panels also from **Polysolar** and it will be considered a position for this panel, that is, with a slope tilt of 30° and a slope orientation of 180°, that is, the panel will be looking south. It will be sized this solution, because in theory, it is with this position...
that it is possible to capture more solar light and consequently produce more energy. The panels from each solution have the main following characteristics.

<table>
<thead>
<tr>
<th>Transparency</th>
<th>Dimensions</th>
<th>( P_{\text{mpp}} )</th>
<th>( V_{\text{mpp}} )</th>
<th>( I_{\text{mpp}} )</th>
<th>( V_{\text{oc}} )</th>
<th>( I_{\text{sc}} )</th>
<th>( \alpha_T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20% ± 3.5%</td>
<td>1100x1300x7mm</td>
<td>90W</td>
<td>103V</td>
<td>0.9A</td>
<td>137V</td>
<td>1.15A</td>
<td>-0.20%/K</td>
</tr>
</tbody>
</table>

Table 3.1: PS-C panel main specifications

<table>
<thead>
<tr>
<th>Transparency</th>
<th>Dimensions</th>
<th>( P_{\text{mpp}} )</th>
<th>( V_{\text{mpp}} )</th>
<th>( I_{\text{mpp}} )</th>
<th>( V_{\text{oc}} )</th>
<th>( I_{\text{sc}} )</th>
<th>( \alpha_T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opaque</td>
<td>1100x1400x8.9mm</td>
<td>160W</td>
<td>131V</td>
<td>1.22A</td>
<td>170V</td>
<td>1.33A</td>
<td>-0.21%/K</td>
</tr>
<tr>
<td>10%</td>
<td>&quot;</td>
<td>135W</td>
<td>125V</td>
<td>1.08A</td>
<td>167V</td>
<td>1.19A</td>
<td>&quot;</td>
</tr>
<tr>
<td>20%</td>
<td>&quot;</td>
<td>120W</td>
<td>125V</td>
<td>0.96A</td>
<td>167V</td>
<td>1.08A</td>
<td>&quot;</td>
</tr>
<tr>
<td>30%</td>
<td>&quot;</td>
<td>95W</td>
<td>120V</td>
<td>0.79A</td>
<td>166V</td>
<td>0.89A</td>
<td>&quot;</td>
</tr>
<tr>
<td>40%</td>
<td>&quot;</td>
<td>80W</td>
<td>120V</td>
<td>0.67A</td>
<td>165V</td>
<td>0.55A</td>
<td>&quot;</td>
</tr>
<tr>
<td>50%</td>
<td>&quot;</td>
<td>65W</td>
<td>118V</td>
<td>0.55A</td>
<td>164V</td>
<td>0.64A</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

Table 3.2: PS-M-NX main specifications

<table>
<thead>
<tr>
<th>Transparency</th>
<th>Dimensions</th>
<th>( P_{\text{mpp}} )</th>
<th>( V_{\text{mpp}} )</th>
<th>( I_{\text{mpp}} )</th>
<th>( V_{\text{oc}} )</th>
<th>( I_{\text{sc}} )</th>
<th>( \alpha_T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opaque</td>
<td>1245x2456mm</td>
<td>177W</td>
<td>132V</td>
<td>1.34A</td>
<td>191V</td>
<td>1.5A</td>
<td>-0.19%/°C</td>
</tr>
<tr>
<td>10%</td>
<td>&quot;</td>
<td>123W</td>
<td>132V</td>
<td>0.93A</td>
<td>191V</td>
<td>1.15A</td>
<td>&quot;</td>
</tr>
<tr>
<td>20%</td>
<td>&quot;</td>
<td>104W</td>
<td>132V</td>
<td>0.79A</td>
<td>191V</td>
<td>0.97A</td>
<td>&quot;</td>
</tr>
<tr>
<td>30%</td>
<td>&quot;</td>
<td>86W</td>
<td>132V</td>
<td>0.65A</td>
<td>191V</td>
<td>0.77A</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

Table 3.3: Main specifications of amorphous silicon PV glass from Onyx

<table>
<thead>
<tr>
<th>Transparency</th>
<th>Dimensions</th>
<th>( P_{\text{mpp}} )</th>
<th>( V_{\text{mpp}} )</th>
<th>( I_{\text{mpp}} )</th>
<th>( V_{\text{oc}} )</th>
<th>( I_{\text{sc}} )</th>
<th>( \alpha_T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>1988x992x7.1mm</td>
<td>320W</td>
<td>36,78V</td>
<td>8,7A</td>
<td>45,49V</td>
<td>9,26A</td>
<td>-0.46%/K</td>
</tr>
<tr>
<td>20%</td>
<td>&quot;</td>
<td>285W</td>
<td>36,52V</td>
<td>7,8A</td>
<td>45,27V</td>
<td>8,28A</td>
<td>&quot;</td>
</tr>
<tr>
<td>30%</td>
<td>&quot;</td>
<td>260W</td>
<td>36V</td>
<td>7,22A</td>
<td>44,65V</td>
<td>7,66A</td>
<td>&quot;</td>
</tr>
<tr>
<td>45%</td>
<td>&quot;</td>
<td>190W</td>
<td>35,93V</td>
<td>5,29A</td>
<td>44,58V</td>
<td>5,61A</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

Table 3.4: PS-PC-SE main specifications

\(^1\text{Temperature Coefficient of } P_{\text{mpp}}\)
Table 3.5: PS-MC-SE main specifications

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>$P_{\text{mpp}}$</th>
<th>$V_{\text{mpp}}$</th>
<th>$I_{\text{mpp}}$</th>
<th>$V_{\text{oc}}$</th>
<th>$I_{\text{sc}}$</th>
<th>$\alpha_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988x992x7,1mm</td>
<td>345W</td>
<td>37,62V</td>
<td>9,17A</td>
<td>47,18V</td>
<td>9,62A</td>
<td>-0,47%/K</td>
</tr>
<tr>
<td>&quot;</td>
<td>300W</td>
<td>38,45V</td>
<td>7,8A</td>
<td>46,26V</td>
<td>8,53A</td>
<td>&quot;</td>
</tr>
<tr>
<td>&quot;</td>
<td>270W</td>
<td>38,08V</td>
<td>7,22A</td>
<td>46,62V</td>
<td>7,76A</td>
<td>&quot;</td>
</tr>
<tr>
<td>&quot;</td>
<td>200W</td>
<td>37,82V</td>
<td>5,29A</td>
<td>46,35V</td>
<td>5,68A</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

The rest of the needed technologies to constitute the system are batteries, a charge controller and an inverter.

In the tower it is necessary to install 5 systems of these, one for each facade and one for the top, due to the characteristics of the chosen technologies. The chosen pack of batteries is from Crown and has the main following characteristics.

<table>
<thead>
<tr>
<th># of batteries</th>
<th>$V_{\text{dc}}$</th>
<th>Ampere hour (Ah)</th>
<th>Capacity</th>
<th>C-Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>48V</td>
<td>430Ah</td>
<td>20,64kWh</td>
<td>0,16</td>
</tr>
</tbody>
</table>

Table 3.6: Battery Bank main specifications

The chosen charge controller is named TriStar MPPT (Maximum Power Point Tracking) and is from MORNINGSTAR.

<table>
<thead>
<tr>
<th>Peak Efficiency</th>
<th>97,9%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Battery current</td>
<td>60A</td>
</tr>
<tr>
<td>Maximum Solar Open Circuit Voltage</td>
<td>600V</td>
</tr>
<tr>
<td>Battery Operating Voltage Range</td>
<td>16-72Vdc</td>
</tr>
<tr>
<td>PV Input Operating Voltage Range</td>
<td>525V</td>
</tr>
</tbody>
</table>

Table 3.7: Charge controller main specifications

The chosen inverter is a high input voltage industrial DC-AC sine wave inverter and is from AB-SOPULSE Electronics Ltd.

<table>
<thead>
<tr>
<th>Peak Efficiency</th>
<th>85% at full load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage$^2$</td>
<td>600Vdc (450V to 800Vdc range)</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>115Vac continuous at 60Hz/400Hz, or 230Vac continuous at 50Hz</td>
</tr>
</tbody>
</table>

Table 3.8: Inverter main specifications

$^2$Input voltages of up to 1200Vdc are possible
The cables used to make the connections between each equipment are from Amazon and cost 25,91 dollars per 30 feet, which is equivalent to 23.69 EUR per 9,144 m and thus 2.59EUR/m. These cables can support until 600 VDC. The number of PVs should be adequate to feed the load during the day and to charge the batteries. This number will be different for each solution.

3.3 Sizing of the solar electric system on the top of the Tower

As explained before, this solution consists in coat the top of the tower with PS-MC-SE panels with a slope tilt of 30° and a slope orientation of 180°. As expected, this position for the panels presents much higher irradiance values than if the panel had simply a slope tilt of 0°, that is, if the panel was completely horizontal and thus stand directly facing the sun, supposedly. And in addition, it is not possible to install panels with a slope tilt of 0°.

Considering the characteristics given in 3.5 and the following formulas.

$$T_{pv} = T_{amb} + \frac{G \times (T_{NOCT} - T_{ambNOCT})}{G_{NOCT}}$$

$$P_{max} = P_{maxpv} \times \frac{G}{G_{NOCT}} \times (1 - \alpha_T \times (T_{pv} - T_{NOCT}))$$

The power produced by one PS-MC-SE panel is obtained. To calculate the power it was also taken into account the irradiance and temperature only in January due to the fact that these values are much smaller in this month and thus it will be needed to install more panels in order to produce the same amount of energy. In the formulas, the considered values from NOCT conditions are: $T_{NOCT} = 50^\circ C$; $T_{ambNOCT} = 20^\circ C$; $G_{NOCT} = 800W/m^2$.

![Figure 3.12: Average daily power produced by one panel PS-MC-SE on the top of the tower](image)

Considering the maximum open circuit voltage of the PS-MC-SE panel, that is 47,18 V, the maximum open circuit voltage of the charge controller and the surface area of the top of the tower, it is possible to
determine the maximum number of panels in series and in parallel to install on the top. The number of panels in series is determined through the following.

\[ 47.18V \times n_{\text{series}} \leq 600V \Rightarrow n_{\text{series}} \leq 12 \text{ panels} \] (3.12)

To calculate the number of panels in parallel it is necessary to be more careful, because if you think about the problem, each panel will have a slope of 30°, so that the area occupied by the panels will be different. Here the following should be taken into account: the fact that each panel has a slope of 30° and that the panels cause the least possible shade to the panels immediately behind it is necessary to have a minimum distance between them. This distance, imagining the Pythagoras theorem, will correspond to the adjacent leg of the angle the panel makes to the horizontal.

![Figure 3.13: Sketch of the position of the panels at the top, seen in profile](image)

Thus this distance is given by,

\[ \cos(30°) = \frac{\text{adjacent leg}}{\text{hypotenuse}} \] (3.13)

\[ \text{adjacent leg} = 0.992 \times \cos(30°) \approx 0.859m \] (3.14)

And, finally, the number of rows in parallel is determined by taking into account the width of the tower and the "adjacent leg" previously determined.

\[ \frac{31,16}{0,859} \approx 36 \text{ rows} \] (3.15)

\[ 36 \times 12 = 432 \text{ panels in total and a total average energy produced of } 3599,84kWh \leq 15632,36kWh \] (this value corresponds to the sum of the energy consumption in each hour considered in a normal day in January) which is less than the average consumption of the tower. Here it is necessary to point out that this energy produced will not only be used to feed the tower but also to charge the batteries. So,
imagining that there were no batteries and not taking into account some shadow effect throughout the
day, only the panels installed on the top would feed around 23% of the building’s energy consumption.

Another important point to note is that the considered slope of the panel and the considered distance
between panels may not be the ideal to capture the maximum irradiance and thus producing a greater
amount of energy. In order to study the optimal slope and the optimal distance, the NSGA-II algorithm
will be a good tool.

3.4 Sizing of the solar electric systems with panels made of amorphous silicon in the facades

3.4.1 Sizing of the first solution

This solution is the cheapest one, where the panel chosen, as seen above, is the PS-C transparent
panel from Polysolar. Considering the characteristics given in 3.1, the power produced by one PS-C
panel, depending on the different orientations of the tower surface, is obtained.

![Figure 3.14: Average daily power produced by one panel PS-C in each facade](image)

Considering the maximum open circuit voltage of the PS-C panel, that is 137V and the surface area
of each façade, it is possible to determine the number of panels in series and in parallel. The number of
panels in series is determined through the following.

\[
137V \times n_{\text{ps,series}} \leq 600V \implies n_{\text{ps,series}} \leq 4 \text{ panels} \quad (3.16)
\]

And the number of rows of panels in parallel is determined by taking into account the height of the
tower and the height of each panel.

\[
\frac{36,58}{1,3} \approx 28 \text{ rows} \quad (3.17)
\]
28 \times 4 = 112 \times 4 \text{ facades} = 448 \text{ panels in total and a total average energy produced of } 513.9 \text{ kWh } \leq 15632.36 \text{ kWh} \text{ which is much less than the average consumption of the tower. Adding this energy to the energy produced by the panels at the top of the tower makes a total of } 4113.74 \text{ kWh, which corresponds approximately } 26.3\% \text{ of the building’s energy consumption.}

### 3.4.2 Sizing of the second solution

This solution is the intermediate one and the panel chosen, as already known, is the PS-M-NX panel from Polysolar. Considering the characteristics given in 3.2 and the formulas given in 3.4.1, the power produced by one PS-M-NX panel is obtained. In the following figures, the curves represent the power produced by the PS-M-NX panel with different levels of transparency.

![Figure 3.15: Average daily power produced by one panel PS-M-NX in facade 1](image1)

![Figure 3.16: Average daily power produced by one panel PS-M-NX in facade 2](image2)
As it can be observed in the graphs, the greater the transparency, the lower the power produced.

Once again, it has to be taken into account the maximum open circuit voltage of each PS-M-NX panel in order to not exceed the PV input operating voltage range of the charge controller. Thus, the maximum number of panels in series and the number of rows of panels in parallel are determined in the same way presented in 3.4.1.

\[
170V \times n_{\text{pv,series}} \leq 600V \implies n_{\text{pv,series}} \leq 3\text{ panels} \tag{3.18}
\]

\[
\frac{36.58}{1.4} \approx 26\text{ rows} \tag{3.19}
\]

\[
26 \times 3 = 78 \times 4\text{ facades} = 312\text{ panels in total and a total average energy produced of 636,2kWh} \leq
\]

53
which is much less than the average consumption of the tower. Adding this energy to the energy produced by the panels at the top of the tower makes a total of 4236.04 kWh, which corresponds approximately 27.1% of the building’s energy consumption. Considering now the other panels with levels of transparency of 10%, 20%, 30%, 40% and 50%, the result of panels in series and in parallel is always the same because their maximum open circuit voltage does not vary much. Relatively to the energy produced, it is becoming smaller and smaller as transparency increases, as it has already been concluded above.

### 3.4.3 Sizing of the third solution

This solution is the most expensive and the panel chosen, as already seen above, is the amorphous silicon PV glass from Onyx. Considering the specifications given in 3.3 and the formulas given in 3.4.1, the power produced by one panel can be obtained. In the following figures, the curves represent the power produced by the panel with different levels of transparency.

![Figure 3.19: Average daily power produced by one panel in facade 1](image-url)
Figure 3.20: Average daily power produced by one panel in facade 2

Figure 3.21: Average daily power produced by one panel in facade 3
Now, taking into account the maximum open circuit voltage of each panel from Onyx in order to not exceed the maximum open circuit voltage of the charge controller, it is possible to determine the number of panels in series and taking into account the height of each facade and the height of each panel, it is possible to determine the number of rows of panels in parallel. Thus, the method is the same used in 3.4.2 and in 3.4.1.

\[
191V \times n_{\text{pv,series}} \leq 600V \rightarrow n_{\text{pv,series}} \leq 3\text{panels}
\]

\[
\frac{36,58}{2.5} \approx 15\text{rows}
\]

\[15 \times 3 = 45 \times 4\text{facades} = 180\text{ panels in total and a total average energy produced of approximately 421,12 kWh which is much less than the average consumption of the tower. Adding this energy to the energy produced by the panels at the top of the tower makes a total of 4020,96 kWh, which corresponds approximately 25,7% of the building’s energy consumption. Considering the energy produced by the other panels with different levels of transparency, it can be concluded that this energy is becoming smaller as expected. Another thing that can be concluded in this sub-section is that this solution is not at all the best option, because in addition to being the most expensive is also the one that produces less energy due to the large dimensions of the panel compared to the panel dimensions of the previous solutions.}

### 3.5 Sizing of the solar electric systems with panels made of crystalline silicon in the facades

It is necessary to mention that the panel considered in this solution is not made with the ideal materials. the ideal would be to use panels made of amorphous silicon, like those that were considered in the
previous options. However, this panel made of crystalline silicon is being considered to show that, nowadays, these panels still produce much higher amounts of energy compared to panels made of amorphous silicon.

This solution will be sized with the PS-PC-SE panel with a transparency level of 10%. Doing the same reasoning that was done in the solutions with the panels made of amorphous silicon, one arrives at the following.

\[ 45,49V \times n_{\text{series}} \leq 600V \Rightarrow n_{\text{series}} \leq 13 \text{panels} \] (3.22)

\[ \frac{36,55}{0,992} \approx 36 \text{rows} \] (3.23)

\[ 13 \times 36 = 468 \times \text{4 facades} = 1872 \text{ panels in total and a total average energy produced of approximately } 7636,01 \text{ kWh which is higher than the average consumption of the tower. Adding this energy to the energy produced by the panels at the top of the tower makes a total of 11235,86 kWh, which corresponds approximately 71,9\% of the building’s energy consumption. It can be concluded that with this type of solution, the average energy produced per day is more than the double of the energy produced by the panels of the previous solutions.} \]

However, with this solution it is still not possible to produce the energy needed to feed the entire tower.

### 3.6 Sizing of the batteries

After this, it is necessary to calculate the required number of batteries to store energy and thus provide the necessary power at night. For that it was obtained the average energy consumption of the tower at night in January, because it is on the winter nights that occurs the highest consumption. Knowing
the inverter and the charge controller efficiencies and the capacity of each battery pack, the necessary energy for batteries to store is calculated.

\[
E_{\text{batt}} = \frac{E_{\text{night, January}}}{\eta_{\text{inv}} \times \eta_{\text{cc}}} = \frac{2487,24 \text{kWh}}{0,85 \times 0,979} \approx 2988,9 \text{kWh}
\] (3.24)

With this, the total number of battery banks is calculated through the following.

\[
n_{\text{batt}} = \frac{E_{\text{batt}}}{\text{Capacity}} = \frac{2988,9 \text{kWh}}{20,64 \text{kWh}} \approx 145 \text{ packs}
\] (3.25)

These battery packs shall be placed in parallel so that the output voltage does not exceed the battery operating voltage range of the charge controller. Based on the load curve in January and on the PV available power of the different solutions previously considered, it is possible to obtain the evolution of the battery power (positive when discharging and negative when charging). Also it is possible to obtain the evolution of the battery state of charge (SOC) considering that it is 100% at 18h. To study these two evolutions it will only be considered the solution with panels made of crystalline silicon.

![Figure 3.24: Daily available PV power and daily energy consumption of the tower](image)

Figure 3.24: Daily available PV power and daily energy consumption of the tower
Figure 3.25: Evolution of the batteries power throughout the day (positive when discharging and negative when charging)

Figure 3.26: SOC of the batteries considering that it is 100% at 18h

In 3.25 it can be observed that even in daylight hours it is used power from the batteries to feed the load because the power produced by the panels is not enough, as shown in 3.24. Relatively to 3.26, it can be concluded the following: imagine that as soon as the system is assembled, the power produced by the panels is immediately used to charge the batteries. These are fully charged, that is, with 100% at 6:00 p.m., as was previously assumed. And by the observation of 3.24, at 6:00 p.m., the power consumption of the tower is already higher than the power produced by the panels, so that the batteries automatically start to feed the tower, whether it is night or not. With this, the batteries discharge over the hours until they get 0% energy, as can be seen in 3.26. As soon as this happens, it is also verified that it is no longer possible to charge the batteries because the energy produced by the panels is not enough to cover all the energy consumption made during a day in the north tower.
Therefore, 3.26 is only considered for the moment when the system is installed in the tower which is when it is possible to get the batteries at 100%. This happens, because, normally stand-alone systems (systems not connected to the utility grid) require batteries to store excess power generated, but as in this case no excess power is generated, the SOC of the batteries is always at 0% and with this it is concluded that with these solutions it is not yet possible to have completely independent systems as they do not produce the energy needed to power the tower. Therefore, it is necessary to connect these systems to the grid so that the grid supplies power when needed.

3.7 Economic study of the presented solutions

To make an economic study it is necessary to calculate the total electricity cost per year in the North Tower and then calculate an approximate investment cost of the solutions presented above in order to compare and reflect on whether or not it will be worth installing these kind of systems these days.

The tariff in the tower is tri-hourly due to the contracted power.

Table 3.9: Electricity sale tariff in Portugal. In the North Tower the tariff is tri-hourly

<table>
<thead>
<tr>
<th>Fixed Expenditure (EUR/day)</th>
<th>EUR/kWh</th>
<th>Peak Hours</th>
<th>Full Hours</th>
<th>Empty Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,8868</td>
<td>0,3010</td>
<td>0,1442</td>
<td>0,0731</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.10: Schedule of peak, full and empty hours during the summer

<table>
<thead>
<tr>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empty Hours</td>
</tr>
<tr>
<td>[0h-8h]</td>
</tr>
<tr>
<td>[22h-24h]</td>
</tr>
<tr>
<td>Full Hours</td>
</tr>
<tr>
<td>[8h-10h30]</td>
</tr>
<tr>
<td>[13h-19h30]</td>
</tr>
<tr>
<td>[21h-22h]</td>
</tr>
<tr>
<td>Peak Hours</td>
</tr>
<tr>
<td>[10h30-13h]</td>
</tr>
<tr>
<td>[19h30-21h]</td>
</tr>
</tbody>
</table>
So considering the electricity sale tariff and the schedule of peak, full and empty hours during the summer and during the winter it is obtained the total electricity cost per year.

\[
\text{Cost}_{\text{summer}} = (0, 3010 \times E_{\text{peak}_{\text{summer}}} + 0, 1442 \times E_{\text{full}_{\text{summer}}} + 0, 0731 \times E_{\text{empty}_{\text{summer}}}) \times \frac{365\text{days}}{2}
\] (3.26)

\[
\text{Cost}_{\text{winter}} = (0, 3010 \times E_{\text{peak}_{\text{winter}}} + 0, 1442 \times E_{\text{full}_{\text{winter}}} + 0, 0731 \times E_{\text{empty}_{\text{winter}}}) \times \frac{365\text{days}}{2}
\] (3.27)

\[
\text{Cost}_{\text{year}} = \text{Cost}_{\text{summer}} + \text{Cost}_{\text{winter}} \approx 365, 5kEUR
\] (3.28)

Knowing the unitary costs of each technology and that the return years is given by,

\[
\text{Return}_{\text{years}} = \frac{\text{TotalInvestment}}{\text{TotalElectricityCostperYear}}
\] (3.29)

It is possible to make a study of the solutions previously presented.
Table 3.12: Economic study of the first solution (PS-C panels to coat the facades and PS-MC-SE to coat the top)

<table>
<thead>
<tr>
<th>Equipments</th>
<th>Costs</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unitary Cost</td>
<td></td>
</tr>
<tr>
<td>PS-C panels</td>
<td>199,5EUR/m²</td>
<td>≈ 128 kEUR</td>
</tr>
<tr>
<td>PS-MC-SE panels</td>
<td>0,188 EUR/W</td>
<td>≈ 28 kEUR</td>
</tr>
<tr>
<td>Batteries</td>
<td>2416 EUR</td>
<td>≈ 1752 kEUR</td>
</tr>
<tr>
<td>Charge Controller</td>
<td>1183,7 EUR</td>
<td>5918,5 EUR</td>
</tr>
<tr>
<td>Inverter</td>
<td>4820,69 EUR</td>
<td>24103,45 EUR</td>
</tr>
<tr>
<td>Cables</td>
<td>≈ 2,59 EUR/m</td>
<td>≈ 3511,2 EUR</td>
</tr>
<tr>
<td>Protections</td>
<td>≈ 2700 EUR</td>
<td>≈ 13500 EUR</td>
</tr>
<tr>
<td>Total (EUR)</td>
<td>-</td>
<td>≈ 1958 kEUR</td>
</tr>
<tr>
<td>Return (years)</td>
<td>-</td>
<td>≈ 5,4</td>
</tr>
</tbody>
</table>

Table 3.13: Economic study of the second solution (PS-M-NX panels to coat the facades and PS-MC-SE to coat the top)

<table>
<thead>
<tr>
<th>Equipments</th>
<th>Costs</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unitary Cost</td>
<td></td>
</tr>
<tr>
<td>PS-M-NX panels</td>
<td>285 EUR/m²</td>
<td>≈ 137 kEUR</td>
</tr>
<tr>
<td>Cables</td>
<td>≈ 2,59 EUR/m</td>
<td>≈ 3123,7 EUR</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Total (EUR)</td>
<td>-</td>
<td>≈ 1964 kEUR</td>
</tr>
<tr>
<td>Return (years)</td>
<td>-</td>
<td>≈ 5,4</td>
</tr>
</tbody>
</table>

Table 3.14: Economic study of the third solution (Onyx panels to coat the facades and PS-MC-SE to coat the top)

<table>
<thead>
<tr>
<th>Equipments</th>
<th>Costs</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unitary Cost</td>
<td></td>
</tr>
<tr>
<td>Onyx panels</td>
<td>449 EUR/m²</td>
<td>≈ 247 kEUR</td>
</tr>
<tr>
<td>Cables</td>
<td>≈ 2,59 EUR/m</td>
<td>≈ 2824,4 EUR</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Total (EUR)</td>
<td>-</td>
<td>≈ 2073 kEUR</td>
</tr>
<tr>
<td>Return (years)</td>
<td>-</td>
<td>≈ 5,7</td>
</tr>
</tbody>
</table>
Table 3.15: Economic study of the fourth solution (PS-PC-SE panels to coat the facades and PS-MC-SE to coat the top)

<table>
<thead>
<tr>
<th>Equipments</th>
<th>Costs</th>
<th>Unitary Cost</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS-PC-SE panels</td>
<td></td>
<td>0.206 EUR/W</td>
<td>≈ 123 kEUR</td>
</tr>
<tr>
<td>Cables</td>
<td></td>
<td>≈ 2.59 EUR/m</td>
<td>≈ 7773.2 EUR</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Total (EUR)</td>
<td></td>
<td></td>
<td>≈ 1954 kEUR</td>
</tr>
<tr>
<td>Return (years)</td>
<td></td>
<td></td>
<td>≈ 5.3</td>
</tr>
</tbody>
</table>

Just to mention that the only things that change from table to table are the price of the chosen panels to cover the facades and the price of the cables used to make the connections.

By observing the previous tables and taking into account which solution produces a greater amount of energy, it is immediately apparent that the best solution of all and therefore the most appealing is undoubtedly the solution in which the panels are made of crystalline silicon, because it is the solution that presents the highest values of energy produced and is also the one that presents the least number of years of return, that is, a lower investment.

Another thing that has to be mentioned is the fact that the number of years of return is not the expected. Because usually, the number of years of return is around 8 years, so these solutions have a low number of years of return. This happens because, most likely, some costs, such as the costs of the panels to cover the facades or the costs of the cables and protections are below normal. These costs were considered approximations after some research in Internet sources and in previous works that are similar to this type of study. Another cost that has not been considered, and which has caused the number of years of return to be below normal, is the cost of labor that always depends on company to company. So it may be due to these approximations made.

Also, this is not at all what one wants to install in the tower. The ideal would be, as is often mentioned in this thesis, to install in the tower, glass windows (windows with panels of amorphous silicon) capable of producing a reasonable amount of energy in order to feed the entire tower. But to do this still many challenges lie ahead.

As seen in the previous theoretical study, the energy produced by the panels during the day is not sufficient to power the tower at night, so in the following section a solution for the production of energy at night through the installation of wind turbines in the top of the tower is going to be presented.

3.8 Alternative for overnight energy production

As an alternative for energy production at night it will be considered wind turbines, which as the name implies, are devices that produce energy through the action of wind. And as is theoretically known, wind
speed is higher at night, both in summer and winter.

It is also important to mention here that the turbines in this solution will not only be used at night but also during the day as a complement to the panels installed on the facades.

Following the introduction of wind turbines at the beginning of this thesis, it is clear that the most suitable turbines to install in this building under consideration are micro wind turbines.

After some research and based on some references it was chosen the Talon 10 wind turbine from A&C Green Energy with the following characteristics.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>10kW</td>
</tr>
<tr>
<td>Peak power</td>
<td>12.5kW</td>
</tr>
<tr>
<td>Rated wind speed</td>
<td>11m/s</td>
</tr>
<tr>
<td>Start-up wind</td>
<td>3m/s</td>
</tr>
<tr>
<td>Working speed</td>
<td>2.5-25m/s</td>
</tr>
<tr>
<td>Survival wind</td>
<td>50m/s</td>
</tr>
<tr>
<td>Blade diameter</td>
<td>7.62m</td>
</tr>
<tr>
<td>Working voltage</td>
<td>DC300V</td>
</tr>
<tr>
<td>Output voltage</td>
<td>AC220V</td>
</tr>
<tr>
<td>Turbine main body</td>
<td>500kg</td>
</tr>
<tr>
<td>Generator lifespan</td>
<td>15 years</td>
</tr>
</tbody>
</table>

Table 3.16: Wind turbine main specifications

This wind turbine has the following power curve.

Figure 3.27: Power curve of the chosen wind turbine
And also knowing the wind speed over the months of January and June.

![Wind speed in January in the north tower](image)

![Wind speed in June in the north tower](image)

Figure 3.28: Wind speed in January in the north tower

Figure 3.29: Wind speed in June in the north tower

It is possible to obtain the power produced by one wind turbine by finding the power curve trend line equation, which in this case is the equation presented in 3.27 where \( y \) corresponds to the power in kW and \( x \) corresponds to the wind speed in m/s. To determine the trend line of the power curve, several approximations were verified, such as linear, polynomial, etc. However, it was found that the polynomial approximation is the closest to the ideal value, thus presenting a coefficient of determination, \( R^2 \), of 0.9987, that is 99.87%. This means that the trend line equation is a good approximation to use to determine the power output of a wind turbine. With this, the power produced by a wind turbine was determined.

In order to have micro-siting, that is the strategy that places the wind turbines in locations where maximum power production is possible throughout the year, certain minimum distances between the
individual wind turbines have to be observed. Obviously, in view of the need for wind power plants to maintain a minimum distance between the generators (at least 4 times the diameter), the possibility of installing more turbines depends on the geometry of the roof and the available power may be less than the one reached by the use of a photovoltaic system installed on the same surface. Then, taking into consideration the dimensions of the top and one turbine, it has been found that it is possible to install 4 turbines in series on the top of the tower. For safety reasons it will be considered only two rows of 4 turbines in series, that is, 8 turbines in total and thus produce the following energy over the months of January and June.

By observing the graphs it is immediately apparent that the energy produced by the turbines, in these months, is not enough to power the tower, so that a completely independent system cannot be installed, i.e., without having to connect it to the grid. Thus, if the turbine cannot deliver the amount of needed
energy, the grid makes up the difference. If, for example, the wind system produces more electricity than the household requires, the excess is sent or sold to the grid. As in this case the system is connected to the grid, the only additional equipment required is a power conditioning unit (inverter) that makes the turbine output electrically compatible with the utility grid, since wind turbines generate direct current (DC) electricity. In these cases, batteries are not usually required.

Relatively to costs, each turbine costs 24514.89EUR, which makes a total cost, only of turbines, of 196,12kEUR. Adding the cost of the panels used to cover the tower facades, considering in this case the panels of the second solution, since they are the amorphous silicon panels with the highest percentage of energy production, plus the cost of the inverters, cables and protections, it gets up a total initial investment of approximately 400kEUR. Here, it should be noted that the investment price is much lower, because the system is not independent or not self sufficient, i.e., it doesn’t produce enough energy to feed the entire tower and to charge the batteries, so it has no batteries or charge controller. Therefore, the system needs to be connected to the national grid.

With this type of solution, the price of the annual energy consumption provided by the grid would decrease as only a percentage of it would be used because the remainder would be provided by the system of panels and turbines.

To install wind turbines on top of the building, it is necessary to take into account several factors, which in this case were not considered, because as the title of this thesis indicates, the main objective is to size a solar photovoltaic system, so this part of wind turbines is just a complement that can be studied further in future works. This type of project is called Built-environment wind turbine (BEWT), because it is a project that is constructed in or near a building, in this case, more properly, it is in the building. Just like the photovoltaic projects, these projects also present an opportunity for distributed, low-carbon generation combined with highly visible statements on sustainability, but the BEWT niche of the wind industry is still developing and is relatively less mature than the utility-scale wind or conventional ground-based distributed wind sectors. A BEWT attached to a building may be an attractive prospect for a project developer because it offers an opportunity for locally produced energy similar to a solar photovoltaic system. However, unlike solar photovoltaic systems, BEWT systems have additional challenges that should be considered. Beyond the normal procedures required by a standard wind installation projects, like understanding customer needs through establishing baselines; develop project goals; perform a technical evaluation: site evaluation; turbine selection; wind resource assessment; production estimate; estimate project costs; conduct a cost/benefit analysis, the built environment adds new dimensions and challenges to these planning process phases. The following parameters must be considered even more carefully when siting BEWT projects: wind speed frequency distribution; predominant wind direction; TI (Turbulence Intensity); inflow angles; building shape (square, rectangular, irregular); roof shape (flat roof, pitched roof, parapets); building orientation with respect to predominant winds; building structural considerations; turbine safety limits; wind speed; extreme direction change; turbine orientation (HAWT vs. VAWT); tower height; initial construction costs; ongoing operations and maintenance costs; building occupant comfort and safety: noise emissions; vibration emissions; turbine failure projectile zone.

It should also be noted that based on several key factors (i.e., wind speeds are typically lower and
costs for implementing projects in built environments are typically higher), projects in the built environment can be difficult to justify on a cost of energy or energy-offset basis. Understanding the expected production of a wind turbine in the built environment is a very complex undertaking; the use of onsite resource measurements combined with high-fidelity models is likely the only way to truly understand the expected turbine production [23].
Chapter 4

Conclusions

4.1 Achievements

Besides the fact that these systems cannot be independent yet, as concluded in 3.6, there are other disadvantages related to the fabrication of photovoltaic panels. Fabricating the panels requires caustic chemicals such as sodium hydroxide and hydrofluoric acid, and the process uses water as well as electricity, the production of which emits greenhouse gases. It also creates waste [24]. Most of these chemicals are used to clean and purify the semiconductor surface. The amount and type of chemicals used depends on the type of the cell, the amount of cleaning that is needed, and the size of silicon wafer. Workers also face risks associated with inhaling silicon dust. And the truth is that Thin-film PV cells contain a number of more toxic materials than those used in traditional silicon photovoltaic cells, including gallium arsenide, copper-indium-gallium-selenide, and cadmium-telluride. If not handled and disposed of properly, these materials could pose serious environmental or public health threats, just like burns on our skin, harmful air pollutants that increase lung disease, and if some of the chemicals are exposed to water can release hydrochloric acid, which is a corrosive substance bad for human and environmental health.

These problems could undercut solar’s ability to fight climate change and reduce environmental toxics [24]. Thus, PV manufacturers must follow US laws to ensure that workers are not harmed by exposure to these chemicals and that manufacturing waste products are disposed of properly. Manufacturers have a strong financial incentive to ensure that these highly valuable and often rare materials are recycled rather than thrown away. While these chemicals can be considered as hazardous, they aren’t so while the panels are on your roof. To avoid confusion, it is necessary to understand that the concern for their toxicity comes into play during the manufacturing process, as well as disposal process from by-products during the manufacturing process, and at the end of the panel’s lifetime. Responsible solar panel manufacturers will ensure that the chemicals used in the manufacturing process are handled properly. Unfortunately, there have also been instances in the past of dumping hazardous into nature in various parts of the world (such as China). The resulting public outcry caused stock prices of manufacturers involved in these instances to drop, and solar companies started to implement more stringent
rules and regulations in regard to recycling and disposal to protect against this happening in the future.

While there are no global warming emissions associated with generating electricity from solar energy, there are emissions associated, as said before, with other stages of the solar life-cycle, including manufacturing, materials transportation, installation, maintenance, and decommissioning and dismantlement. Most estimates of life-cycle emissions for photovoltaic systems are between 0.07 and 0.18 pounds of carbon dioxide equivalent per kilowatt-hour. Also, depending on their location, larger utility-scale solar facilities can raise concerns about land degradation and habitat loss. Unlike wind facilities, there is less opportunity for solar projects to share land with agricultural uses. However, land impacts from utility-scale solar systems can be minimized by siting them at lower-quality locations such as brown fields, abandoned mining land, or existing transportation and transmission corridors. Smaller scale solar PV arrays, which can be built on homes or commercial buildings, also have minimal land use impact.

Another important environmental impact is the visual impact that PV systems may have on buildings and areas. The visual intrusion of a building-integrated PV system can be very high but can also be addressed with relative ease. Careful architectural designing and materials can introduce the photovoltaic panels as architectural elements, complementing the appearance of the building instead of degrading it. It is not necessary for the architect to hide panels and components entirely, only to implement them as part of the overall building design. From the side of PV panel manufacturers, modern designs can easily be developed specifically for their installation in populated areas and on buildings, with colored versions already in the market for the few years. Colored PV panels are frequently used to simulate the appearance of ceramic roof tiles or typical glass. Retrofitting PV systems on roofs and large surfaces of older buildings usually is a viable solution as well, with the exception of buildings that cannot be visually altered, i.e. those which are of historical or cultural importance. Furthermore, thin film panels could easily replace the mirrors and glass surfaces of large buildings. As thin film panels have a lower solar transmittance than glass, they could also be used as a means to reduce the cooling load of buildings, offering shading or even heat extraction. However, the architect always has to consider the effects of glare as well. The replacement of glass surfaces may very well be the only method applicable to historical buildings and buildings with high cultural value, where visual modifications of the structure itself are impossible [25].

Utility-scale installations are a more complicated matter. The installation of a utility-scale installation at or near areas of natural beauty, tourist attractions, archaeological sites, ecological areas and other similar locations is problematic and should be avoided. Large installations need to be properly sited, usually outside residential and commercial areas as well. Abandoned areas and low-quality land usually are the most suitable sites for such installations [25].

Right now and coming back to the subject of recycling solar panels, this suffers from a chicken-or-egg problem: There aren’t enough places to recycle old solar panels, and there aren’t enough defunct solar panels to make recycling them economically attractive [24]. Dangers and hazards of toxins in photovoltaic modules appear particularly large in countries where there are no orderly waste management systems, especially in less developed countries in the so-called global south, which are particularly predestined for the use of photovoltaics because of the high solar radiation, it seems highly problematic...
to use modules that contain pollutants. In other words, there are firms that may advertise themselves as "solar panel recyclers" but instead sell panels to a secondary market in nations with less developed waste disposal systems. According to a 2015 United Nations Environment Program (UNEP) report, somewhere between 60 and 90 % of electronic waste is illegally traded and dumped in poor nations. Perhaps the biggest problem with solar panel waste is that there is so much of it, and that's not going to change any time soon, for a basic physical reason: sunlight is dilute and diffuse and thus require large collectors to capture and convert the sun's rays into electricity [26].

Yes, solar PV does require heavy amounts of energy up front to mine and manufacture the materials, but when that emission is dispersed over a 30 year generation profile the emissions/kWh are much more favorable. This key metric must be considered when evaluating the environmental impacts of solar panels. Solar power is not perfect, but overall it provides a positive net environmental impact and excellent long-term financial. The energy required to create a solar panel will be recouped after just 2 to 4 years. Even considering the manufacturing and processing stage of solar, the emissions generated are 3x to 10x less than generating the same amount of energy from fossil fuels. Naturally, the benefits will vary depending on the energy generation and solar irradiance of your location, but overall solar panels provide a positive net impact. So, while solar power isn’t a perfect solution, it is much more environmentally friendly than producing electricity from non-renewable sources, especially coal [27].

Regarding the efficiency of the panels there are several conclusions that can be drawn. One of the conclusions is that the panel color influences its efficiency. When a panel is covered with a color-filter, it means it is exposed to a light of specified wavelength: shorter for blue, medium for green and longer for red. Red color light generates more electricity than other colors. Contrary to popular belief, longer wavelengths of visible light, the ones with less photon energy, are more efficient with photovoltaic cells than shorter, more energetic wavelengths. The efficiency of solar panels in general could be improved by exposure to red light. If a way could be found to eliminate or even only reduce the light intensity lost due to tinting, the efficiency of solar panels in general could be improved by exposure to red light. Future studies might examine ways of accomplishing this [28]. In short, PV cells are sensitive to light from the entire spectrum as long as the wavelength is above the band gap of the material used for the cell, but extremely short wavelength light is wasted. This is one of the factors that affects solar cell efficiency. Another is the thickness of the semiconducting material. If photons have to travel a long way through the material, they lose energy through collisions with other particles and may not have enough energy to dislodge an electron [29]. A third factor affecting efficiency is the reflectivity of the solar cell. A certain fraction of incident light bounces off the surface of the cell without encountering an electron. To reduce losses from reflectivity and increase efficiency, solar cell manufacturers usually coat the cells with a non-reflective, light-absorbing material. This is why solar cells are usually black [29]. The cell’s silicon material responds to a limited range of wavelength, ignoring those that are longer and shorter. As the wavelength varies from short to long, the cell’s output rises and falls in a jagged curve. Newer photovoltaic cells design achieves higher efficiency by converting more wavelengths into useful energy. A color filter is a material that allows the passage of light through it, a colored filter of a specific color allows its own color to pass through and absorbs the remaining colors. For example, if you pass white
light through a red color filter, then red light comes out the other side. This is however so because the red filter only allows red light through, the other colors (wavelengths) of the spectrum are absorbed. Color filters were used to absorb all wavelengths of light except that of their own color, thus tinting the light that color [30]. For decades, engineers have been waiting for an ultimate solution to customize the color of solar components and a mishmash of photovoltaic technology and glass have given birth to a colorful laminated glass, which are generating electricity. The use of new screen-printing techniques and special interlayers are giving a visual interpretation to the no-longer-so called solar panels which has come up as a new active material. The designers managed to maintain a perfect match between design and electrical efficiency. They are most commonly called “colored solar panels” but they have certain technical characteristics which makes them complex as compared to simple ones. Covering frontage or a roof with standard solar panel system to generate electricity will change a building’s original appearance. At present, only dark colored solar panels are widely available on the market as they are designed to reflect few light as possible. This way the colored solar cell will produce maximum power output. Monocrystalline solar cells are typically black, grey or blue while polycrystalline solar cells are usually dark blue or blue. Speaking of thin-film amorphous silicon cells, the color is always the same; it has a dark surface with grey, black and brown as common colors. Interestingly, the color of the solar cells can be changed by varying the thickness of the anti-reflection coating. The colored solar panels looks different at the time of solar panel installation, however by altering the thickness of the anti-reflection layer, the overall reflection of solar panels will increase and the efficiency will decrease by 15-30% depending on the color. Simulations showed that the efficiency of colored solar panels could increase up to 20 percent. In reality, the solar panel efficiency basically depends on the designs of the solar system as well as the direction of building faces. But there is the thing that not every color allows you to generate the same amount of electricity. However, there are limitations with certain blends of blue, red and green. Scientists will be using laser-based optical welding processes to connect several solar cells to create a single module. They enable accurate work at a micrometer scale without damaging the surrounding materials. As a result, it will end up making manufacturing faster plus allowing additional degrees of flexibility in design. SIS (Semiconductor-Insulator-Semi-conductor structured) solar cells could even be used to make billboards that generate their own electricity. Moreover, patents already cover the production of colored solar cells, as well the capability to integrate design elements into solar PV system along with whole modules [31].

To be effective and credible, these plans cannot address mitigation alone: they must show the way toward a full transformation of economies in line with sustainable development goals. They should not create winners and losers or add to economic inequality; they must be fair and create new opportunities and protections for those negatively impacted, in the context of a just transition. And they should also include women as key decision-makers: only gender-diverse decision-making has the capacity to tackle the different needs that will emerge in this coming period of critical transformation [32].

The Summit will bring together governments, the private sector, civil society, local authorities and other international organizations to develop ambitious solutions in six areas: a global transition to renewable energy; sustainable and resilient infrastructures and cities; sustainable agriculture and man-
agement of forests and oceans; resilience and adaptation to climate impacts; and alignment of public and private finance with a net zero economy [32].

Business is on our side. Accelerated climate solutions can strengthen our economies and create jobs, while bringing cleaner air, preserving natural habitats and biodiversity, and protecting our environment. New technologies and engineering solutions are already delivering energy at a lower cost than the fossil-fuel driven economy. Solar and onshore wind are now the cheapest sources of new bulk power in virtually all major economies. But we must set radical change in motion. This means ending subsidies for fossil fuels and high-emitting agriculture and shifting towards renewable energy, electric vehicles and climate-smart practices. It means carbon pricing that reflects the true cost of emissions, from climate risk to the health hazards of air pollution. And it means accelerating the closure of coal plants and halting the construction of new ones and replacing jobs with healthier alternatives so that the transformation is just, inclusive and profitable [32].

Thus, in terms of manufacturing matter there is still a long way to go and many challenges lie ahead. The evolution of PV technology and the development of new materials and building components are fundamental pieces in this work. Both, PV sector and construction industry must work together and join their experiences and knowledge in order to develop innovative elements, which in turn comply with all regulations and standards of quality and in accordance with photovoltaic engineering competences. Although an increasing number of BIPV products can be found, looking to the future, collaboration between the photovoltaic and construction industries must be reinforced in order to develop innovative and attractive products, easy to installation, reliable, with low environment impact and cost-effective. In particular, new developments of PV technologies are needed to enable the integration into several materials that make up the skins of buildings today, easy application of PV cells in conventional materials is imperative because that, in a lot of ways, will allow the development of new solutions and thus make the world a better place.

4.2 Future Work

In this dissertation, the study was based on theoretical formulas, so the results presented are completely dependent on the theory. However, to have a clearer notion of reality it is necessary to perform laboratory tests in the future and thus verify if what has been studied is correctly sized. Apart from the theoretical and practical studies it would also be very interesting and useful to use the already developed optimization algorithm NSGA-II so as, as the name implies, to optimize the installation positions of the panels and turbines in the tower so that they produce the maximum power possible.

Another important point will be to explore and study organic cells, which are part of the third generation of solar photovoltaic technology and made of materials that are much more appealing to our environment. Beyond this, OPV presents other important advantages, especially with respect to BIPV. OPV modules do not show the performance drop usually observed with traditional inorganic photovoltaics in diffuse lightning conditions and under elevated temperatures — typical conditions found in facades [33]. One aim of integrating OPV technology into facade elements is to reduce both the energy con-
sumption and CO2 emission of a building [34]. Compared to classic PV technology, OPV can better serve both the functional and aesthetic demands of designers and architects while also enabling the use of building-integrated photovoltaic. OPV modules have been integrated into various glass facades and into structural membrane architectures [34]. However, organic solar cells have very low efficiencies compared to conventional silicon cells. Therefore, a lot of scientific research is currently being done in order to develop these cells because of its various advantages in other branches, as mentioned above.

Finally, it should be mentioned that more inverters and more battery charge controllers could have been used to increase the panel set output voltage, that is, so that more panels could be installed and thus obtained a much higher output power. However, this was not done in this study because it was intended to provide a more cost-effective solution.
Bibliography


