Using renewable energy sustainably - Industrial Symbiosis Potential

Alexandre de Sousa Raimundo Vilas Boas

Thesis to obtain a Master of Science Degree in

Industrial Engineering and Management

Supervisor: Prof. Maria do Rosário Sintra de Almeida Partidário

Examination Committee

Chairperson: Prof. Tânia Rodrigues Pereira Ramos
Supervisor: Prof. Maria do Rosário Sintra de Almeida Partidário
Member of the Committee: Prof. António Miguel Areias Dias Amaral

November 2022

Agradecimentos

Em primeiro lugar quero agradecer à minha orientadora Professora Maria Partidário por me ter acolhido numa altura em que mais precisava, algo que nunca vou esquecer. Para além disso, nos momentos mais difíceis, mostrou-se presente e encontrou forças para me dar todo o suporte necessário durante esta Dissertação.

De seguida gostava de agradecer também à Fabiola Bordino por toda a sua disponibilidade, ajuda e informação providenciada para que pudesse acrescentar mais valor à minha tese de mestrado.

Por fim, um grande obrigado aos meus pais e irmã por me terem continuado a motivar e acreditarem em mim durante esta fase.

Resumo

A energia solar tem vindo a ser das maiores apostas no combate à dependência de combustíveis fosseis e subsequentemente na ajuda ao combate às alterações climáticas. No entanto têm sido levantadas algumas preocupações relativamente à sua instalação dado à quantidade de espaço territorial necessário e ao impacto na biodiversidade para as suas estruturas. Posto isto dá-se a introdução ao conceito de simbiose industrial, um dos ramos dentro da economia circular e da ecologia industrial. Este conceito visa a abordagem colaborativa e mutuamente benéfica entre diferentes indústrias ou empresa trocando recursos entre si de modo a melhorar o seu desempenho e eficiência.

O objetivo central desta dissertação foi desenvolver uma metodologia que ajudasse a identificar e avaliar simbioses industriais e aplicá-la aos parques solares que a Start Campus irá construir. A metodologia permitiu identificar primeiramente os *stakeholders* envolvidos em projetos similares. De seguida, com base em casos de estudos similares, as potenciais simbioses foram identificadas. Por fim procedemos à sua análise em dois passos, em que o primeiro consistiu em avaliar os benefícios e desvantagens de cada alternativa seguido das motivações e barreiras que poderão ter pela frente para as estabelecerem.

A aplicação da metodologia apresentou três possíveis simbioses para o projeto da Start Campus. Os resultados mostraram bastante potencial visto que expuseram de uma forma clara, como é as comunidades e/ou indústrias podem ser envolvidas em projetos solares. A pesquisa demonstrou também, que é possível contrabalançar os custos elevados do investimento inicial com outros benefícios tanto ou mais importantes.

Palavras-chave: Energia Solar; Simbiose Industrial; Start Campus; Sustentabilidade; *Stakeholders*

Abstract

Solar energy has become one of the biggest drivers in the quest of reducing our reliance on fossil fuels and, subsequently, fight against climate change. However, some concerns have been raised regarding its installation given the amount of land required and the impact on biodiversity from its structures. This introduces the concept of industrial symbiosis, one of the subfields of circular economy and industrial ecology. This concept aims at a collaborative and mutually beneficial approach between different industries or companies exchanging resources with each other in order to improve their performance and efficiency.

The central objective of this dissertation was to develop a methodology to help identify and evaluate possible industrial symbioses and apply it to the solar parks that Start Campus will construct. First, the methodology identified the stakeholders involved in similar projects. Then, based on similar case studies, the potential symbioses were identified. Finally, we proceeded to analyze them in two steps, in which the first consisted of evaluating the benefits and drawbacks of each alternative followed by the drivers and barriers they may encounter in establishing them.

The application of the methodology presented three possible symbioses for Start Campus project. The findings were quite promising as they clearly demonstrate how communities and/or industries can be involved in solar projects. The research also showed that is possible to offset the high initial investment costs with further benefits.

Keywords: Solar energy; Industrial Symbiosis; Start Campus; Sustainability; Stakeholders

Table of Contents

List of Figures

List of Tables

List of Equations

List of Acronyms

IEA – International Energy Agency

EJ – Exajoules

CO_2 – Carbon Dioxide

GHG – Greenhouse gas

RES – Renewable energy sources

PV – Photovoltaic

MW – Megawatt

GDP – Gross Domestic Product

ED – Energy dependence

EU – European Union

EZ – Eurozone

ZEB – zero-energy building

DC - Direct current

AC – Alternating current

PPA – Power purchase agreement

IRENA – International Renewable Energy Agency

EPBT – Energy payback time

EoL – End-of-life

IE – Industrial Ecology

CE – Circular Economy

IS – Industrial Symbiosis

EIP – Eco industrial Park

APV – Agrophotovoltaic

SC – Start Campus

NGOs - Non-Governmental Organizations

O&M - Operations and Management

Ha – Hectares

REC - Renewable Energy Communities

1. Introduction

1.1. Context and Problem Definition

Over the past century, the energy sector has been one of the most important drivers of the global economy, supporting economic and social progress, improving quality of life, and bringing prosperity to people all over the world. Since the Stone Age, energy has been a part of people's lives in many forms, starting with fire and progressing to a vast range of energy forms (coal, oil, natural gas, and renewable energies, such as solar, wind, hydropower, etc.) in contemporary days. The emergence of all these sources of energy over time, as well as their widespread application in everyday life, resulted in a massive dependency upon energy by the world's population, particularly in developed countries.

According to International Energy Agency (IEA) statistics[1], the world's total final consumption of energy was 194 exajoules (EJ) in 1973 and 418 EJ in 2019, reflecting a change of roughly 115% over 46 years. IEA further adds that this consumption will continue to grow as global energy demand is expected to increase 47% over the next 30 years. However, for the demand to be met and given global energy reliance, the energy supply must imperatively continue to grow. Additional data provided by the IEA in the same time frame indicate that the total world energy supply increased 2.6 times, from 230 EJ to 606 EJ. Unfortunately, resources are not all unlimited, therefore we will need to carefully plan how we will respond to the demand, as other major concerns arise, namely climate change.

The biggest driver of climate change is carbon dioxide (CO_2) emissions, which is the most dominant greenhouse gas (GHG) produced by fossil fuel burning (87%), land use change (9%), and industrial production (4%) according to Our World in Data[2]. It is urgent to stabilize the global climate as serious consequences can emerge (severe storms, rising ocean, poverty, etc.), hence society must commit to making a significant change to drastically reduce GHG emissions.

At the heart of this discussion lies the fossil fuels which continue to be the primary energy sources, as reported by IEA, with oil accounting for 30.9%, coal for 26,8%, and natural gas for 23.2% from the 606 EJ produced in 2019. Butturi et al. (2019) state that the industry sector is one of the main contributors to the release of CO_2 direct and indirect emissions, which originate from "fuel combustion and industrial processes (direct) and energy production, such as electricity and heat (indirect)". Now in order to reduce these GHG emissions, a rapid world transition to renewable energy sources (RES) must occur. Horbach & Rammer (2018) further adds that the solution is through buying clean energy for industrial processes or integrating renewable energy systems.

---

[1] See https://www.iea.org/reports/key-world-energy-statistics-2021/final-consumption (accessed in October 2022)

[2] See https://ourworldindata.org/co2-emissions (accessed in October 2022)

The most suitable RES for industrial applications is solar radiation, either photovoltaics (PV) or thermal, biomass and wind. Among these RES, Solar PV presents itself as one of the most technically feasible and environmentally sustainable solutions to address the abovementioned concerns. As per Our World in Data[3], solar energy is currently the third largest generated renewable energy, only behind hydropower and wind, but is expected to lead the way in transforming the energy sector in the next 10 to 20 years.

Typical solar energy projects are ground-mounted solar parks, which consist of solar panels installed on metal supports on the ground. Normally such structures require between 2 to 4 hectares per megawatt (MW) of generating capacity (Pearce, 2008). Solar parks have been appearing more across the globe, but in the European Union, Germany took the lead with the highest PV generation with 1910 MW produced in 2005. Germany is until today the largest solar energy producer, but other players have appeared in the market, like Spain, Italy, France, and the Netherlands.

Yet, despite being considered a sustainable energy source, given its exponential growth in the last decade, possible implications on the ecosystem might have been overlooked. Impacts on land use and the local environment and communities are currently relatively unknown and need to be explored otherwise it will offset the benefits that this RES brings to climate change mitigation. For example, land use change can alter or degrade habitats affecting some species and leading to habitat loss, which constitutes a direct threat to biodiversity (Blaydes et al., 2021). In the local environment, concerns related to the changes in the microclimate, soils, or vegetation arise and for local communities, visual pollution starts to become a problem.

The significant increase in interest in these projects can potentially lead to land use competition, which can result from economic, social, or political conflicts in the future (Guoqing et al., 2021). To prevent further escalations, the solar energy sector will need to look out for solutions that counterbalance these concerns. In this sense, the solar energy generating companies could promote resource exchanges to create mutually beneficial relationships between them and other organizations that could mitigate some problems that have been raised with the solar parks' implementation.

One concept that reflects such relationships is industrial symbiosis, which aims to create synergies between different organizations to develop a system with resource exchange, e.g., materials, energy, or by-products. Its goals include using and sharing economic and natural resources increasing economic performance, reducing the environmental impact, and creating benefits for local communities (Al-Karkhi & Fadhel, 2020). IS networks can also lower inputs, increase resource productivity, and decrease the environmental impact while increasing economic growth and employment prospects.

[3] See https://ourworldindata.org/renewable-energy (accessed in October 2022)

Despite all the potential, the concept is still not widespread among companies and industries. Yet, to our knowledge, few assessments have explored these problems or the integration possibilities of IS and solar energy generation, particularly in Portugal. A major motivation for this study is the fact that solar energy is gaining more relevance in Portugal, given the number of hours of sun exposure that the country possesses. Year after year, the installed solar capacity and, subsequently, the PV production has been breaking records, and by February 2022, Portugal had produced for the first time more than 1 gigawatt (GW) per day (Expresso, 2022). One of the big projects that will contribute to the installed capacity in Portugal already in 2023 will be the Sines 4.0 project, led by Start Campus. This project will create a mega data center in Sines that will be supplied by PV power generation of about 1GW. This installed capacity will require several solar parks, which resurrect the aforementioned issues.

Hence, this master's thesis will aim to investigate viable possible symbioses for the Start Campus project with other industries or local communities to share mutually advantageous opportunities. Main specific objectives of the study are:

- How will it be possible to involve the community and industries with respect to solar energy production?
- How can the high costs of investment and the appropriate infrastructure development associated with solar energy production be balanced?

1.2. Structure

The structure of this dissertation is as follows:

- **Chapter 2**: A literature review starts by contextualizing how the energy sector has evolved over time and also focuses on the current situation using quantitative data, such as energy consumption and production. Next, the energy source under evaluation will be identified. Thereafter, fundamental concepts to understand the dissertation's objectives will be presented such as Industrial Ecology and Circular. This chapter closes with the most important concept of our dissertation, Industrial Symbiosis, alongside some international IS case studies with solar energy generation.
- **Chapter 3**: Methodology development for the discovery of new potential symbioses. This methodology involves a stakeholder analysis, followed by the identification of symbioses to our case study and ending with their analysis, considering benefits, drawbacks, drivers, and barriers.
- **Chapter 4**: Presentation of the case study succeeded by the application of the methodology to this described case study.
- **Chapter 5**: Discussion of the main results
- **Chapter 6**: Conclusions and recommendations

2. Literature Review

2.1. The Importance of Energy across times

One of the concepts that significantly impact the evolution of civilizations across time is energy. The term energy originates from the Ancient Greek *ergos*, which means work. Over the centuries, the energy matrix has evolved considerably. Energy, along with water and food, has become a crucial resource for human life since prehistoric humans. Mankind's first energy source was the sun, which provided light and heat. Later, a crucial source was discovered with the help of nature, through lightning strikes, which was fire. To use this source, it was essential to master the art of dominating fire. Humans perfected this art throughout time, and when combined with wood, the most abundant and easily accessible resource in that era, it was feasible to meet the basic needs of primitive humans such as heating, cooking, and other necessities (Zou et al., 2016).

The harnessing of water and wind power was the next breakthrough in the history of energy usage. Both marked the beginning of the Agricultural Revolution, which aided agricultural and livestock production. The application of wind in sailing was also critical for colonization and trade on the Mediterranean's borders, replacing rowing boats (Johansen, 2021).

Aside from it, the diversity of energy sources and patterns of use remained constant over the ages until the Industrial Revolution, which is considered one of the most important breaks in history. This revolution ushered in the transition from wood to coal and introduced three significant technological changes – (1) Mechanical devices replaced human skills; (2) Steam engines took the place of human and animal strength; and (3) Improvement in the acquisition and processing of raw materials, in the metallurgical and chemical industries (Landes, 1969).

By the end of the 19th century, coal accounted for half of the world's energy basket, due to European countries. Coal's energy share continued to grow until the 1930s, when other sources of energy, such as oil, began to gain importance.

Petroleum, derived from the Latin words *petra* (rock) and *oleum* (oil), is the most common fossil fuel, used to power vehicles, heating units, and machinery, as well as it can be transformed into plastics and other materials (Lim & Lee, 2020). As a result, the second major transition, from coal to oil, occurred, even though coal continues to be an alternative nowadays, but with less importance. Nowadays, the petroleum sector is immensely powerful and has a significant impact on global politics and the economy since most of the world relies on petroleum for many goods and services.

Nonetheless, in the early 1980s, the oil crisis, in which international oil prices quadrupled, and subsequent climate change concerns over the oil's exponential consumption, heralded a shift in energy patterns (Henriques & Borowiecki, 2014).

Both forced countries, particularly European countries, to diversify their energy mix, increasing the share of coal, natural gas, and nuclear power, but primarily to consider alternative solutions based on different renewable energy sources, such as solar, water, and wind, in which companies and governments have been heavily investing (Henriques & Borowiecki, 2014; Wüstenhagen & Menichetti, 2012).

Thus, we have entered the third significant transition, from oil to new energy sources, of which renewable energy, along with hydrogen, are elements. Hydrogen is the most abundant chemical element in nature, and it is a clean energy source that releases only water vapor and leaves no residues in the air, unlike coal and oil, yet consumes a significant amount of water. Taking into consideration its properties and the global economic decarbonization process, an aim established by all countries up to 2050, we are undoubtedly dealing with one of the future fuels.

With this historical outline, it becomes crucial to evaluate the current definition and organization of the energy sector, to respond to a constantly evolving globalization and technological progress, but most importantly to provide further context to the problem faced in this dissertation.

2.2. Energy Sector

The energy sector is an industry sector that includes companies and businesses engaged in the production and supply of energy. The Global Industry Classification Standard, a global classification standard used by thousands of market participants across all major groups involved in the investment process, was developed by Morgan Stanley Capital Investment and S&P Dow Jones Indices and provided an efficient investment tool to analyze the industry sectors. The energy sector was described as the companies that explore, produce, refine, market, store, and transport oil, gas, coal, and other consumable fuels (Szczygielski et al., 2021).

(Amador, 2010) further adds that energy is a basic input in all industrial processes and a significant component of household final consumption. As a result, structural aspects of energy production and consumption have a significant impact on most economic variables, encompassing several interconnected variables, from microeconomic issues related to regulation to macroeconomic effects on Gross Domestic Product (GDP), inflation, and current balance.

The energy sector is a dynamic and complex structure involving multiple organizations and agents that is constantly changing to respond to global and European challenges. As a result, numerous energy sources attempt to meet the world's demands while also addressing the aforementioned concerns. These sources, as well as their allocation, are shown below (Fig. 1):

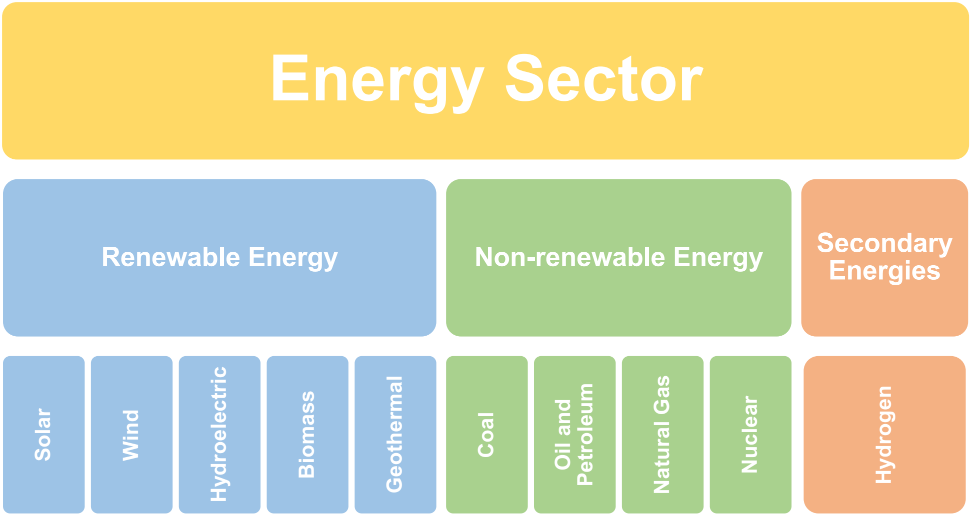

Figure 1: Energy Sector Structure (Adapted from U.S. Energy Information Administration 2021)

As is generally understood, not all countries have the same capabilities to generate energy. Each has different sources of energy available, based on the resources, but above all, depending on the investment provided by governments or companies. Each entity will always serve its interests, thus it will be its responsibility to decide how to best allocate the investment made or received, whether to produce more energy or import it. Consequently, in the following chapter, not only European and national distribution will be evaluated, but also consumption.

2.2.1. Portuguese and European Energy Sectors

The energy sector is today a critical pillar of every country's economy, both for people and businesses. However, as Henriques & Borowiecki (2014) state, the energy sector was not always this vital, and its evolution over time can be divided into two phases: before World War II and afterward.

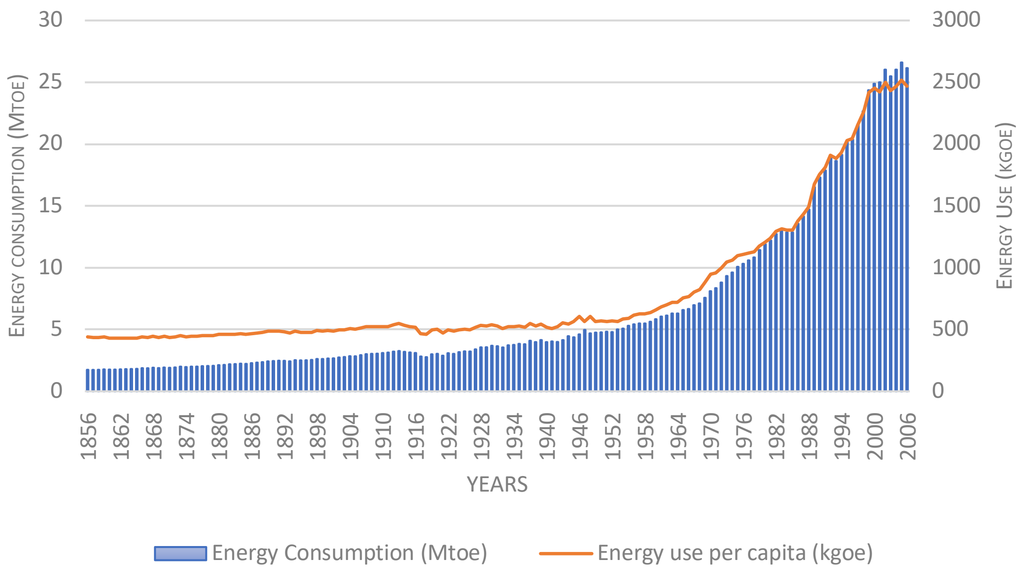

Figure 2: Energy Consumption and Energy Use per Capita in Portugal from 1856-2006 (Henriques, 2009 and DGEG)

This second phase is known across the world as the global expansion of modern energy, upon which many sectors and activities have come to rely. As it is possible to observe, the trend in energy consumption is similar to the trend in energy use per capita (Fig. 2). Until the end of World War II, energy consumption increased steadily in tandem with population expansion. In terms of energy consumption, it increased slightly until roughly 1945, indicating a growth factor of two from the beginning of the study. Energy consumption and energy use per capita increased dramatically in the post-war period, illustrating an exponential progression.

With these extremely high consumptions, one can deduce that society is heavily reliant on energy. These data will thus be examined in greater detail below, as well as the reasons behind them.

2.2.1.1. Energy Dependence

The energy dependence (ED) metric describes how much an economy relies on imports to meet its energy demands (Miguel et al., 2018). The indicator is determined by dividing net primary energy imports (Imports minus Exports) by the sum of gross energy consumption.

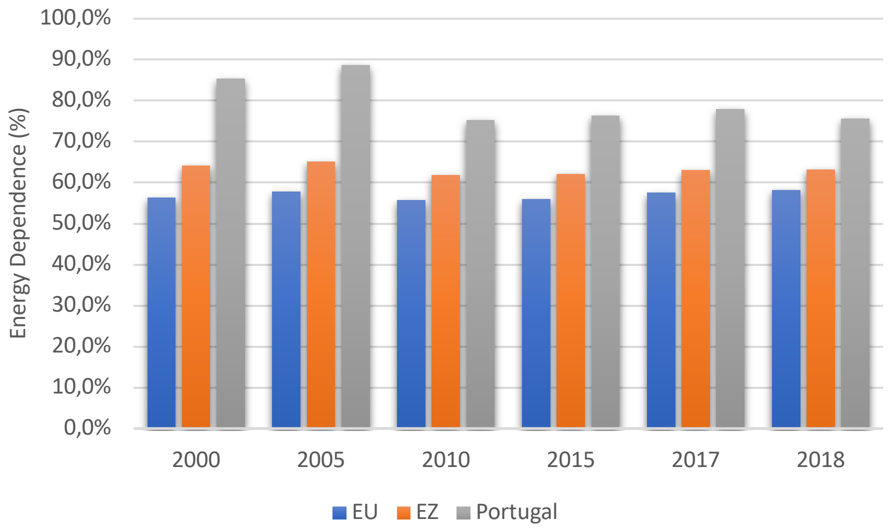

Figure 3: Energy Dependence in Europe (Eurostat 2020)

Figure 3 indicates that ED in the European Union (EU) and the Eurozone (EZ), consisting of 19 countries that use the Euro currency, has remained nearly constant over the previous 20 years, with fluctuations inferior to 5 percentage points. This is primarily due to the stable energy consumption of most countries of around 50-60%, and the countries that differ, end up counterbalancing each other, such as Belgium, with an ED of around 80% in 2018, and Romania, on the other hand, with 24% (Eurostat, 2020).

Portugal's behavior, in contrast, is highly distinct and atypical of the EU. Until 2005, Portugal's energy dependency was relatively high, at around 88%, until the government adopted a new strategy to solve this problem, later that year.

The National Energy Strategy outlined a series of actions to ensure energy supply, protect the environment and maintain economic competitiveness. Market liberalization, the promotion of renewable energy, and increased energy efficiency and innovation were considered crucial strategies to attain these goals (International Energy Agency, 2009). After five years of implementation, Portugal's energy dependency plummeted by 15% and it remained stagnant at roughly 75% in subsequent years. However, when compared to the EU average, this value is still relatively high and further policies should be enforced. To better understand which steps to take to reduce this indicator, its components must be thoroughly assessed.

2.2.1.2. Energy Production

Each country's energy production stimulates changes in ED. Production is highly reliant on natural resources and previous investments such as manufacturing facilities (e.g., dams or nuclear power plants) and it is on this premise that one may analyze the energy developments undertaken by various European countries (Amador, 2010).

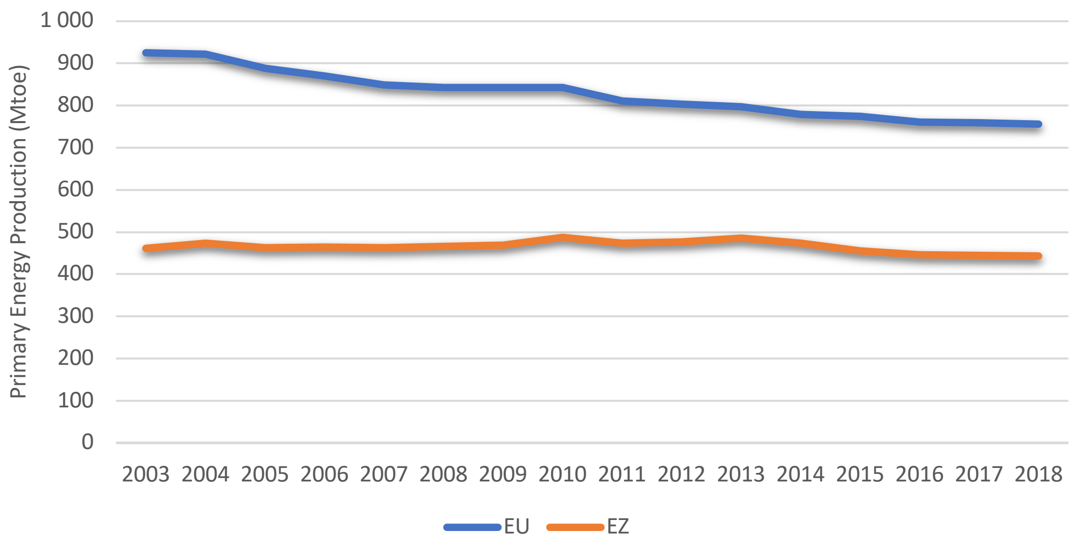

Figure 4: Primary Energy Production in Europe (Eurostat, 2010, 2020)

Focusing on figure 4, three distinct trajectories are identifiable. When data from 2003 to 2018 is evaluated, the EU demonstrated an 18% decrease in primary energy production. The trend in primary energy production in the EZ line has been stagnant over the previous years with just a 4% drop from the start of the 15 years to the end.

This decline in Europe was caused by a significant decrease in the production of solid fossil fuels, crude oil & other hydrocarbons, and natural gas, which totaled to around -21%, -26%, and -46% between 2010 and 2018, respectively (Eurostat, 2020).

2.2.1.3. Net Imports

Domestic production is insufficient to meet all the countries' energy requirements (Fedoseeva & Zeidan, 2018), except for a few countries which achieved energy self-sustainability such as Iceland and Brazil, thus imports play a critical role. By subtracting exports from imports, we obtain net imports, which will be used to compute the aforementioned energy dependency.

For example, as previously stated, not only Portugal, but the majority of Europe, is lacking in fossil fuels, particularly crude oil, and hence needs external supply. According to Eurostat (2020), EU Member States imported 508.4 million tonnes (Mt) of crude oil from third countries in 2018, with Russia representing 151,6 Mt, accounting for 30% of total crude oil imports to the EU.

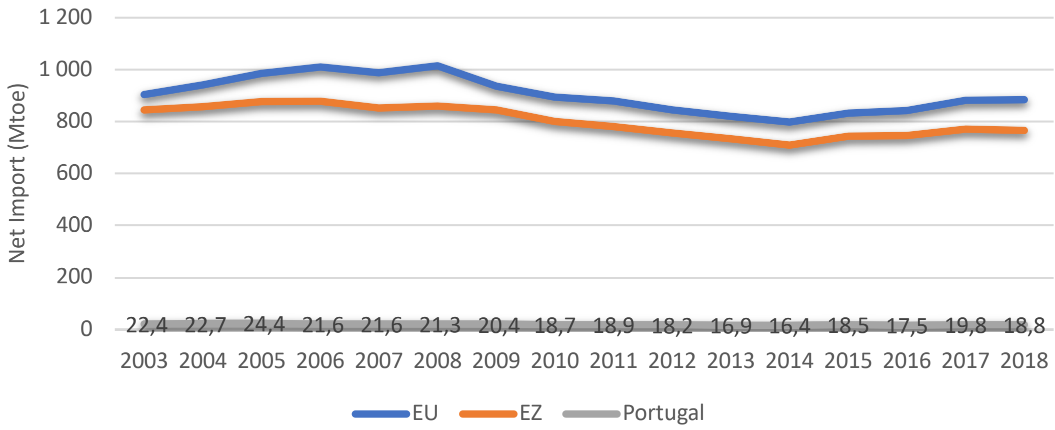

Figure 5: Net Import in Europe (Eurostat, 2010, 2020)

In 1990, Europe's energy imports were expanding dramatically, and so was the country's reliance on energy. It was then, in the late 2010s, that there was a surge in renewable energy supply, resulting in a decrease in energy imports, as shown in the figure above (Fig. 5). This decline occurred in Portugal a little earlier and, since then, the import of energy has been decreasing, though it is still high since fossil fuel still plays a big role (Fig. 6).

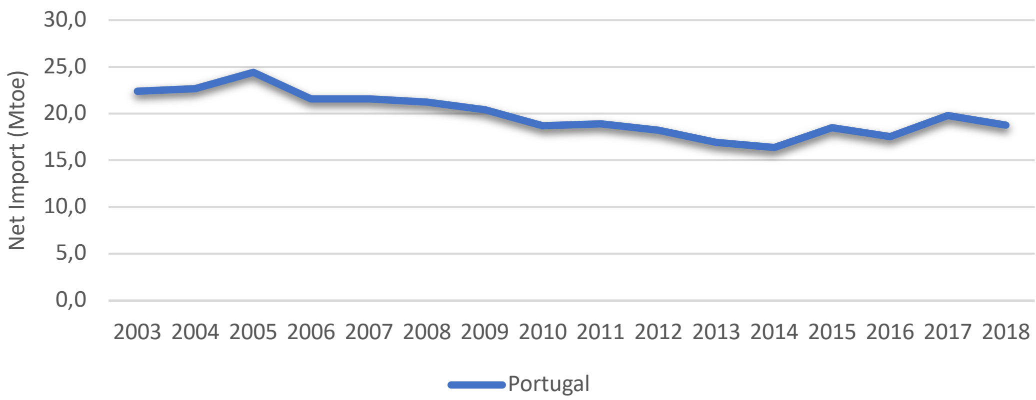

Figure 6: Net imports in Portugal (Eurostat, 2010, 2020)

Yet, in the last years addressed, it is conceivable to see an increase in imports due to an increase in global primary and final energy consumption, which will be assessed in the following section.

2.2.1.4. Energy Consumption

The second source of energy dependence is energy consumption. This can be classified into three categories: primary, energy products that come directly from sources (coal, oil, natural gas); secondary, referring to new forms of energy obtained by transformation processes of primary energy (Refining of crude oil acquiring gasoline and diesel) (Hitchin, 2019); and final, which *Eurostat* claims "Final energy consumption refers to what end-users consume." Bearing this in mind, the final energy consumption is obtained through the following equation (Eq. 1):

$$Final\ Energy\ Consumption\ =\ PEC\ -\ NFE\ -\ CES - CRM$$

Equation 1: Final Energy Consumption

where

PEC = Primary Energy Consumption

NFE = Consumption for new forms of Energy (achieved through transformation, i.e., Cogeneration, Electricity)

CES = Consumption within the Energy Sector (Refining; power stations; coal, oil, and natural gas extraction)

CRM = Consumption as Raw Materials.

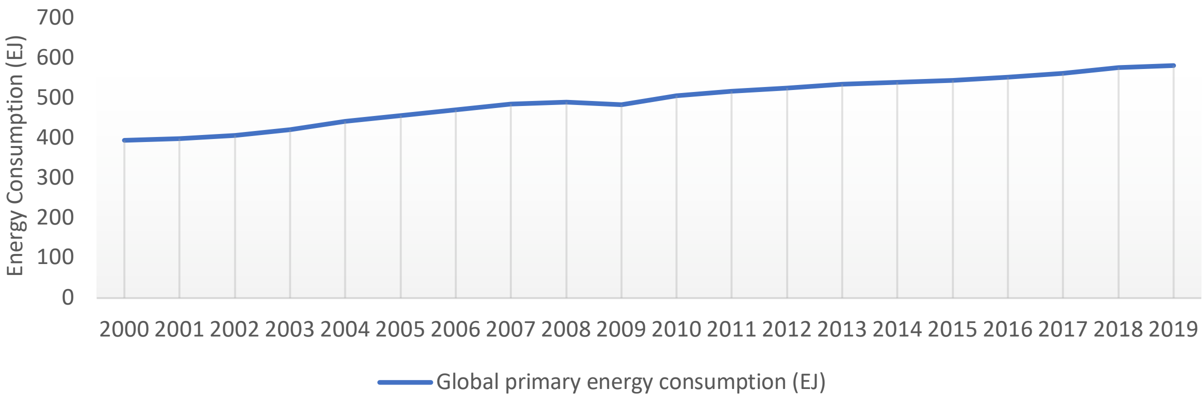

Figure 7: Global Primary Energy Consumption (Statista 2021)

Since 2000, primary energy consumption has followed the same pattern, i.e., consistent annual growth of roughly 2%, except for 2009, when consumption decreased (Fig. 7). This drop was largely caused by the global economic crisis, which began in the United States due to the housing crisis and swiftly moved to the banking sector, resulting in a snowball effect with global repercussions at all levels. The price of the oil barrel was mostly affected.

As previously stated, the world is still heavily reliant on fossil fuels and this crisis has substantially helped oil-exporting countries, as the price of a barrel in 2000 was approximately \$25, reaching \$148 in July 2008, the peak of the crisis (Ali Bekhet & Yasmin, 2014).

According to Figure 8, the transportation sector has the greatest economic weight, i.e., it consumes the most final energy. Within this sector, motor vehicles spend the most, accounting for almost 93% of total consumption, emphasizing once again how dependent Europe is on oil.

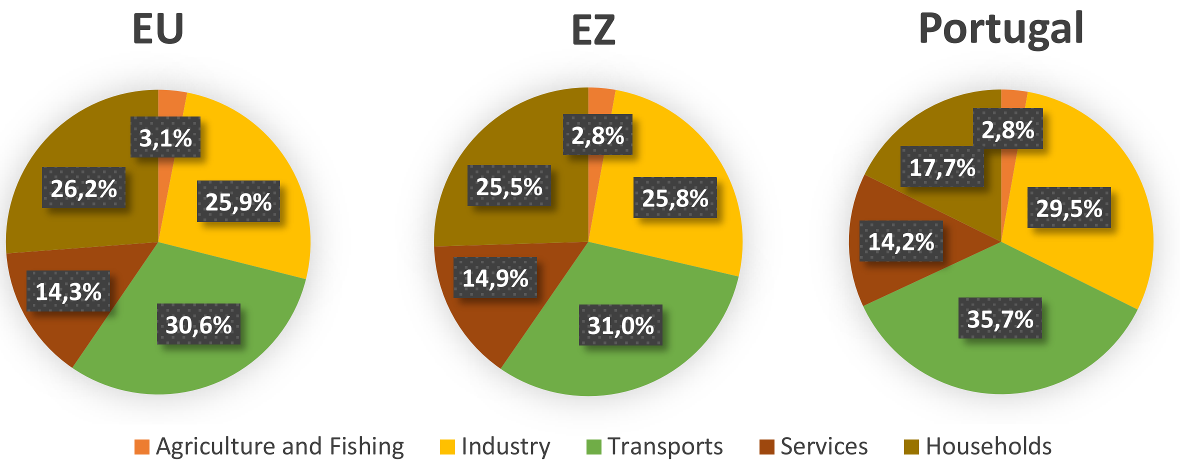

Figure 8: Final Energy Consumption per Sector in 2018 (Adapted from Eurostat 2020)

Even more alarming is the excessive usage of this resource and vehicles, which release CO_2 emissions into the atmosphere, contributing to the environmental crisis the world currently faces.

Henriques (2011) argues in favor of reducing energy consumption, which can be accomplished by changing the relationship between energy and economic growth, turning it more efficient, and shifting the energy basket's composition to sources with lower greenhouse gas emissions, such as moving from coal or oil to natural gas, renewable or nuclear energy.

Our focus will shift to one of the previously discussed alternatives, solar energy due to its growth potential over the last years and the maturity reached in the exploitation of the other two major sources, wind energy, and hydropower. Investing in solar energy could be an option to reverse the energy distribution at a global level, considering that it is one of the world's most abundant energy resources and serve the adjacent industries or communities in various ways, creating a mutually beneficial environment. Thus, this energy source will serve as a framework for this dissertation's studies on industrial or community symbioses.

2.2.2. Solar Energy

Solar energy is obtained from light and heat by the world's principal source of energy, the sun. It can be used as a clean source of heat and electricity and is considered a key solution in combating the current climate crisis and lowering the world´s fossil fuel dependency. As for its production, solar energy can be harnessed in three possible ways: passive heat, solar thermal, and photovoltaic.

The first method is through passive heat. This strategy is mostly used in the construction of houses, where it is critical to ensure that certain conditions are fulfilled for the occupants. To ensure that the ideal circumstances for absorbing the heat of the sun are in place, two elements must be considered: the layout/location of the building and the quality of the materials used. These are crucial for the implementation of zero-energy buildings. They consume minimum energy to operate since they rely on solar energy to provide indoor thermal comfort without the use of electricity or mechanical equipment (Omrany et al., 2016).

Another benefit of these constructions is their significant contribution to global climate change mitigation, as they improve building energy efficiency and reduce overall building energy consumption, minimizing carbon emissions. On the other hand, reliability is a drawback due to the entire dependence on the weather. Even though most of these systems are designed to maximize heating even with the smallest exposure, one cannot escape bad weather. However, the major concern would be the cost, since a redesigning or replacement of the rooms/walls of the building must take place, not to mention that these systems must have high-efficiency rates and otherwise will suffer from the aforementioned disadvantage (Gong et al., 2022).

The second is solar thermal energy, which is used as a source of energy both in the residential and industrial sectors, where it is converted into mechanical energy and then into electrical energy. The equipment used to do this exchange is solar collectors, which convert solar radiation energy into heat. The sun's rays are concentrated in a receiver, which may reach temperatures of up to 1000°C. Depending on the collector's classification, this heat can be used in a range of methods (Peng et al., 2022):

- Low-temperature collectors – Most commonly used to heat swimming pools or ventilated spaces
- Medium-temperature collectors – Used to heat water or air for both domestic and commercial applications.
- High-temperature collectors – Use mirrors or lenses to concentrate sunlight and are utilized in businesses to meet certain heat requirements as well as for electric power generation (Industry applications)

Solar thermal has been used for a long time over the world, making it a mature technology. On the other hand, these systems are still promoted as a good investment due to their "sustainability, maturity, resource and technology availability, reliability, and low maintenance costs" (Virgílio & Robalo, 2009). Furthermore, the cost of these systems has been steadily reducing over time, and payback times are now far below the system's lifetime, rendering them a very appealing and safe option for both household and industrial use.

Finally, PV energy is generated by PV panels. The sunlight emits photons onto a panel, and it absorbs this energy from the PV cells inside.

This energy drives electricity to flow by forcing electrical charges to shift in response to an internal electric field in the cell. On cloudy days, this technique can also generate electricity. Slightly cloudy days can produce better energy yields than days with a perfectly cloudless sky due to sunlight reflection. The flow of electricity is generally proportional to the intensity of light, meaning more absorption results in higher electricity generated. The PV system's construction and functioning are depicted in the image below.

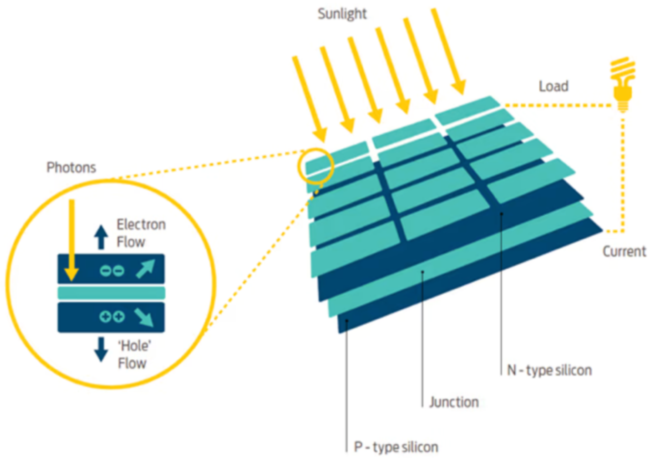

Figure 9: Constitution of a Solar panel (Adapted from Good Energy 2022)

The PV cells form the basic building blocks of the unit and are sandwiched between layers of semiconducting materials such as silicon. When photons strike each layer, they activate them, causing an electric field to form. The photoelectric effect is what generates the current required to produce electricity. Direct current (DC) electricity is the type of electricity collected by PV panels. The DC electricity is subsequently transformed into alternating current (AC) electricity via an inverter. This AC electricity is usable and can be used to power your home, car, or be supplied to the power grid.

When it comes to solar cell performance, it's measured in terms of how well it converts sunlight into energy, meaning its efficiency. According to theoretical results, PV panels have a maximum energy efficiency of only 29%, and commercial products only 26%. As a result, efficiency is the most important consideration when installing a PV system. According to Topić et al. (2017), the efficiency of a PV system is influenced by six factors: solar wire, temperature, shade, charge controller, inverter, and battery. To ensure maximum efficiency, these six criteria must be carefully considered when constructing a PV system.

1. Solar wires – PV systems produce a DC voltage of 12-48V. Using the incorrect solar wire could result in the electrical devices failing to power up or the battery bank failing to charge fully. In addition, if the cable is connected backward, the inverter's output may be harmed because it will be unable to determine whether there is enough electricity coming from the generator to power your home (Gan et al., 2014; He et al., 2021).

2. Temperature – More sun rays equal a higher temperature, and this temperature influences the PV panel's effectiveness despite its necessity for a certain amount of sunshine. A PV panel's optimum temperature is 300K and when it exceeds it, the panel output is lowered by 0.25%. A cooling system, either passive or active, is then used to prevent overheating of the solar panel (Dubey et al., 2013)
3. Shade – The output power is immediately affected when something rises above the panel (shading). Shading might be temporary, or it can build up over time, like dust accumulation, thus cleaning the panel regularly and installing it without any permanent shade from trees or buildings in the surroundings can be a solution.
4. Charge controller and battery – Off-grid and on-grid PV systems are the two forms of PV system connections. The term "off-grid" refers to a PV system that generates electricity without the help of other grid utilities. In this situation, the system will require a battery and charge controller to power the load without experiencing any power shortages during overcast days while also conserving energy produced during the day. On the other hand, an on-grid connection does not need any battery and charge controller since it is linked to the grid utility.
5. Inverter – As previously stated, PV systems provide DC voltage, while most consumer loads are powered by AC. As a result, an inverter is required, but its efficiency is less than 100%, resulting in energy losses.

After covering the various methods of capturing solar energy, this dissertation will examine the PV market in greater depth, as it searches for possible synergies.

2.2.2.1. PV Market in Europe

In Europe and worldwide, photovoltaics and renewable energies are increasing at a considerably higher rate than the rest of the economy. This, combined with large spikes in oil prices in 2005 (stated in Section 2.2.1.4), has resulted in a significant restructuring of the renewable energy sector by governmental and financial institutions. Even though there are still disagreements worldwide on how to address climate change, renewable energy will play a critical role in it, since it has been fueled by the implementation of various supporting agreements, regulations, policies, and strategies (Jäger-Waldau, 2007).

In terms of strategies, according to Dusonchet & Telaretti (2015), the PV industry has sought to close the gap between the cost of PV energy and the cost of energy from conventional sources. PV energy costs have decreased because of the implementation of support programs, but it remains uncompetitive and requires proper support mechanisms, simple grid connection procedures, and other factors.

The EU has already taken some steps to boost renewable energy sources (RES) by developing a new framework. The Renewable Energy Directive - Directive 2009/28/EC (EU, 2008) - establishes a target for each EU member for 2020, based on the share of RES in gross final consumption. The proposed objective is a 20% reduction in primary energy consumption and GHG emissions, as well as a 20% increase in renewable energy consumption. However, the Commission has already modified this directive twice, in 2019 and 2021, by raising the 2030 aim to 32% and 40%, respectively (EU, 2018).

PV is one of the most appealing renewable energy sources accessible today for its potential, which is already evident in its contribution to the share of renewable energy. As it stands in the graph below (Fig. 10), PV energy is currently the third most productive RES with the biggest growth aside from wind energy.

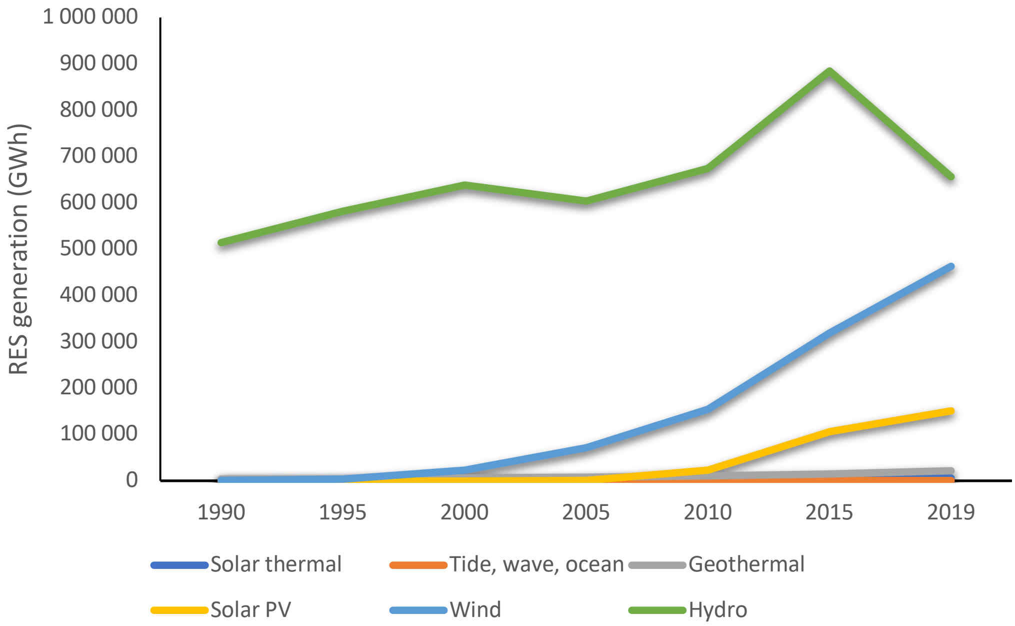

Figure 10: Renewable Energy Generation by Source in Europe (IEA 2022)

Considering that the cost to build or purchase solar panels for the end customer is quite high compared to the power generated, the construction of numerous solar farms is the driver of the growth shown in figure 9. Despite similar challenges to those described previously, these projects are still in high demand, therefore the costs versus the advantages will be analyzed in the next chapter.

2.2.2.2. Solar farms

Solar farms on a large scale are increasingly being built worldwide to produce renewable energy. Also called solar parks or photovoltaic power stations, solar farms are a large collection of photovoltaic solar panels as described in the previous chapter. These provide electricity to the power grid, which is then distributed to end consumers. Depending on the scale, this power can be collected and delivered in two ways.

First, utility-scale solar farms refer to vast swaths of land covered with hundreds of solar panels, which generate electric current and distribute it via high-voltage power lines, before arriving at the consumer's house (Glick et al., 2020). Utility-scale solar can generate, on average, more than 20 MW and most of these facilities run on power purchase agreements (PPA), in which firms agree to buy a certain quantity of electricity from a utility or a generator. Solar tax equity investments are another alternative, which, while rare as they can only be found in the US in certain states, are just as beneficial as other corporate solutions. It entails investing in specialized solar projects that have a dual benefit – they acquire green power in the form of Solar Renewable Energy Credits while also assisting in the development of local solar energy infrastructure (Lee et al., 2017).

The other project is community solar farms, which are small-scale solar projects that generate power up to 5 MW for local communities or businesses. Participants in this type of program, in this case, residents of the community, invest in or subscribe to a specific amount of kW capacity or kWh generation. Afterward, the project's power output is credited to investors in proportion to their investment, with adjustments to account for ongoing changes in technology, capacity, electricity rates, and costs. The distances that the generated power covers are the most significant distinction between utility-scale and community solar projects. Since community solar farms generate power for nearby homes, the likelihood of these households losing power if the grid goes down is significantly smaller than for residences served by utility-scale solar farms, given the lengths of the grid this power must travel.

In addition, to determine what kind of project is moving forward, additional factors must be accounted for rather than just scale. The decision must be strategic considering the timeframe – short, medium, or long term – and balancing the benefits with the disadvantages to obtain an advantageous project. Thus, a more in-depth evaluation will be performed to see what influences the choice of a solar farm project.

A general law for all types of businesses is that no company or organization is in the business of losing money. Since solar farm projects head in the same direction, one of the most, if not the most important factors that need to be considered is the investment cost. To assess whether the project will be profitable, it must be less than the revenue generated or at least provide more benefits than concerns. However, according to Sodhi et al. (2022), various variables affect this cost, including:

- Size
- Type of panel
- Location/Land to use
- Installation process

Several parameters that will have an impact both at the start of the project and throughout must be taken into consideration when evaluating the solar farm that will be built. Starting with the solar farm's size, it is assumed that the larger the installed system the greater the investment cost. Nevertheless, to note that one benefit that can be drawn from this is that the larger it is, the faster the return will be (Brodziński et al., 2021).

The second characteristic is the type of panel to be installed, i.e., the type of material it is made of. Most fall into one of three categories: monocrystalline, polycrystalline, and thin film. In general, the difference between them lies in their efficiency, weight, high-temperature capability, and above all cost, as seen in Table 1 (Badawy et al., 2022; Mirzaei & Mohiabadi, 2017).

	Monocrystalline	Polycrystalline	Thin film
Efficiency	An average conversion rate of 20%. Highest efficiency panel in the industry with the new generation of panels reaching up to 22% efficiency rate.	The efficiency rate is normally between 15% - 17%.	Lowest efficiency among the 3 types, typically below 15%.
Weight	Negligible difference to polycrystalline PV panels.	Negligible difference to monocrystalline PV panels.	Lightest material amongst them as its thickness is quite thin.
High-temperature capability	Most resistant to high temperatures and they almost do not affect the panel's productivity.	Not very resistant as the high temperatures not only affect their productivity but also their durability.	Small impact on productivity but is inferior to the polycrystalline PV panels.
Cost	Most expensive type of solar panel.	Intermediate price, possessing a good balanced cost and efficiency ratio.	Lowest material price in the market.

Table 1: Comparison between types of PV panels

Third, the strategic location of the solar farm can be considered the prime concern since it is necessary to deploy sizable solar farms at suitable sites. The determination of feasible geographical sites for the implementation of solar parks is influenced not only by the number of solar hours the PV panels capture but also by other factors.

To corroborate this statement, different analyses of the location selection in Europe were accounted for. There are a variety of methods that can be used to determine a suitable solar farm location since a lot of intricacies and uncertainties are involved and the decision-making is still being made by human judgment depending on the case. Thus, Multi-Criteria Decision-Making is being mostly applied in the solar energy literature where the Analytic Hierarchy Process handles the weighting of each factor and the Threat-Oriented Person Screening Integrated System normalizes each criterion to discover the optimal solution, in this case, location.

Reference	Country	Parameters
(Finn & McKenzie, 2020)	Northern Ireland	PV potential, slope, and aspect of the location
(Uyan, 2013)	Turkey	Land use and distance to transmission lines
(Sánchez-Lozano et al., 2016)	Spain	Distance to cities, power lines, and electricity transformer substations
(Palmer et al., 2019)	United Kingdom	Land use, distance to the grid, and slope

Table 2: Most important parameters for a PV farm location selection

To sum up, land use, slope and distance are the most crucial aspects to select a location. Land use management helps to regulate how much land is allotted for specific applications and ensures that these resources are used as effectively as possible while minimizing negative consequences, which can be critical for the solar farms' sustainability. The distance to the grid is a typical cost-effectiveness criterion used in PV solar farm projects and the slope affects the hours of sun incidence on the solar panel, which is one of the most vital factors in the project considering fewer hours of sun equals less solar energy generation, meaning generally lower yields.

As a result, as can be observed from these papers and scientific articles, selecting a location is difficult since all these factors have implications economically or environmentally not only for the organizations that might proceed with such projects but also for society.

Last but not least, the installation process is not negligible, and thus must be observed. This factor represents all extra expenses related to the easiness of installation. This includes labor costs, which are affected by other elements already described here, such as location – the hourly rate of workers depends on the site they are working on (could just be country-related) or size – in case of a project with more solar panels, more labor will be needed. Another expense could be the installation or use of additional components while installing the PV panels that are not accounted for at the beginning which might affect the installation costs.

All in all, it is common knowledge that solar power plants have high installation costs, yet due to the learning curve over the past years, these costs have been declining (Sharma, 2011). Corroborating this statement is a report made by the International Renewable Energy Agency (IRENA), where it can be observed that the total installed cost in selected countries in Europe has dramatically declined from 2010 onwards (Fig. 11).

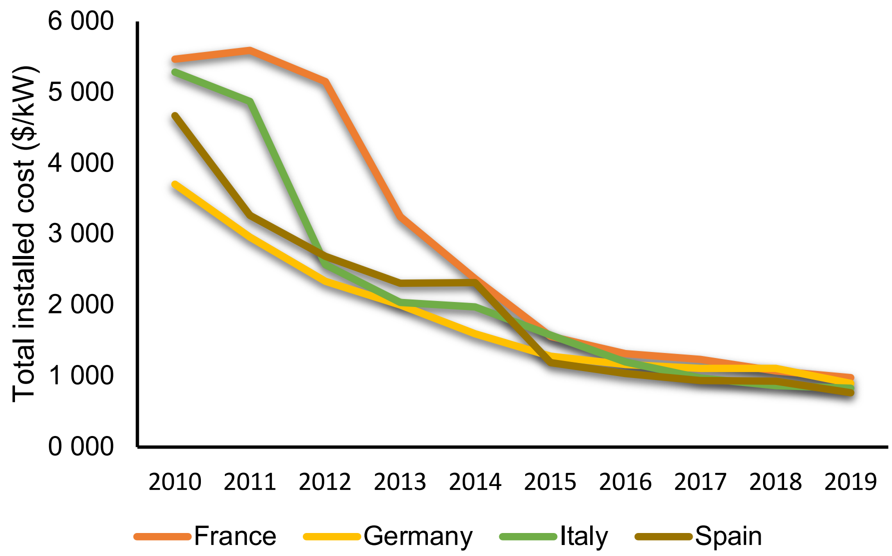

Figure 11: Utility-scale solar PV total installed cost in selected countries in Europe, 2010-2019 (IRENA)

This downward trend has several causes including government financial incentives or credits granted by governments throughout time to increase the bet on this source of energy. Economies of scale have also been a factor allowing lower costs in the construction of solar panels.

In addition, there is one highly significant indicator, which constitutes the basis for evaluating such a project, namely the energy payback time (EPBT). It serves not only as an indicator of solar panels' long-term viability but also as a measure of how fast a power-generating system can produce the amount of energy equivalent to the amount used in the system's production.

In the past couple of years, the EPBT has been decreasing drastically due to the improved production technology that has been influenced by the materials used in the system, the solar cell efficiency, and the location and related irradiation (Fraunhofer Institute for Solar Energy Systems & PSE Projects GmbH, 2022).

In terms of materials, the thickness of silicon wafers has been steadily lowering, leading to lower silicon usage and, as a result, lower solar cell costs. The power generated is influenced by the efficiency of the solar cells, since the higher the efficiency, the more power generated and the shorter the EPBT. Finally, solar irradiation enables the panel to absorb more sun rays if it is exposed for longer periods.

Thus, Gerbinet et al. (2014) outline multiple life cycle assessment studies for various types of solar panels undertaken in numerous countries and conclude that the average EPBT is two to four years but varies between 1.45 (Bayod-Rújula et al., 2011) and 7.4 years (Pacca et al., 2007). With this in perspective, this is one of the most compelling arguments in favor of adopting solar panels considering each PV panel has a 25-year lifespan, ensuring 80 percent of its original performance.

Furthermore, the product's end-of-life (EoL) must be taken into consideration since it is indirectly tied to the previous factor. Given the intricacy of a solar panel, it takes some maintenance, and when it's time to replace it, the recycling choices must be evaluated, since they can produce additional revenue, benefit other industries or society, or most importantly contribute to sustainability. Currently, each type of solar panel requires a distinct method of recycling. The silicon-based PV panel is the most common approach since they account for over 95% of the PV market, thus the main effort should be recycling crystalline and not thin-film-based PV panels. Disassembly, cable treatment, incineration, glass separation, grinding, sieving, and filtering are a few of the phases in the recycling process, but they carry a cost to the environment as well as the economy-wise. However, as Majewski et al. (2021) point out, this is a bulk procedure because 95% of the glass can be recycled and all external metal components may be utilized to make new cell frames.

All aspects related to the products' EoL have been a hot topic nowadays due to the increase of waste and pollution around the world leading to global warming. Different ideas and concepts have developed throughout the years, and their major objective is to minimize some of the previously mentioned issues. Thus, in the next chapter, we will deeper investigate some of these concepts, namely Industrial Ecology (IE), Circular Economy (CE), and Industrial Symbiosis (IS).

2.3. Industrial Ecology and Circular Economy

Starting with Industrial Ecology, began to gain relevance in the early 1990s since concerns about the effects of industrial activity on the environment were raised. Due to the rapid growth of this scientific topic, many authors and writers have tried to define the concept to the best of their abilities. Ehrenfeld & Gertler (1997) and Erkman (1997) claim IE is a field that designs industrial systems using the ecosystem as an example, to minimize their environmental impact by closing energy and resource loops. Kapur & Graedel (2004) states that "IE is how humanity can deliberately and rationally approach and maintain sustainability, given continued, economic, cultural, and technological evolution" and demands that the ecosystem should be seen in harmony with its surrounding systems rather than in isolation from them. El-Haggar (2007) expresses that "the ultimate goal of IE is to achieve sustainable development that will eventually lead to achieving compliance with the environmental regulations aimed at protecting the environment".

Another important view is, according to Harris & Pritchard (2004), that IE can function at different levels of scale - the facility level, the interfirm level, or the regional/ global level.

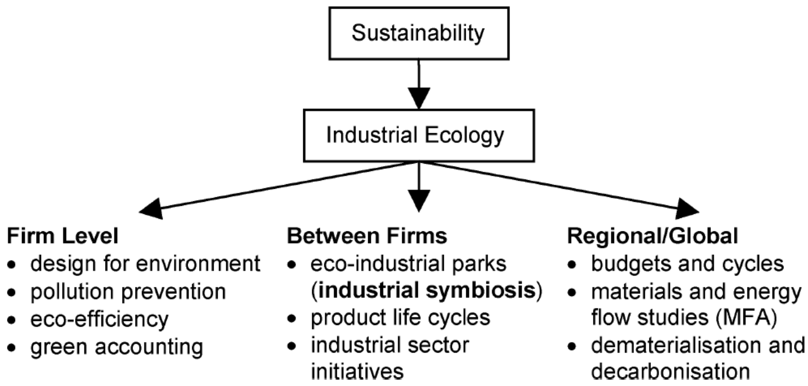

Figure 12: Elements of IE at different levels (Harris & Pritchard, 2004)

Important to highlight here is the interfirm level which is largely seen as the path to industrial ecology due to the forming of product life cycles and eco-industrial parks, which possess industrial symbiosis networks (Harris & Pritchard, 2004). At this level is where we can link to the other concept, namely circular economy since nowadays it is one of the most used processes/models to define a product life cycle.

The term circular economy resembles a circle in its process since it encourages the recycling of resources and energy flows within the economy. It can also be characterized as an economic strategy as it seeks to transform the current idea – the linear model (Fig. 13) called “take-make-dispose” (Puig, 2019).

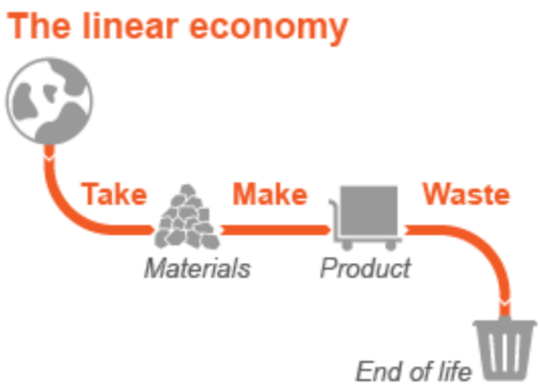

Figure 13: Linear economy model (Puig, 2019)

This industrial process in a linear economy is defined by a unidirectional material flow, where raw resources are converted into finished goods and then disposable waste (Elia et al., 2017). On the other side, a circular economy can be defined as turning goods “that are at the end of their service life into resources for others, closing loops in industrial ecosystems and minimizing waste” (Stahel, 2016). This process would change economic logic as it substitutes production with sufficiency, which Stahel (2016) classified as: “reuse what you can, recycle what cannot be reused, repair what is broken, (and) remanufacture what cannot be repaired”.

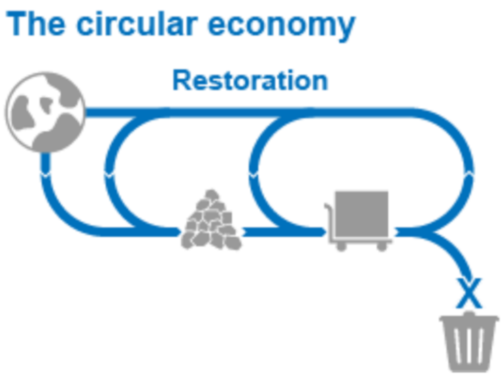

Figure 14: Circular economy model (Puig, 2019)

Figure 14 is a visual representation of Stahel (2016) statement, where the model values efficiency in the usage of resources and materials, thus reducing environmental pollution and promoting economic growth.

For a deeper understanding, Morseletto (2020) identifies different targets defined by organizations to achieve a CE. Figure 15 exemplifies the five main groups of application: efficiency, recycle, recovery, reduction, and design. Moreover, these areas are not independent due to their high level of interconnections which is displayed in the figure below by multiple overlaps among the different cycles.

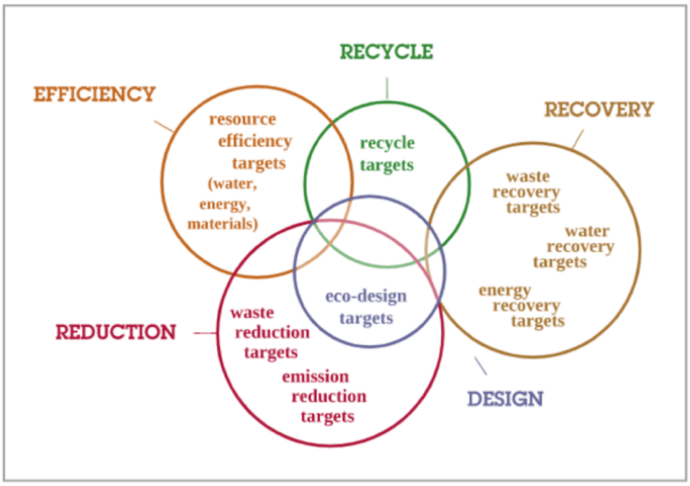

Figure 15: Main existing CE targets by areas of application (Morseletto 2020)

To further analyse CE targets, the framework presented by (Potting et al., 2017) contains 10 existing CE strategies, known as R-strategies, to reduce resource and material consumption in product chains and increase the circularity of the economy (Fig. 16). The fundamental way that R-lists differ from one another is in how many circularity strategies they provide. Usually, they offer a variety of tactics arranged from high circularity (low R-number) to low circularity (high R-number).

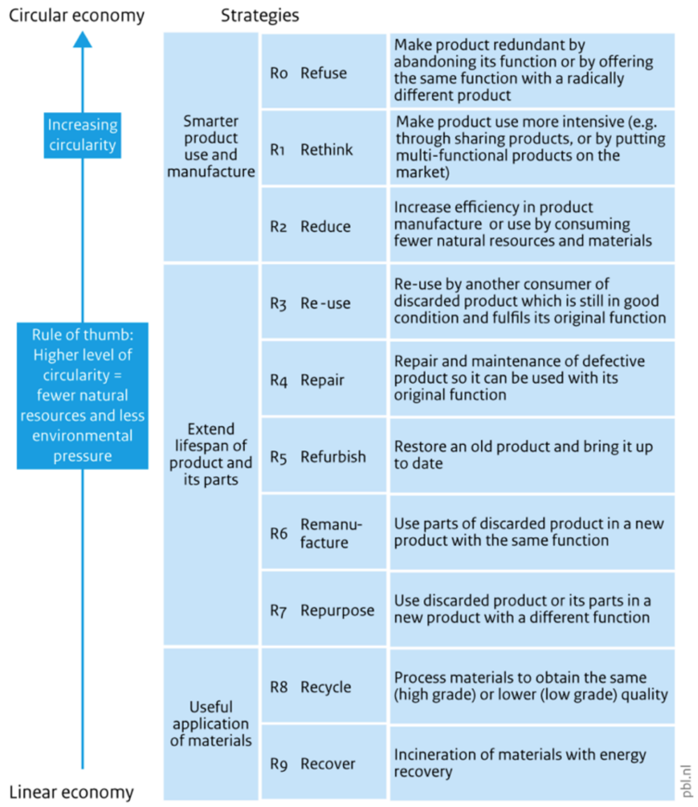

Figure 16: CE strategies, from (Potting et al., 2017)

As seen, this model is currently a popular concept due to its large areas of application and different strategies, which are still emerging and gaining traction among academics, businesses, and policymakers (Korhonen et al., 2018). Due to this popularity, IE has also found itself in the spotlight again, due to its similarities with CE. These similarities have ignited a lively debate among academics, whether through opposing scientific articles (Bruel et al., 2019; Saavedra et al., 2018) or using the internet discussion forum ResearchGate to figure out if they are truly the same concept. Saidani et al. (2020) and Baldassarre et al. (2019) studied the relation thoroughly and came to the following similarities, complementarities, and differences:

Similarities:

- The concept of “industrial symbiosis” is widely present in both perspectives, even though it is viewed differently from both sides
- Closing energy and material loops are the foundation of both IE and CE, which aims to make reducing industries' environmental effects economically appealing.

Complementarities:

- Without IE concepts and tools, the development of CE would not be conceivable.
- In order to further develop the CE concept towards widespread adoption and alignment with sustainable development, we would need to revisit the economic and social theories established by IE.

Differences:

- IE perspective explains how a cluster develops through time and how it affects the economy, environment, and society, while the CE perspective clarifies how a cluster operates from a business aspect in the operating phase.
- Requirement of a global approach to achieve the overall objectives of a CE, while on the other hand, a more local approach is needed for the realization of the IE objectives.
- The CE approach offers a solid grasp of economic logic but does not focus on the systemic behavior of IE, whereas the IE perspective offers a good understanding of how IS arises but pays little attention to the role of economic logic in symbiotic interaction (e.g., “the role of path dependencies and lock-in in the development of IS”)
- IE defines IS as a “dynamic process based on the cooperative interaction of separate business entities exchanging materials, energy, water, by-products, services and infrastructures to achieve competitive advantage”. On the other, CE identifies IS as a circular business model, which is inserted within the CE strategic framework to reach one of its main groups of application – Reduction.

This being said, the concept of IS lies at the heart of this discussion, thus we shall examine it in greater detail.

2.4. Industrial Symbiosis

Taking the background from the previous chapter 2.3 into consideration, one way to define IS is the “adoption of a collective approach between companies, in which materials, energy, water, or by-products are exchanged and incorporated into business processes” (Schlüter et al., 2020). Another way to explain IS relates to the purposes the outputs can be used for. Instead of redirecting these products to business products, they can serve as inputs for the surrounding communities, without forgetting the main goal, where the exchange must result in mutual economic and/or environmental benefits.

The concept of biological symbiotic interactions in nature, in which at least two otherwise unrelated organisms exchange materials, energy, or information in a mutually beneficial way is the foundation of the term "symbiosis". Researchers have examined IS from three main angles: characterization of the circumstances in which complexes of industrial symbiosis emerge, the exchange relationships that support their growth, and the advantages that benefit the participating industries. Therefore, cooperation between enterprises is a requirement for an industrial symbiosis complex, which will lead to the establishment of a network (Zhang et al., 2008).

An IS coordination network is often understood as entities like government agencies, environmental services providers, academic institutions, or individuals who collaborate to support inter-firm IS activities in a region (Q. Wang et al., 2017).

Furthermore, the concept of IS network considered by Q. Wang et al. (2017) is divided into two possible cooperation strategies. IS facilitation indicates working with a third-party organization whereas IS coordination refers to the participation of numerous organizations and governmental entities in the IS process.

There are numerous networks worldwide that frequently share resources and infrastructure, trade waste products, and work together on environmental projects such as in Kalundborg, Denmark (Grant et al., 2010). Kalundborg is known internationally as the most popular industrial symbiosis (Lehtoranta et al., 2011) and has been studied by many researchers over the years. Not only it is the origin of the term "industrial symbiosis" but understanding the Kalundborg system is a critical factor in industrial ecology (M. Chertow & Ehrenfeld, 2012). The emergence of industrial symbiosis in Kalundborg has been characterized as an evolutionary process where a variety of separate by-product exchanges have progressively developed into a complex web of symbiotic connections between five collocated enterprises and the local town. A power plant, an oil refinery, a biotech and pharmaceutical company, a manufacturer of plasterboard, and a soil remediation company are the businesses involved in the industrial symbiosis (Jacobsen, 2006).

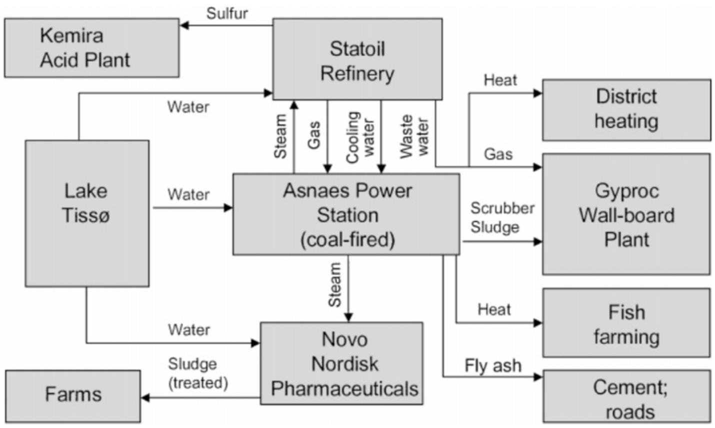

Figure 17: Industrial symbiosis at Kalundborg (M. R. Chertow, 2000)

Kalundborg exchanges a range of residues that are used as feedstocks in other processes as well as exchanges groundwater, surface water, wastewater, steam, and energy (Fig. 17). About 2.9 million tons of material are exchanged in waste alone every year. Together, water use has been decreased by 25%, and district heating is now available to 5000 houses. This kind of cooperation, which involves sharing employees, equipment, and information, has greatly improved environmental and economic efficiency (M. R. Chertow, 2000). Indeed, the term industrial symbiosis was first created to describe the network of connected companies in this town and that over three decades spontaneously evolved a system of by-product exchanges using collaboration (Zhu et al., 2007). Kalundborg is an example of how the emergence of IS can be triggered and further developed by a dynamic process of government and corporate initiatives (Vodã, 2018).

Moreover, other ideas followed Kalundborg that are working on the implementation of IS. A very similar project is Aalborg East, where several key stakeholders had an ambitious collaboration to promote sustainability over several years. This project involves the Aalborg Municipality, Aalborg Forsyning (Utilities), RenoNord, Aalborg University, and the Port of Aalborg, to make Aalborg East a cornerstone in the sustainable synergies and industrial symbiosis projects (Kørnøv et al., 2020).

An example within this project is the industrial symbiosis established between the Port of Aalborg and the Nordjyllands power station, one of the companies in Aalborg Utilities (Fig. 18).

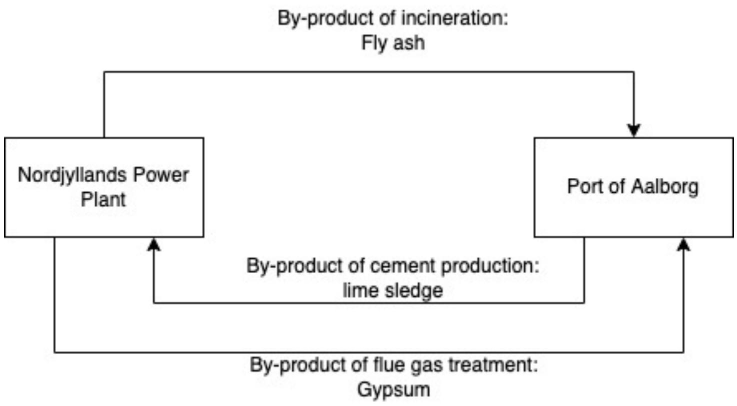

Figure 18: Industrial symbiosis at Aalborg East (Mortensen & Nors, 2020)

The symbiosis starts to develop when fly ash, a by-product of the power plant's incineration, is supplied to the Port of Aalborg. Instead of transferring this by-product to a landfill, it is utilized in its cement manufacture. Afterward, a second two-way symbiosis occurs when the Nordjyllands Power Plant receives lime sludge from Aalborg Portland, a waste product of cement production, and they in turn send gypsum back to them. At Nordjyllands Power Station, the lime sludge is used to treat flue gas, which produces gypsum of a high enough quality to be used in cement production at Aalborg Portland (Fig. 18).

This symbiosis is just one of the dozens created within the Aalborg East project, where it was possible to obtain significant environmental savings. “The whole project achieves energy savings of more than 3.000 MWh and CO_2 emissions reductions totalling 10.000 tons per year between the participating companies. It is estimated that 264 MWh are saved, and 800 tonnes of CO_2 emissions are reduced, on average, per symbiosis.” (Kørnøv et al., 2020).

In addition to reducing energy use and greenhouse gas emissions, symbioses also have several unanticipated positive effects on the environment. For instance, the initiative resulted in significant material savings while also reducing the amount of material transported by vehicles, which implies less air pollution and microplastic from tire wear (Kørnøv et al., 2020). This demonstrates how important industrial symbioses are for assisting businesses in going green.

Another idea, after the precedent of Kalundborg and Aalborg in Denmark, is the concept of eco-industrial parks (EIPs). EIPs started to appear through the implementation of industrial ecology concepts (Gibbs & Deutz, 2005), as this field promotes the establishment of resource trading networks in EIPs as a strategy for resource preservation. EIPs can be viewed as an application of IS specifically devoted to industrial systems since they are naturally adapted to promote collaboration and resource sharing among businesses (Butturi et al., 2019). Similar to IS, EIP efforts are thought to have enormous potential to help the environment, the economy, and society as a whole and, therefore, to aid in the creation of an industrial sector that is environmentally sustainable (Geng et al., 2009).

A definition often adopted for EIPs is "an industrial system of planned materials and energy exchanges that seeks to minimize energy and raw materials use, minimize waste, and build sustainable economic, ecological, and social relationships" (Demir Duru & Kechichian, 2021). An industrial park can further improve its environmental benefits through different utility-sharing options, such as a cooperative use of wastewater treatment plants, combined heat/power, or a collectively owned windmill (Eilering & Vermeulen, 2004) benefit more than the environment and have drivers across the three main sectors: environmental, social, and economic (Table 3).

Environmental	Social	Economic
Climate change commitments	Better working conditions	Creation of employment
Greener supply chain through circular economy practices	Creation of local employment	Upgrading labor force skills
Cost-effective infrastructure which adapts to climate change	Support for local community well-being and community outreach	Linkages between industrial park firms, SMEs enterprises, and other communities
Response to environmental and social concerns	Improved occupational health, safety, and crime prevention	Technology and knowledge transfer through foreign direct investment
A catalyst to improve efficiency and growth	Provision of social infrastructure to workers and community	Benefits of applying good international industry practices and regional development approaches

Table 3: Key drivers of EIPs according to (Demir Duru & Kechichian, 2021)

The drivers of EIPs along these three important sectors can be found in IS as well. After examining previous studies, Mirata & Emtairah (2005) outlined the following benefits of IS networks:

- Environmental benefits are related to increased resource efficiency, decreased use of non-renewable resources, and decreased pollutant emissions.
- Economic benefits result from lower costs for resource inputs in production, lower costs for waste management, and increased revenue from higher values of by-products and waste streams.

- Social advantages include the creation of new jobs, improvements to existing ones, and the enhancement of the working environment in terms of cleanliness and safety.

Last but not least, another industrial symbiosis that has been growing more in recent years is the connection between solar energy and agriculture. Establishing a connection to the central theme of the dissertation, the implementation of solar farms has been a major target for agriculture leading to a new concept known as agrophotovoltaic (APV) energy. The concept, which has gained popularity over the past ten years, consists of using the same plot of land for both agriculture and solar energy production (Rahman et al., 2022). The panel's shade affects some crops' productivity since they receive less light, but for others is beneficial and most importantly the energy generation makes up for this loss. Rahman et al. (2022) lists the existing types of APV systems - solar-powered glasshouse, solar-powered food drying, and solar-powered irrigation - and point out their main advantages and disadvantages.

Advantages:

- Reduction of GHG
- 30% increase in the economic value of APV farms due to improved output and land use efficiency
- Higher crop productivity
- Harmful radiation can be blocked and filtered by the panels
- Protection of some crops that suffer excessive heat and can mitigate soil temperature
- Use of the generated energy for irrigation systems which also replaces currents means (diesel pumps) and are the most cost-effective

Disadvantages:

- Panels' shade can negatively affect the productivity of some crops
- High initial investment cost
- Cloudy weather countries are limited in their energy storage
- Can cause obstructions to farm machinery
- Can cause soil erosion at times of heavy rainfall
- Product quality might be affected

To conclude after this balance, Rahman et al. (2022) state that these systems work meaning the advantages outweigh the disadvantages. To support this hypothesis, other studies, namely in Europe, conclude the same – Germany (Feuerbacher et al., 2022; Trommsdorff et al., 2021); France (Elamri et al., 2018; Toledo & Scognamiglio, 2021); Spain (Casares de la Torre et al., 2022; Martínez et al., 2022).

All these ideas serve as motivations to pursue industrial or community symbioses. Starting with IS, conventional business shares their resources to have their costs reduced and/or their revenues increased. IS might improve long-term resource security by expanding key resources like energy, water, or specific raw materials. Furthermore, symbiosis is sometimes pursued by businesses in reaction to pressure from regulations or permits that force industrial operators to use resources more efficiently, eliminate waste, or minimize emissions.

As for community symbioses, it would also be smart to give back some benefits to the adjacent communities, as doing so, will not typically mean incurring additional costs. In this way, some negative effects that these EIPs may have, such as visual or environmental pollution, can be mitigated by greater social acceptance.

Consequently, this dissertation will examine potential industrial or community symbioses that can exist between any sort of organization, by providing a proper step-by-step methodology on how to implement such solution.

3. Methodology

This master's thesis aims to propose a methodology to support the creation of an industrial or community symbiosis with solar energy generation. The methodology will be applied to a real case study, namely to the Sines 4.0 project, which is run by Start Campus (SC). The project will be to build a Hyperscale Data Centre campus of up to 495MW, however our focus will be on the solar parks that will be constructed to provide energy to the data centers. The case study will be more deeply analyzed in the upcoming Section 4.

3.1. Research Design

The methodology attempts to conceptualize a step-by-step plan to investigate potential symbioses for these solar parks. This plan was conceptualized by taking several research and analyses of industrial symbioses. By crossing all this research, we were able to innovate in this dissertation by creating a new research design.

The methodology consists of three steps: Project Planning; Identification of potential symbioses; Analysis of the alternatives. In the first step, we will introduce the project by describing the case study and the participating stakeholders. Next, we will demonstrate how to identify the possible symbioses that could be applied to our case study. Finally, we will discuss the approach how to analyze them to bring the decision-maker closer to a final decision on each alternative to pick.

It will be in SC's best interest to conduct this analysis since it would highly increase the project's efficiency by taking advantage of some potential waste generated in the solar farms' creation. Additionally, it is intended to be a generic study so that, in the future, other organizations can replicate it. Not only is solar energy considered inexhaustible and 100% clean, which makes it essential for sustainable development, but creating symbioses with its generation can bring mutually beneficial arguments to the organizations that try to establish them.

3.2. Project Planning

First, the project must start by assembling partners and defining the site, where the symbiosis will take place. It might be a city, a municipality, an industrial park, or any type of area where such project can coexist. Next, it is necessary to identify and engage the stakeholders and gather the necessary resources to fund the project. The person responsible for the last steps has also the responsibility to determine the project goals and to create his task force. Together they must take strategic decisions, such as communication, which is crucial to give permission, visibility, and credibility to the project, to secure the community's approval.

Project planning plays an essential role in guiding the project manager throughout all the phases helping him in reducing risks, missing deadlines, and ultimately delivering the expected result. It also helps guide all the stakeholders involved, so that they have a wider and more comprehensive view of the project, as they also have their stake and interest in it.

This section will be broken into two parts: first, we will describe our case study to provide the reader with some context, and then we will present and analyze the project's stakeholders.

3.2.1. Case Study Description

The case study's description will allow us to discover some key points and concepts about the project, so that, afterward, we can apply the proposed methodology. Some main topics that we will mention are the Sines 4.0 global project, the project responsible organization SC and some key data, which will be highly valuable for our study.

3.2.2. Stakeholders

The next step for the project planning will be to analyze the engaging stakeholders. However, before any analysis, it is necessary to define basic concepts, meaning to explain what stakeholders are. Bryson (2004) managed to gather definitions from different research and papers and some definitions for a project stakeholder are:

- "An individual, department or organization that could be impacted by a project's outcomes or have an impact on how the project is carried out."
- "People or small groups with the power to respond to, negotiate with, and change the strategic future of the organization"
- "Any person group or organization that can place a claim on the organization's attention, resources, or output, or is affected by that output"

In summary, it is possible to conclude that stakeholders play a crucial role in developing an implementation plan as they may have experience, information, or insights to define its success. Furthermore, and most importantly, they are often in a position to support or block the strategy implementation according to their interest, demonstrating their true value.

While stakeholder definitions vary, one certainty, according to different sources, is that "key stakeholders must be satisfied, at least minimally, or public policies, organizations, communities or even countries and civilizations could fail" (Bryson, 2004; Colvin et al., 2016). To understand how they are satisfied and what are their expectations, a stakeholder analysis must take place to identify them and comprehend their role in these types of projects as it will unveil how important and influential, they will be to the symbiosis.

Stakeholder analysis is “an approach for understanding a system, and changes in it, by identifying key actors or stakeholders and assessing their respective interests in that system” (Maguire et al., 2012). The author also outlines the steps to deliver such an analysis:

1) Identify and group the stakeholders, which influence the system
2) Determine the stakeholder’s roles in the project
3) Identify the relations between each other
4) Understand the possible conflicts that could threaten the system

Starting with stakeholder identification, it is crucial to determine the project’s stakeholders and consequently, to manage the expectations of all parties involved in a project. The research of Aviso et al. (2022) & Heeres et al. (2004) provides a background of which stakeholders are involved actively in symbioses and their according roles. This research will serve as inspiration to apply to our case study which will contemplate potential symbioses with solar parks.

- Participating organizations – These are the organizations that directly participate in the exchange network by being either the supplier or receiver of energy, materials, products, or by-products.
- Government – The governmental agencies can be local, regional, or national. They are directly responsible for creating policies and regulations, providing incentives, or applying sanctions, thus indirectly affecting the participating organizations.
- Suppliers – Crucial for the symbiosis, as they sell goods and/or services to the participating organizations. These organizations rely on them to proceed with their businesses and projects. Example: Company in charge of developing and selling solar panels to Start Campus.
- Communities – major stakeholders since they are close to where the project will take place and will be directly and/or indirectly affected by the activities that will take place. They seek health, safety, income, and economic development to improve their personal and professional path.
- Non-Governmental Organizations (NGOs) - They are non-profit organizations created by people who work voluntarily in defense of a cause. Applied to our case, the cause in question will be environmental protection, so it is prudent to consider the NGOs

Hence, in the next chapter, we will apply these concepts to our case study analysis, which will then be displayed in a structure similar to the table below (Table 4).

Stakeholders		**Role**
Group 1	**Stakeholder 1**	
Group 2	**Stakeholder 2**	
Group n	**Stakeholder n**	

Table 4: Stakeholder's identification

The third step is the identification of the relationships between each stakeholder to understand how they are connected. In this stage, we will utilize a visual representation to determine whether the stakeholders have an impact on both the symbiosis and the organizations that take part in it, which logically implies that they also have an impact on the symbiosis indirectly.

The last step will determine whether there might be possible conflicts between stakeholders in the future. This phase is critical since, if the conflicts exist, they pose a serious threat to the symbiosis and, more importantly, to the overall project.

3.3. Identification of potential symbioses

The second phase will be the identification of possible symbioses. To identify them, we cross-referenced a set of alternatives provided by SC with the literature review done in chapter 2. SC provided possible applications for PV integration into various parts of the human environment – buildings, lakes, traffic routes, agriculture, etc. Nevertheless, based on our case study, some applications are not compatible with the solar parks that SC wants to implement, for example, Vehicle-Integrated PV. The purpose is to create symbioses with the solar parks thus we will resort to the literature review, which presented different types of solutions in line with our objective.

The literature review will give a knowledge base of how symbioses are created and work and, more importantly, present examples of possible applications, serving as inspiration for possible alternatives, which are compatible with our purpose. The key to create successful symbioses will lie in finding win-win situations where both organizations mutually benefit based on a trustful relationship.

Following this identification, we will make a more in-depth analysis of the alternatives, which will occur in the following chapters. To note that, SC had to validate the alternatives as feasible projects, before applying them.

3.4. Analysis of the potential symbioses

Finally, we will conduct a two-step analysis of the previously discovered symbioses. The first step consists of outlining the benefits and drawbacks from each party's perspective. At last, we will discuss some intervening factors, such as potential drivers and barriers that may be encountered.

This section will be pivotal to gaining a broader and deeper grasp of each symbiosis. Knowing the advantages and disadvantages of any topic is crucial for examining and making value judgments. This evaluation will help the decision maker to make the optimal choice from the alternatives presented. We will resort to a fair assessment from each side, meaning from each entity's point of view, since the motivations and goals for both can be distinct.

3.4.1. Benefits and Drawbacks

The content presented here will mostly be based on best practices and lessons learned from previous implemented symbioses. Here, a good approach might be revisiting the literature review to recall some benefits and drawbacks mentioned to the creation and implementation of solar park symbioses. In addition, we will do thorough research on similar examples implemented throughout the world. This way, equivalent ideas might appear, however, we will need to evaluate them to see if they are valid and applicable to our case study.

3.4.2. Drivers and Barriers

To develop a symbiosis, it is essential to understand the driving forces and barriers of this model. Understanding the drivers will assist society to perceive the advantages that symbioses can generate, and leveraging them, making them models of best practices. On the other hand, studying the barriers will allow the involved organizations to understand what they will face when it comes to implementation, thus avoiding unpleasant surprises.

In short, this section aims to facilitate the comprehension of the key factors involved and explain how they can affect positively and negatively an IS process implementation. Different papers not only support this theory but also add that these are primarily related to four aspects (Al-Karkhi & Fadhel, 2020; Azevedo et al., 2021):

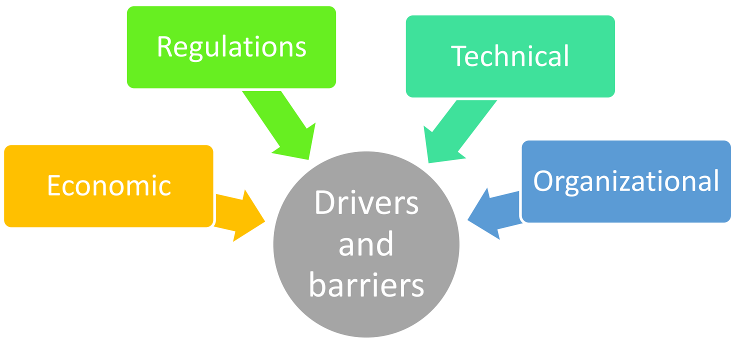

Figure 19: Main drivers and barriers to the IS development

The economic factor continues to be the main priority the businesses. In our case, the capital and operations and management (O&M) costs to create solar parks are a heavy burden financially, meaning that the potential IS to be created must guarantee economic efficiency, otherwise would not be considered. As a result, Start Campus may be reluctant to participate in an IS, if the economic viability is not there.

The second force is related to legislation and regulations. Many industrial symbioses have been developed throughout the years due to some regulatory pressures that have been put on organizations to stimulate their sustainable development. These laws and regulations driven by governmental institutions can go both ways. On one hand, they provide financial support and attract investments for the organizations acting as drivers. On the other hand, these institutions have created high taxes on waste management to meet their targets, i.e., the Paris Agreement, which, consequently, has a significant impact on the companies, thus acting as barriers.

The technical aspect relates to technological improvements and innovations. In this case study, studying the possible symbioses with solar parks, it will be important to pay attention to this aspect, since new technologies could come up due to the constant development in the solar energy generation area.

Finally, the last force is the organizational aspects that arise from implementing an IS. Collaboration among companies and organizations is fundamental for an IS to work, thus the more knowledge is transferred between each other, the more competitive advantage in their industry they will have.

4. Application to the Sines Data Center

The purpose of this chapter is to get familiarized with the case study to apply the proposed methodology in chapter 3. First, we will provide a case study description alongside some collected data about it. Next, the stakeholders relevant to the project will be identified. At last, the methodology will be put into practice so that SC has a step-by-step example of how to identify and analyze possible alternatives for its solar parks.

4.1. Case study description

The case study in question is an hyperscale data center, part of the Sines 4.0 project, which is being developed by Start Campus, the project's management company. Start Campus, started in April 2022 the construction of the campus's first building called NEST (New & Emerging Sustainable Technologies), which will be completed in the first quarter of 2023 having a total capacity of 15 MW (ECO, 2022). This first phase of the project represents an investment of 130 million euros out of an overall investment estimated at 3.5 billion euros by 2027. The Sines 4.0 project will consist of 9 buildings (NEST with 15MW and 8 more buildings with 60 MW capacity each), reaching 495 MW of total capacity (ECO, 2022).

The data center's energy supply will be 100% renewable and among the most affordable in Europe. Afonso Salema, CEO of SC, claims that "up to 1 GW of solar photovoltaic electricity is being generated on nearby owned property and fed through a dedicated cable (60 kV), guaranteeing affordable power for the lifespan of the data center" (DataCenterDynamics, 2022).

The Sines 4.0 project will be located on the southwest coast of Portugal in the Sines Industrial and Logistics Zone[4], on land adjacent to the recently closed Sines Coal-fired Power Plant, which is inserted in the District of Setúbal. Start Campus chose Sines due to its strategic location placed along major international trade routes and its aim toward industrial, logistical, and service activity. Some specific advantages of the park are: Next to the port of Sines, situated at the intersection of the major maritime North-South and East-West bound routes; plentiful availability of domestic and industrial water; a large infrastructure for electricity supply; and natural gas and fiber optics that serve the park, among others.

Even more important than the general location of the project is where the dissertation's applicability will be, meaning the location of the solar parks that will supply the data center. After collecting the information provided by SC, we were able to pinpoint the first lands purchased and ready to be licensed since all documentation is ready. These lands are presented with a red-marked perimeter filled in grey in the figure below (Fig.20).

[4] See https://sinestech.pt/zils (accessed in October 2022)

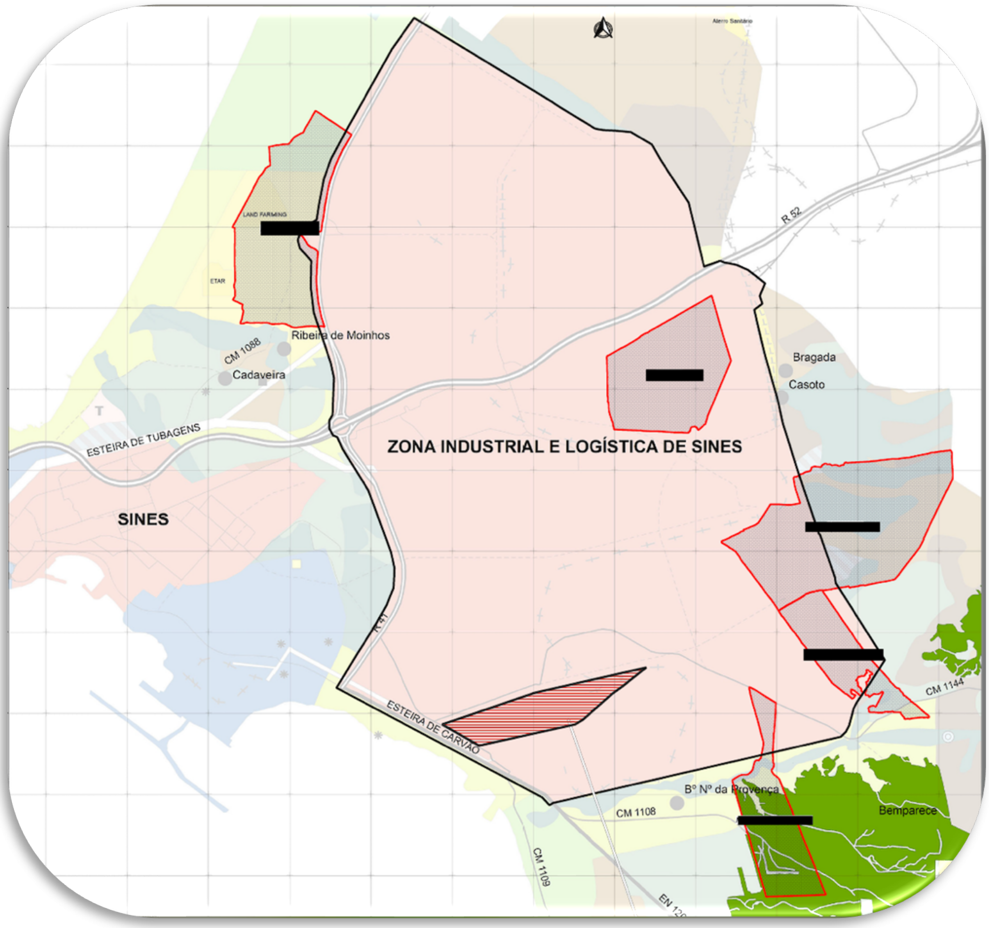

Figure 20: Start Campus purchased lands for solar energy development

For confidentiality reasons the land names are not shown, but it was possible to obtain the 5 locations' total size, which is equal to roughly 1500 hectares. Throughout the following years, SC will be looking to acquire more land as it is still not sufficient to follow the data center structure's demand. With the locations defined, we can move on to the next relevant step, the stakeholder analysis.

4.2. Stakeholders

To identify the stakeholders, we used the 5 categories listed in the methodology and cross-referenced them with the information provided by SC, namely the most common stakeholders present in their solar projects.

All stakeholders found are applicable to any of the alternatives that we will present in the next section. The only exception will be the stakeholder defined as the "Target organization". This stakeholder is the second organization part of the symbiosis besides Start Campus and will be presented more carefully when it is introduced. The table below presents the stakeholders with their respective roles in our case study.

Stakeholders		Role
Participating Organizations	Start Campus	Entity that will directly participate in the established symbiosis and will mainly assume the role of energy and land use supplier. As for what the company will receive (material, products, and/or by-products), it is still not possible to determine at this point in research since the target organization has not been yet defined.
	Target Organization	Second participating entity will receive what Start Campus has to offer (energy and/or land use). As a mutually beneficial process, this organization will also bring something to the table, which has to please Start Campus filling one of its gaps.
Government agencies	Ministry of Environment	Government department in charge of the Environment and Climate Action area and offers support for policymaking, manages, and allocates funding programs, and provides technical and administrative support within the same area.
	Sines City Hall	The city hall is the executive body of the municipality of Sines. The entity is responsible for the approval of any construction projects, meaning in our case study, all the necessary licenses for the construction of solar parks will have to go through this entity.
Suppliers	Solar panels development company	This stakeholder is not yet defined by Start Campus. Is responsible for providing and installing solar panels on the land purchased by the company.
	Redes Energéticas Nacionais (REN)	REN operates the national energy transport network which connects producers to consumption centers. In this case, it will be responsible for distributing the energy produced in the solar parks to the data center and eventually to the Target organization.
Communities	Local/Adjacent Communities	Communities of the municipality of Sines and/or adjacent locations where solar farms may be developed. They represent a powerful stakeholder since they can directly affect or be affected by the establishment of these farms.
NGOs	C6 Coalition	A group constituted of 6 NGOs intending to defend the preservation and promotion of nature and biodiversity before civil society and public and/or governmental institutions.

Table 5: Stakeholders in the case study

Since the stakeholders have already been identified, we can now determine the relationships between them in light of any potential symbiosis that might be formed (Fig. 21):

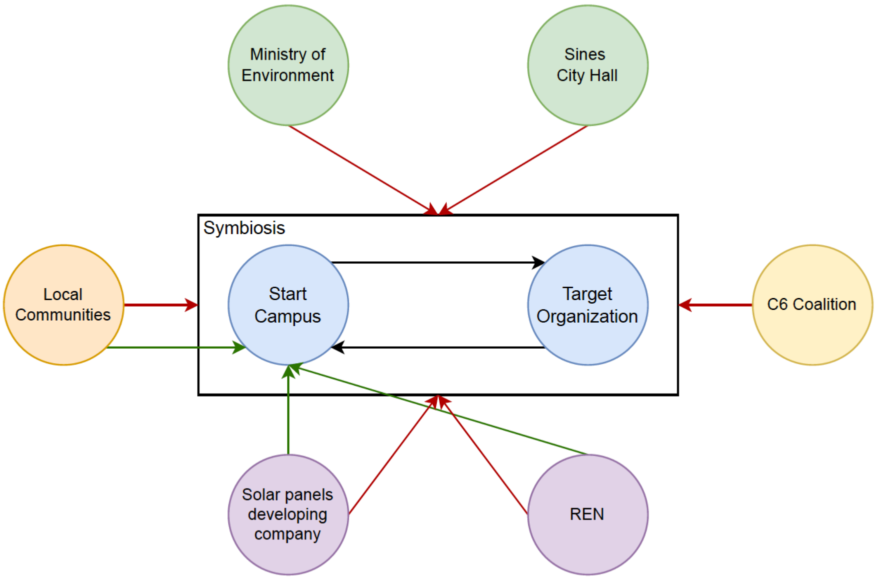

Figure 21: Stakeholders interconnection

Before we analyze the relations between the stakeholders, we have to explain the figure alongside with its color coding and mention some assumptions/limitations made:

Figure explanation:

- Circles represent the previously identified stakeholders in Table 5 with the according colors, which represent the groups they are inserted in.
- Square illustrates the symbiosis that is formed between the participating organizations
- Green arrows imply that there is a direct relationship between the stakeholders and Start Campus.
- Red arrows indicate a relationship between stakeholders and the symbiosis, which indirectly affect both participating organizations

Assumptions/Limitations:

- The relationships between the stakeholders outside the symbiosis have been neglected since they do not serve the purpose of this dissertation.
- At this point of the analysis, the target organization has not yet been identified, hence no direct links were established between stakeholders and the target organization.
- Directly connected to the last bullet point, we did not consider further possible stakeholders that could have appeared once the target organization is set.

With this context, we can now clarify the relationships that have been established between the different stakeholders involved in the symbiosis. Additionally, potential conflicts in these relationships will be described to have a better understanding of the drivers of all interest parties.

Start Campus & Target Organization – As mentioned previously, these two stakeholders engage in a mutually beneficial relationship. The participating organizations need to understand and trust each other to succeed and must develop a strong communication strategy. Without communication and trust, conflicts may arise in which one organization may feel insecure against the other and end up turning down the symbiotic relationship. Furthermore, if the Target Organization does not have any valuable assets to aid in the project, this stakeholder will not be beneficial for the symbiosis.

Local communities & Start Campus – Start Campus has the responsibility to consider the local communities' necessities after analysing their behaviours. This collaboration will allow Start Campus to empower its plans for the symbiosis and rely on the support of the local community. Moreover, the members of the municipally of Sines will have access to key messages of the stakeholder´s perspective, interests, and concerns, and can be a valuable source of disclosure of information. If this relationship is not nurtured and the local communities do not agree with the Star Campus´s plans and actions, the project will lead to general discontent. The community is extremely important to build a positive reputation and for the project to positively impact the Sines community.

Local communities & symbiosis – Similar to the benefits of Start Campus, the communities need to agree with the decisions behind the project and have them encourage the construction.

REN & Start Campus – REN, as an energy distributor, will be in charge of delivering the energy generated by the solar panels for the uses specified by SC. SC will rely on them to supply power flawlessly to the data centres as they 24/7 meaning a failure could trigger a stream of problems for the company.

REN & symbiosis – In this relationship, the same applies as the previous one, but this time additionally, REN will be in charge of delivering the energy to the intended organization. Without its distribution, the project cannot proceed.

Solar panel-developing company & Start Campus – Start Campus has the responsibility to define the best suitable solar panel company for the project. The risks of wrongly choosing the solar panel company can lead to several issues as insufficiency of solar panels or panels with efficiency defects or even damaged. Potential disagreements could force SC to select a different supplier to create the required panels, putting deadlines or potentially the entire project at risk. The developing firm will be the most affected since they would miss out on millions by losing a project of this magnitude and significance.

Solar panel-developing company & symbiosis – The relationship is identical as with Start Campus with the same adjacent risks. The solar panel company needs to be dedicated to the symbiosis and supply the necessary solar panels for the efficient functioning of the project or else the target organization will also be affected.

Ministry of Environment & symbiosis – This relationship is extremely important since it is a source of investment for the symbiosis and the main interest is to protect the project and lower financial obstacles. If there are conflicts between the two, the consequences could lead to the reduction of technical and administrative support, and the absence of an alternative funding program.

Sines City Hall & symbiosis – The Sines City Hall is responsible for approving the necessary licenses for the construction of the solar parks and, therefore, is crucial for the symbiosis. Without the support of this entity, the project can be delayed or even cancelled for non-compliance with regulations, lack of construction planning, and others.
C6 Coalition & symbiosis – The relationship of the symbiosis with the 6 NGOs is focused on environmental benefits. C6's main concern will be sustainability, so it will make sure that companies meet certain goals such as engaging in eco-friendly actions, preserving the planet, and promoting biodiversity in Sines. By following these guidelines, the stakeholder will be satisfied, and the symbiosis will not be threatened. Yet, not addressing their concerns, may generate manifestation against the project that could gain enough awareness forcing the government to intervene in favor of the coalition's concerns, which ultimately can create obstacles for the symbiosis.

After identifying the stakeholders, analyzing their relationships, and pointing out some conflicts that may arise, we will move on to the identification of possible symbioses alongside with the stakeholder - "Target Organization". This section will help us later when analyzing each symbiosis individually as it will facilitate to understand the motives behind each stakeholder's decision.

4.3. Potential Symbioses

Start Campus started by providing 6 possible applications for PV integration with its data center, namely: Vehicle-Integrated PV; Building-Integrated PV; Agrivoltaics; Road-Integrated PV; Floating PV; and Urban PV. To contextualize each application a brief description is provided below:

- Vehicle-Integrated PV – Solar panels installed in an electric car's roof. The main target is to provide extra mileage to the electric car and the energy generated is not fit for other purposes.
- Building-Integrated PV – Solar panels are integrated into the building's envelope and are part of the building's components such as roofs or windows.
- Agrivoltaics - Simultaneous use of land areas for photovoltaic solar energy generation and agriculture.
- Road-Integrated PV - Incorporation of solar panels into and near land areas reserved for transportation.
- Floating PV – Set of solar panels mounted on a water-floating structure.
- Urban PV – Construction of solar modules in urban landscapes such as public squares or recreation areas. Allows the combination of energy generation with shading elements, rain shelters, or charging infrastructures.

Except for "Vehicle-Integrated PV", all applications, depending on the size of the structure, can generate electricity not only for their main purpose but could also produce excess or store unused energy for other desires or applications. Example: In the building-integrated PV solution, if the building's envelope is completely covered by solar panels, it could generate electricity not only for the building's needs but also distribute it to surrounding buildings at a set price.

Focusing on the case study at hand, before analyzing which application would be matching, it is important to point out what SC is looking for or what it is offering to form such symbioses. By developing these solar farms, SC will be trying to fill two gaps:

- Land use required to construct a solar park of this magnitude
- The energy produced during the hottest hours of the day, which typically exceeds the constant supply needed by the service, in this case, the data center.

Considering that a symbiosis requires mutually beneficial inputs and outputs and the previously described applications, one of them stands out and has been previously mentioned in this dissertation, which is agrivoltaics. The agriculture industries are willing to receive these types of inputs/explore these opportunities and can produce benefits for the Start Campus with their outputs, thus promoting sustainable development (Toledo & Scognamiglio, 2021). Despite not being mentioned in the applications, the adjacent communities could also have something to contribute, as seen in the literature review. Community solar projects could definitely satisfy the needs from Start Campus and would guarantee the company a powerful ally.

Although these organizations are eager to receive electricity or land as a perk, they must also demonstrate how they would add value to Start Campus, so that they can be chosen as the best alternative. Before we analyze the benefits and drawbacks that each organization can provide to the Start Campus and vice versa, we must understand how the symbioses can be established.

Bearing this in mind, the matching process will begin, which will present the potential symbioses that Start Campus could develop with the identified organizations. First, we will explain the symbiosis and provide some successful examples already existing around the world with some quantitative data so that afterward we can apply them to the SC reality.

4.3.1. Ground-mounted solar panels with sheep farming

The first symbiosis involves letting animals graze the ground beneath the installed solar panels. Not only do the panels have to be cleaned, because obstructions, such as dust, can negatively impact the panels' performance, but also the land underneath them. For example, when grass and weeds are not maintained, they can grow to a height where they block the panels and let dirt into them, which drastically reduces the energy production of solar farms. Therefore, having animals graze the area where the solar farms are located will be very advantageous for the farms' upkeep because it will also result in a decrease in expenses.

Figure 22: Sheep grazing soil beneath the solar panels

However, not just any animals can walk on these soils since they can damage the solar arrays. At the moment, according to Bay Journal (2022) sheep are the best fit to create a symbiosis. The panels are typically built between 0,7 and 1,5 meters off the ground, which is already a limitation to some animals, like cows. So, sheep fit nicely under the panels, with an average of 1 meter high, and most importantly, they keep their heads down for the business at hand, on the contrary to goats, which tend to eat the wires and jump onto the panels. This will also provide the opportunity for the sheep herders to acquire fresh and expansive grazing territory for their flocks.

A success story is described by Jose & Calver (2022) in Central West, New South Wales. The project began four years ago and the "local grazers have labeled the set-up a complete win-win". On one hand, the wool collected from these sheep was of higher quality, and, on the other hand, they helped to keep grass and weeds down to not obscure the panels, thus preventing the soil from drying out. More results will be shown in the Benefits & Drawbacks evaluation.

<u>Case study application</u>

Applying this to our case study, Start Campus has two options to implement this symbiosis:

1) The first option will be to inquire the adjacent communities about the presence of shepherds and their corresponding sheep flocks. If so, SC will need to assess how many sheep it will need to graze its land and determine whether the supply matches its demand. Only then will the company be able to create contracts with the shepherds and comprehend their demands to establish this symbiosis.
2) The second option will only come into question if the supply from the neighboring areas does not match the required demand. In this situation, SC will need to track down and get in touch with sheep producers to create partnerships. Finding producers is not likely to be the most complicated task since the Alentejo region has 68% of the national sheep production (RTP, 2017). The challenging part will be transporting the desired livestock to the required land. SC will have to evaluate this option' economic viability as it will require a specific area to rest the flock and the according shepherds to walk them, meaning it will demand the construction of a farm nearby. Ultimately, the process expenses might not outweigh the advantages that the SC will gain from engaging in this symbiosis.

4.3.2. High-mounted panels with berries production

The second possible symbiosis is high-mounted panels to cultivate specific crops. These high-mounted panels create a large area of shaded land since they are raised to a certain height, between 2-5 meters, which greatly impacts the type of agricultural product it can be grown. This type of installation has been widely used for berry crops since these trees have a medium height.

Almost all types of berries are typically planted under plastic wrap, which keeps the fruits partially shaded. Every few years this plastic needs to be replaced mainly due to the wind and its low resistance. Replacing this plastic with solar panels above the plants would shield them from the sun and require much less plastic, making it a more sustainable process.

Figure 23: Red currants production under PV panels

An example of this synergy is the german company BayWa, which finished the construction of its first APV project for red currants in the Netherlands in 2019 (Fig. 23) (Mavrokefalidis, 2021). The result of the pilot project proved to be a success as Stephan Schindele, the product manager of the company, stated, where it showed “that the installation of solar panels created both favorable lower temperatures for the plants and better protection from adverse weather conditions” (Mavrokefalidis, 2021). This project is also able to generate around 1.2MW with more than 4.500 solar panels and produces approximately 23 tones of redcurrant harvest every year.

Another case is the Dutch company GroenLeven, which is already involved in six initiatives, namely in the cultivation of strawberries, blackberries, and raspberries. In one of the projects, i.e., strawberry production, the company's owners, Theo Swinkels & Carina Manders stated that “GroenLeven allowed them to now have not only a roof to protect the berries from adverse weather conditions, but also have a roof that replaces plastic, making their company more sustainable.” (GroenLeven, 2020).

In this alternative, we must take into consideration that the presented and other existent projects are pilot and recent projects, meaning high complexity involved both in terms of implementation viability and the difficulty of replicating them.

Case study application

In this situation, SC may search for a berry-producing company that is willing to try this innovative technique. For instance, Lusomorango, the largest national producer organization in the fruit and vegetable sector, is dedicated to the production and sale of raspberries, blackberries, blueberries, and strawberries. Most of the crops are located in the southwest region of Alentejo, Algarve, and Ribatejo, where the soil and climate, which are significantly influenced by the Atlantic Ocean, are highly favorable for growing high-quality fruit with a powerful flavor.

This company has a lot of potential for several reasons: 1) Sines is located in the ideal region for the production of these products, as mentioned in the previous paragraph; 2) Lusomorango is strongly committed to the environment and innovation. The company is focused on generating the minimum waste, so it has allocated considerable resources to the acquisition of various equipment that allows the use of water resources in an optimized way. Therefore, creating a symbiotic relationship and testing it out with a pilot project may be a smart move for both businesses.

4.3.3. Community solar projects

The last symbiosis involves providing energy to the adjacent communities. In this situation, we could be talking about on-site or off-site community solar projects. On-site would mean that the communities have the panels installed on their own properties, whether on the roofs or owned land. Off-site is the most common practice since the communities can still have a piece of the energy generated even when they don't own a home or have a suitable roof to install.

The system will function via a subscription model, where communities enter into a contract with the owner or operator of the solar installation, in this case, Start Campus. Here, the electricity generated would go to Start Campus, but as a subscriber, you would get a fraction of the system's production. Depending on the subscriber share, the person would have to pay an agreed-upon rate for the electricity he/she uses, but always inferior to a utility company cost. As for the billing, Figure 24 illustrates the process:

Figure 24: Before vs. After implementing community solar

Before the solar community is established, the vendor issues an invoice with the cost of all the electricity consumed. After the establishment, two bills are created. One from the solar community, showing the portion of solar generated and the credits given. The other is the utility company's invoice with the amount of consumed energy but subtracted with the person's share of the solar community.

Keeping in mind that Start Campus will have a hyperscale data center to supply, the only way to accommodate such projects is to distribute the excess solar power it generates to them. Depending on the type of project, on-site or off-site, there are two ways to supply this surplus: On an on-site project, if there are few panels installed, the solar excess could be directly supplied to the property where they are located; Off-site project, the surplus would be injected into the grid for everyone to benefit from it and each receiving its share.

Regardless, what matters is to understand Start Campus's ability to produce surplus energy. Figure 25 represents a general view of how much electricity is produced per day by solar panels with certain parameters defined by Jahid et al. (2019), which are negligible for our analysis as this behavior is observed for most panels.

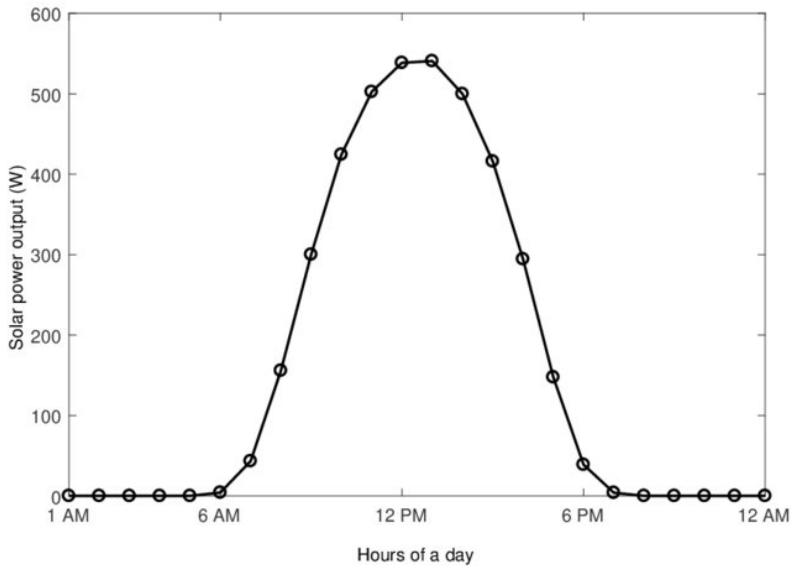

Figure 25: Solar power output for one day (Jahid et al., 2019)

By breaking down this graph into three stages, we can simply explain this parabolic behavior. The first stage is from 12 am – 6 am and 6 pm – 12 am where the solar output is close to 0W since the solar panel cannot capture solar energy during the night times. These times can vary, depending on two factors, namely the location in the world and the season in which it was measured. The second stage is represented between 6 am – 12 pm and 2 pm – 6 pm when the solar panels are starting to produce energy. Here factors such as inclination or the pointed direction of the solar panels can influence how much energy is generated. At last, the interval between 12 pm – 2 pm is the peak production of electricity since the sun is at its highest and hottest point.

Important to keep in mind is that data centers will function around the clock, therefore there needs to be storage to ensure not only uninterrupted operation at night but also potential peaks during the day. Apart from that, the data center will consume a constant value of electricity, which will always be less than the peak production of solar farms, representing an excess in production in some intervals. In this case and without compromising the supply to their data center, these solar community projects can be examined and formed so that Start Campus can sell energy at a reduced price to prevent wastage of excess.

4.4. Symbioses analysis

This analysis will be unbiased and conducted by considering both the donor's and the receiver's perspectives. We will compare each alternative's advantages and disadvantages in the presented order in the previous section.

4.4.1. Benefits & Drawbacks

Ground-mounted panels with sheep farming

→ Perspective – Start Campus

Benefits:

- After the leasing cost of the land, land maintenance is the second most expensive cost for firms that want to build a solar farm. One of the major maintenance expenses is controlling the growth of grass and plants surrounding the solar panels, which requires labor, machinery, and products like herbicides. Allowing lamb grazing on these fields will slow down or even prevent plant growth leading to a significant reduction in the maintenance costs for SC.
- Directly related to the last point, SC can promote environmental sustainability since they are reducing or even replacing the use of lawnmowers that run on fossil fuels. This action would mean a GHG emission reduction since the machinery would be replaced by sheep. Additionally, this system would have a positive overall impact on the ecosystem in fields such as “animal science, soil carbon sequestration, vegetation biodiversity, and pollinator habitats” (Y. Wang, 2022).
- To make the proper installation of solar panels, it is vital to consider the soil’s health. In this situation, Start Campus would benefit from choosing agricultural farms due to better-treated soil, saving time and money on the installation.
- According to Yue et al. (2021), the vegetation grazed under the solar panels helps to keep the panels cool, which boosts energy production. Dubey et al. (2013) state that severe heat can reduce the output efficiency of solar panels by 10%-25%. So, if allowing sheep to graze in the fields below the solar panels would decrease the panels’ temperature, this would increase the electricity generation efficiency.

- Sheep farming can generate stronger ties with local communities, making the infrastructures more attractive and easier to install, due to the social acceptance.
-

Drawbacks:

- Regardless of whether sheep are the most suitable animal to coexist with ground-mounted panels, they still pose a threat to the structure. Given the low height of the panels or some exposed components, these animals can still damage components or even create a fire in a worst-case scenario (Y. Wang, 2022).
- "On average, to keep plant growth under control, one to five sheep per acre are needed." (Bay Journal, 2022). Making an average means that 2.5 sheep per acre are needed. One acre is equal to roughly 0,4 hectares (ha). For the current 1500 ha that Start Campus possesses, 9375 sheep would be needed to graze the grounds. This being said, it is difficult to estimate whether Sines or nearby farmers have enough herds to meet the company´s needs.
- For the aforementioned number of sheep, equivalent shepherds would be needed. The number needed is calculated depending on the type of land they have to pass through. If it is necessary to walk the flock through village centers, one shepherd can only look out after 400-500 sheep. However, if it is only necessary to graze the flock on large lands without civilization and danger, a shepherd can watch 800-900 (Bay Journal, 2022). The second case is more applicable to our case study, meaning 10-12 shepherds would be needed, which SC would have to provide extra income.

→ Perspective – Shepherds/ Sheep farming companies

Benefits:

- Lamb welfare is improved by solar panels since the shade provided helps the animals to preserve energy (Clean Energy Regulator, 2022).
- With the protection during periods of high temperatures and during rain and hail in the lambing season, it was observed that the sheep "were slightly lighter stocked than the average in the district but were cutting an amazing amount of wool with higher quality" (Jose & Calver, 2022)
- SC can also provide electricity in return, which will be useful on the shepherds' properties or in the sheep farmers' facilities.
- These solar farms have greater security measures and a fence around their perimeter is part of their protection. The ability to defend their flocks more easily from predators like foxes directly benefits sheep farmers (Clean Energy Regulator, 2022).
- If Start Campus ends up renting the shepherd's land to install their panels, it will be an extra income for these pastors. This is highly valuable for these shepherds, as they are struggling most of the time due to low wages, thus it would increase the rural community's livelihood and financial viability.

- A successful project can equal higher visibility and other opportunities to shepherds or sheep farming companies, as other solar companies would be looking to establish such symbiosis.

Drawbacks:

- The shepherds are in charge of the cattle and usually, it is too big for them to have a view of all of them. After all, sheep are animals, and lack of supervision can lead to the sheep damaging the solar panels and they may be held accountable for their actions, which will cause the symbiosis to break down.
- Sheep farming companies have a hard time finding shepherds as normally is shown as a family business[5]. For this the sheep farming company or communities would have to ensure that there are enough shepherds and consequently pay their wages.

Bearing in mind that this is a future project, we present some quantitative data collected from a similar symbiosis. This data will be able to present more detailed information about some expected results if this symbiosis is applied. This data is from research conducted in 2019 and 2020 at the Corvallis campus of Oregon State, US (Nealon, 2021):

1) In both years, lambs gained nearly the same amount of weight on the two types of pasture.
2) In early spring of 2019, the daily water consumption of lambs on both types of pasture was similar, but in late spring, lambs on open pasture consumed more water than those grazing beneath solar panels. The lambs' water consumption was unchanged in the spring of 2020.
3) The solar grasses produced 38% less forage than the open pastures over the two years.
4) Overall, the pasture yield was 1,046 $/ha/year on open pasture and 1,029 $/ha/year on solar panel pasture (solar energy produced was unaccounted for).

High-mounted panels with berries production

→ Perspective – Start Campus

Benefits:

- The land use for the solar park would be fully explored. By establishing this symbiosis, the Start Campus could still generate its solar energy while also making better use of the area by encouraging an agricultural company to exploit the land. In addition, this would relieve the pressure on ecosystems and biodiversity as these are affected when cultivated areas are expanded.

[5] See https://www.euractiv.com/section/agriculture-food/news/will-germanys-sheep-farming-industry-die-out/ (accessed in October 2022)

- Directly related to the last point is economic viability. Start Campus could charge for a space-use rent, which could either get them some return on their original investment when they bought the land.
- Start Campus could sell electricity to the agricultural business in case of surplus output, instead of wasting this energy or selling at production cost.
- PV panels will have increased electricity generation since the crop water evaporation helps decrease the modules' temperature (natural cooling), resulting in a higher energy production efficiency (Dubey et al., 2013).
- Land maintenance would also be assured by the berries production company, since having good soil health would be fundamental for its fruits to bloom. Hence, healthy soil will guarantee that the installation of the panels will be easier and more resilient.,
- This symbiosis meets the clean energy goals by providing renewable energy to this industry and makes Start Campus compliant with the targets they established contributing to Portugal's commitment towards the Paris agreement.
- Environmentally speaking, berries such as raspberries or strawberries contribute to the reduction of GHG emissions since their carbon footprint is pretty low and allows them to collect a significant amount of CO_2 emissions. Hence, Start Campus would benefit as they continue to promote sustainable development by establishing this industrial symbiosis and enhancing the ecosystem.

<u>Drawbacks</u>:

- Installing such systems will represent a considerably higher cost than just installing ground-mounted panels, meaning a higher cost per kilowatt-hour generated due to larger capital expenditures. Normally these industries do not possess a strong economic power thus these costs would rely on Start Campus.
- Still a relatively new technology with very few pilot cases, which implicates a high-risk project and difficult to convince all stakeholders to be part of it.
- Also related to the last point, support mechanisms for these types of projects are almost non-existent, meaning Start Campus would have to import these technologies and the necessary knowledge to implement them from other places, such as Holland as the example presented, translating into a much higher cost (Tumilo, 2022).

→ Perspective – Berry farmers / Berries production companies

<u>Benefits</u>:

- The agricultural business could purchase electricity at a set price from Start Campus in case of surplus output to run its irrigation systems or machinery.
- Improvements to the farmers' health who often harvest crops in extremely hot conditions, could result in serious health issues. Thus, this technique enhances their work conditions by providing shade while harvesting.

- Solar panels' shade can lessen the burden that high temperatures and UV rays have on shade-tolerant plants and protect crops against bad weather conditions like hail or strong winds (Tumilo, 2022).
- Fruit production's quality is 2 to 3 times better under solar panels and it requires about 50% less water than without this protection.

Drawbacks:

- Like all fruits, berries require sunlight to grow, therefore the panels will partially reduce their energy yield and might harm their production.
- Moving the crops to another location may be a difficult task, as there are many factors involving this relocation such as economic and productivity aspects. Berries may not do well where the solar parks are located due to the climate and these companies should not expect any compensation, meaning the relocation costs will be on the companies.

Again here, the quantitative data is presented to show some possible results when this symbiosis is implemented. Data if from an Agri-PV project that started in 2019 between GroenLeven and fruit farmer Piet Albers in Babberich, in the Netherlands (de Vries, 2021):

1) "We started with solar panels that allowed 11% light through, but that didn't work. We then eventually rose to 40%. Now, the crop is similar to raspberries grown under plastic. Their size, flavor, and shelf life are pretty much the same."
2) This solution is highly costly as "It costs millions to install the 10,000 panels in Babberich. One hectare already costs more than 500,000€."
3) According to reports, there were moments throughout the summer when the temperature was close to 38°C and then the temperature measured under the panels was approximately 29°C.

Community solar projects

→ Perspective – Start Campus

Benefits:

- Start Campus can use this opportunity to increase its acceptance rate within local communities. This would present an opportunity not only to save money but also to boost the local economy and create job possibilities. Such projects require engineers, contractors, electricians, etc., so even if locals do not end up taking these positions, it will already increase the activity in the surrounding areas.
- Since the electricity transportation distance to the consumer is shorter, there is less energy loss, representing additional savings or gains for SC
- According to a newspaper article (Idealista, 2022), the government is granting financial incentives when developing projects like these solar communities, so this could present an opportunity for Start Campus to explore.

- Installing solar communities can assist the company in achieving compliance with more environmental regulations, even though they might already be accomplishing this by being a 100% green energy-powered company. Adding to this could be the acceleration of hitting their goal of having carbon-neutral operations.

Drawbacks:

- As previously mentioned, Start Campus already purchased 1500 ha to construct its solar farm and is still looking for additional land to enhance it even further. Lots of space is needed, meaning land clearing will probably be required before installation can take place. This could have unforeseen environmental effects like habitat loss and deforestation. Start Campus will have to take this into account and demonstrate sustainable land-use practices to gain support from local communities and most importantly, not compromise one of their core values and goals of being 100% sustainable and environmentally friendly.
- This energy surplus will never be too excessive because the needs of the data center will always take priority. Thus, the electricity provided to locals will or might not be enough for everyone, which probably will lead to disputes over who should be supplied or prioritized. Start Campus needs to be careful when negotiating with the stakeholders to avoid causing dissent among the communities and seriously jeopardizing the project.

→ Perspective – Communities

Benefits:

- Local communities will have access to this energy that would be directly fed into the grid by Start Campus at reduced prices, meaning very close to the production cost, representing a considerable gain for the locals. It is anticipated that subscribers will save between 20-30% on their monthly electricity bills by choosing this alternative (Silva, 2021)
- Considering the energy crisis, the world is currently experiencing, where electricity prices have been rising constantly, this synergy can represent an opportunity for local communities to fight this increase and have some protection against price volatility by having access to this cheap supply.
- Using this symbiosis presents a chance for communities to lessen their reliance on fossil fuels, particularly natural gas, which is still frequently utilized in Portuguese houses today.
- The infrastructure is one of the major obstacles for people who want to turn to solar power. This solution guarantees that there is no physical infrastructure on any property, either on land or on the owner’s roofs. In this way, communities are relieved of the burden of having to be involved in the installation or maintenance process, even if these costs are incurred by Start Campus.
- These solar parks could lead to a stronger focus on the digital transition, particularly for electric mobility. With all the facilities that will be available, there will be more opportunities for the incorporation of new charging stations for all-electric vehicles, which communities could take advantage of.

Drawbacks:

- Communities should be ready and consider this synergy as a temporary rather than a permanent benefit. Due to the high investment, SC might have the incentive to, in the future with a solid customer base, increase prices to cover the initial investment. Not only that but they could find more advantageous, viable, or profitable ways in the future to supply energy, stripping the communities of this privilege.
- If on-site projects are chosen, the installation and material costs are the responsibility of the user for the project's fraction, thus incurring much more costs and responsibilities than off-site projects.

This quantitative data was collected Eco Sapo newspaper (Silva, 2021), which presents the research conducted in Portugal in 2019 by CSIDE, a software company that develops energy management solutions, i.e., solar communities

1) The price per kWh of self-consumed energy in renewable energy communities can be 40% lower than the average prices charged by retailers
2) Depending on the project and the grid connection type, consumers may additionally benefit from savings of between 10% and 15% on their electricity bill or from total exemption from grid access costs.
3) A residential consumer with an average monthly electricity bill of 50€ is expected to have a monthly savings of 20% to 30% in the amount paid to the electricity supplier.

4.4.2. Drivers & Barriers

Following the study of the benefits and drawbacks, we will proceed to the analysis of the drivers and barriers, as described in the methodology. This evaluation can reinforce some of the already highlighted benefits since there may be drivers pointing in this direction or have the opposite effect, which will present various barriers making the alternative more challenging to implement or adopt. Some selected strategies for overcoming these hurdles are also going to be highlighted, as they can create favorable conditions for the symbioses to become a reality. Hence, we will evaluate each alternative individually considering the 4 parameters defined in section 3.3.3 – Economic; Regulations; Technical; Organizational.

Ground-mounted panels with sheep farming

Economically speaking, the biggest driver for Start Campus will be the reduced O&M costs of this alternative and possibly some minor reduction in the initial costs. When it comes to the upfront expenditures, it should be kept in mind that the land's health is one of the factors that contribute to the successful and effective installation of the panels, meaning the company will have to incur costs before installing them to ensure that the soil's conditions are in place to proceed with the installation.

As a result, if the land purchased has been previously used for grazing, it will always be in better condition than ungrazed land, leading to lower initial investment costs for the business.

As for O&M costs, Start Campus will be able to cut back on some labor expenditures by using sheep to keep the fields healthy since they partially do the worker's job. As a consequence, their labor hours can be allocated to the panel's cleaning and ensuring they remain 100% operational. However, to this equation, we must consider the contracts that need to be established with the farmers. Weighing these costs in the balance, it will always be more financially viable to sign these contracts because they will always be lower than the costs incurred with maintenance.

On the subject of contracts, this is the principal economic driver for the shepherds as it will provide them additional revenue both directly and indirectly. Directly, they will collect a certain wage established in the contracts with Start Campus to graze their sheep on the solar parks when, in fact, they were already doing it on their land but without any income. Indirectly, and in line with some of the earlier research, the protection of the panels throughout the different seasons will improve lamb welfare and the quality of the wool harvested, raising the shepherds' income.

Start Campus won't need to be too hesitant about the synergy economically since the only barrier that might arise is if farmers are difficult to negotiate with and try to take advantage of the situation by demanding more money than is reasonable. Even so, the company possesses a dominant position in this symbiosis, since it is clearly obvious that the project can move forward without the sheep grazing. So strategically, Start Campus will be able to take advantage of this position to negotiate more easily with the farmers.

However, on an economic level, the same cannot be confirmed for the shepherds. To establish the contracts, the corporation may demand an increase in the sheep herd and sheep production to be expanded to accommodate the land's demand. Given the farmers' income, it may be difficult to meet these requirements as sheep rearing is a resource and time-consuming process, such as nutritional, health, and lambing management. Another problem that may arise is if the flocks have to be relocated, as the farms may not be directly adjacent to the solar parks, involving extra costs and efforts to flock owners. To overcome these two problems, the owners could request additional funding in the contracts for both, increased sheep production and relocation, which will be advantageous to both parties.

Moving on to the regulatory parameter, Start Campus will have as its biggest driver the status as a project of national interest[6]. This distinction aims to facilitate the development of projects that are key to the growth and competitiveness of the economy. This status gives Start Campus access to vital benefits such as priority in licensing and permits, and an open door to tax benefits

[6] See https://www.computerworld.com.pt/2021/04/23/data-centrr-em-sines-e-maior-investimento-estrangeiro-desde-autoeuropa/ (accessed in October 2022)

or even communitarian funds. One example among the many communitarian funds is the environmental fund, created by the Ministry of Environment, which aims to support environmental policies for the pursuit of sustainable development goals, namely those related to climate change and nature conservation and biodiversity, which perfectly suits this symbiosis.

However, there has recently been some disagreement in Portugal over the installation of photovoltaic plants. According to Dinheiro Vivo (2021), the C6 coalition has asked the parliament to legislate on solar photovoltaic plants to prevent their locations in critical areas in the country. C6 believes that the installation of these plants is jeopardizing the natural heritage, namely the fertile soils and ecosystems.

On the other hand, a newspaper article in Expresso by (Prada, 2022), reports that the government accepted the legislative solution found by the Ministry of the Environment to speed up the installation of new photovoltaic capacity in Portugal, ensuring faster licensing, but also financial compensation for municipalities. Photovoltaic projects below 1 MW are exempt from urban planning operations prior control, however, projects above this remain unchanged, which is our case study, but with the promise of greater agility. Municipalities will be entitled to receive a fixed compensation of 13,500 euros for each MW installed in their territory.

That being said, the government as the obligation to hear carefully to complaints from entities such as C6, but given the last article, it seems that they are opening the way to the installation of more solar plants. Since it is the municipal councils that approve or reject the projects, they are the ones who will be the biggest obstacle, since they will be in charge of protecting and preserving their natural areas. In this case study, this task will be dealt by the Sines city hall, which can invalidate some locations. Nonetheless, SC will always be recognized for its status and the promised benefits to the local communities, which will help in the social acceptance before such governmental agencies.

This symbiosis, at the technological level, may have several drivers as well as barriers. One reality is that despite the concept of solar farms has been introduced several years ago and being researched and implemented more intensively, the number of innovations towards this concept has increased rapidly to enhance their efficiency and boost their benefits so that their drawbacks are minimized (Neves et al., 2019). As drivers, new techniques of movement and herd management within these lands can push this symbiosis to a new level. Yet, innovations that favor more organizations individually might emerge more quickly. For Start Campus, as there is this symbiosis, there can be other technological breakthroughs, which can present themselves as more viable at all levels. In the same way that for sheep farmers and breeders it may no longer make sense to graze their flocks on these parks if they find more fertile soil or if they find new technologies that improve their wool production.

High-mounted panels with berries production

On an economic level, this symbiosis will have more barriers than drivers in its favor. Installing high-mounted solar panels represents a very high upfront cost for SC, which consequently means a high barrier to the formation of this symbiosis.
Given the quantitative data presented in the previous section, millions of euros would be required to finance such solution on the more than 1500 hectares available to the company. Even if the chosen agricultural firm were to cover all the land maintenance costs and would pay a fixed amount in order to have a percentage of produced electricity to power their necessary systems (irrigation, machinery, etc.), it would never be enough to offset the high initial costs that SC would incur, or at least on a short to medium term.

Furthermore, since this is an innovative project and recent concept to be implemented in Portugal, it implies a project with many risks and uncertainties associated. These two factors combined result in a difficulty increase to obtain funding whether this comes from banks or from investors. Not only that, but looking at the project as a whole, a large workforce will be needed to coordinate a project of this magnitude, which results in additional costs.

On the other hand, the chosen berries production company will be economically driven to force this symbiosis because it can significantly improve its revenue and savings. The aforementioned benefits state that the quality of the food produced is 2 to 3 times better, which can directly translate into higher volume of sales or prices, thus increasing its revenue. In terms of savings, the agricultural company can not only save on water consumption for the maintenance of its crops, but also gain from purchasing energy to SC at a lower price than the market. However, the agricultural industry will always have to keep in mind the initial entry cost such as relocation investment or new crops to be planted, and compare with the benefits after the symbiosis has been established.

In this symbiosis, regulation, and policies besides being linked to the governmental agencies are also highly correlated with social and community acceptance. To start, this symbiosis is still in line with the last alternative being a PV energy project, and, therefore, will have the full support of the Ministry of Environment and the government as seen in the news from Expresso. Yet, in contrast to the last alternative, the C6 coalition stakeholder could be satisfied, as we would take 100% advantage of the land use capabilities, benefiting the ecosystems and biodiversity.

In addition, it would appease another stakeholder, the communities, since involving them in the project development would reflect local values and positive attitudes towards the project. Taking into account that some regulations and policies are started by the local communities' dissatisfaction and unhappiness, with their approval of this symbiosis, we would be one step closer to the governmental agencies to rule in its favor. However, we must always take into account the significant influence that communities have over the government, allowing them to apply pressure and prevent such a symbiosis. Nevertheless, in general, the latest regulations and policies established by governmental bodies seem to be favorable to these types of projects.

At last, the technology factor is of great importance in this symbiosis. Such APV projects are complex to pull off, which generates a lot of concerns for all stakeholders involved, specifically for SC. Focusing on the technical specifics, some concerns are the complexity associated with integration of dual usage beneath the solar panels, the impact of non-optimal angles for the electricity generation, technological know-how to implement the solution, and not to mention the fact that this is a new technology with few pilot projects in Europe, meaning that the technological and human know-how would have to be imported to implement the solution. Considering all these barriers and given the complexity and uncertainty of the project, a slight error, mistake, or change will imply more work, maintenance, training, people, etc., which culminates in more money.

On the other side, this complexity could be seen as a major driver. If the capital is no subject here, this innovative system could generate growth in multiple aspects. This symbiosis may be one of Portugal's pilot initiatives, and with the learning curve, we'd be able to eliminate some drawbacks and reduce some risks in the event of success. As modern technology is advancing so quickly, new technologies could be adopted both for the construction of the SC structures and for the maintenance of the crops by the agricultural company. But looking on a larger scale, to implement such system, a large workforce would be required, so there would be a significant increase in job creation in Sines leading to an increase in local income which in turn leads to a greater local demand for goods and services generating a cycle of growth. In conclusion, this factor can create many drivers as well as barriers, however the key point will be the initial capital, which represents the biggest problem in this equation.

Community solar projects

Remembering that there can be on-site or off-site projects, both have different economic effects, either for the SC or for the participating communities. In this case, SC will not have much incentive to establish this symbiosis except for 2 drivers: 1) SC will be able to obtain some additional revenue with the sold electricity. Even though the company will not be able to sell it at market price, it is surplus sold, which normally would be traded at production cost; 2) In the case of on-site projects, it would allow some savings in the land acquisition – exchange of land for solar panels and energy; installing costs – cheaper to install panels on the roof than on the ground given the structure and materials needed; and O&M costs - The landowners would be in responsibility of maintaining the solar panels that were installed on their properties and ensuring the good functioning in accordance with SC's guidance and best practices.

The story changes when it comes to the communities' perspective. These projects represent a great opportunity for the communities given the economic recession we are currently experiencing, induced by the covid pandemic, and aggravated by the situation in Ukraine that ultimately resulted in a global energy crisis. Being part of such projects, communities would have access to lower-cost energy and additional lease revenue, which consequently would increase the likelihood of this symbiosis to be established. Given the low-income households in the area, these savings are expected to have a major impact by lowering the energy burden for local communities. Moreover, establishing these projects can largely stimulate the job creation on construction and operations jobs. Not only would landowners develop know-how to operate solar panels, but, in the future, help with the upkeep of other solar farms.

At the regulatory level, this symbiosis is well supported by regulators. The Ministry of Environment with the Environmental Fund[7] has created a program of support for the implementation of Renewable Energy Communities (REC). This program aims to finance initiatives that promote the production of electricity from renewable sources under REC. Specifically it is intended to lead to a 30% reduction in primary energy consumption, on average, in the benefiting buildings, and to increase REC capacity in the residential, central public administration and service sectors by at least 93 MW. Both residential customers and companies will be eligible for this funding, therefore in this instance, SC and communities can seek to participate in this program. This is just one of several government-created initiatives to assist communities and move society toward a sustainable, clean-energy-based future. In addition, this symbiosis will be providing more opportunities and benefits to the communities thus the government agencies will act as drivers and not barriers as they hardly oppose to such project and will even encourage and facilitate it.

This symbiosis will not be a technological innovation as there are already some REC projects underway in Portugal and the infrastructure will be the most typical, meaning ground or roof-mounted solar panels. In this sense, this project will have no technological barriers, only if some properties have particularly uneven and rough ground or cannot sustain such infrastructure, or if the houses/buildings are not suitable for the installation of solar panels on their roofs. So, technologically, it can only result in advancements in either increased panel efficiency, which enhances electricity generation or new techniques for installing panels allowing faster installation and less environmental impact.

At last, the organizational parameter is transversal to all the alternatives and is essentially linked to the good relationship that the stakeholders will require as they will determine whether or not to start a symbiosis. In this case, some best practices are: full engagement of the respective stakeholders in the phases that concern them; good and effective communication between all

[7] See https://www.fundoambiental.pt/apoios-prr/c13-eficiencia-energetica-em-edificios/c13-i01-02-03-apoio-a-concretizacao-de-comunidades-de-energia-renovavel-e-autoconsumo-coletivo.aspx (accessed on October 2022)

parties; and above all transparency. All these will drive and accelerate the realization and implementation of any alternative.

Or else, various barriers can be formed as frequently there is a lack of openness, willingness, and trust (Bacudio et al., 2016; Park et al., 2018), which could hinder the start of this kind of collaboration for several reasons. An example is if one of the participating organizations realizes that they are not benefiting from the agreement as much as Start Campus or are being undermined. In such scenario, one strategy to overcome this barrier will be to introduce facilitating entities that act as intermediaries in the negotiations as they will act impartially. Yet, above all that, there should be trust and honesty between the participating entities, as this is the basic principle of any symbiotic relationship.

5. Discussion

Through the case study analysis, we identified three major stakeholders that are critical to the establishment of an IS with the solar parks that SC will build to power its data centers.

From the analysis, we highlight the Sines City Hall, which is in charge of approving the upcoming projects for SC, since all solar parks so far are located in the Sines municipality. Encouraging a good relationship with the city hall will be in the best interest of the company in the short and long term, to guarantee a faster-licensing approval, or else, the project's deadlines might be delayed and jeopardize other stages. Second, the company is responsible for developing the solar panels and for mounting all structures according to the SC's guidelines. The company will only be chosen after knowing the type of solar park and symbiosis that SC wants to install. This choice has to be thoughtful and meticulous since a large portion of the capital cost will be applied here. Therefore, the expectations and quality standards of the product supplied will be very high, as it represents the foundation of the whole project. At last, the local communities exert a great deal of power over the project's social acceptance. Conflicts with this stakeholder will likely lead to disagreement and possible demonstrations that could damage the project's reputation and, in extreme cases could result in the project's termination.

Afterward, three possible symbioses to be formed with solar parks were found, namely: Ground-mounted panels with sheep farming (Option 1); High-mounted panels with berries production (Option 2); and Community solar projects (Option 3). After these findings, all symbioses were submitted to a benefit vs. drawbacks and drivers vs. barriers evaluation.

Starting with the first option, ground-mounted panels with sheep farming show interesting results. Without a doubt, the biggest advantage and driver for SC will be the significant reduction in O&M costs. Sheep grazing the land not only replaces the machinery and herbicides required for land maintenance but also ensures that weeds and plants do not grow large enough to block the panels, which would lead to less sun exposure and less electricity generated. As a result of not requiring fossil fuel-powered machinery, this symbiosis reduces GHG emissions and promotes a positive impact on biodiversity, vegetation, and soil sequestration. It is vital to perform a deeper evaluation of this impact since it deeply concerns society in light of the exponential growth in solar parks' construction as research shows that land use change can cause much habitat loss.

Economically speaking, the shepherds will certainly also be pleased given the additional revenue this symbiosis can generate for them. It can be either by receiving a direct fee for grazing sheep on the fields or supplied with energy generated meaning a decrease in their electricity bills or even indirectly where sheep generate higher wool quality thus originating higher prices. However, the big question that remains is whether the local communities have enough flocks and human resources to match the 1500+ ha that SC will need to care for.

Moving on to the second identified symbiosis, high-mounted panels with berries production, it was possible to conclude that it is a complex system but with potential. Financially it will way more expensive than our last referred option, ground-mounted panels, as the structure is a new technology with high implementation complexity with less than a dozen cases in Portugal. Even with the benefits brought by the agricultural industry, namely maximization of land use efficiency, control and cost assurance over land maintenance, and carbon footprint reduction, SC will still be reluctant due to the high costs since they are not in business to lose money. In addition, the technological barrier will bring difficulties since the technological and human know-how has to be imported from successful pilot cases abroad.

In order to overcome these drawbacks and barriers, at an early stage, SC could recur to governmental institutions, such as the Ministry of Environment, to provide incentives and funds to support the establishment of these new systems full of potential. Afterward, economies of scale could appear leading the solar panels' production price to decrease, which has been happening for all types in the last decade. This way, SC would have the initial leverage needed to start this project which would greatly help communities by stimulating job creation, and consequently, the local economy. With this proper incentive, the berries production companies could then apply to these projects taking advantage of perks such as power supply for irrigation systems or the machinery responsible for crop maintenance.

Finally, the last symbiosis refers to community solar projects, which have grown in popularity in Portugal. Clearly, the biggest driver for SC to move forward with this project will be the increase in its social acceptance rate within the communities and country. Involving the local communities will only make some of Start Campus' problems, such as the large land use needed, be overlooked given the benefits generated to locals, for example, the possibility to have a 20% - 30% electricity bills reduction, which makes a significant impact on certain families due to the global energy crisis we currently face.

Looking to governmental agencies and their policies, these projects will have their support and incentives like the Environmental fund, rather than becoming a barrier as this symbiosis will only promote sustainability and stimulate the Sines local economy. Nevertheless, local communities will have to be careful and establish well-defined contracts bearing in mind that this could be a temporary project. It is important not to forget the main purpose for the creation of these solar parks, which is the power supply to the data centers. Only after assuring this, can SC start providing the energy excess to the transmission grid for other purposes.

Based on the results obtained, all three symbioses seem to have a lot of potential. Comparing all symbioses in general, the most viable economic option for SC would be sheep grazing in its solar parks, as they would continue to construct the most used structures on the market, ground-mounted panels, and would save on maintenance costs.

As for sustainability, all alternatives promote good practices, however establishing a connection with a berries production company stands out due to its major benefit of guaranteeing maximum land efficiency. In terms of regulations and policies, Portugal is currently offering many incentives towards solar energy production and if it can provide further benefits to the communities and nation even better, making all symbioses viable initiatives. As for the technological factor, the most innovative is undoubtedly the high-mounted panels over agricultural crops, yet also the most complex and difficult to implement. In the social aspect, developing community solar projects will be the most appealing symbiosis given the direct benefits it generated in the face of this energy crisis. Last but not least, the organizational aspect will be the key to establishing any of these symbioses as all stakeholders need their concerns to be heard and interests to be taken into consideration, to achieve a successful project.

All this is purely a theoretical analysis, so it is recommendable that SC actually evaluates the initial costs and the possible environmental impact to be able to draw more concrete conclusions. Additionally, most information obtained is based on case studies in other countries, so it is recommended to understand the major differences to implement such projects in Portugal.

6. Conclusion and Recommendation

This last chapter aims to synthesize the work developed on the possible implementation and promotion of new symbioses for the upcoming solar parks that Start Campus will construct. This section also presents some recommendations for future work on this topic.

Nowadays, even though companies are more aware of the circular economy and industrial ecology, it is necessary to develop strategies and techniques to promote this new economic model. This dissertation explores one of the associated strategies within these two concepts, namely industrial symbiosis. This concept promotes the resource exchange between firms in industrial processes, where the outputs of a company can be the inputs of other organizations or vice-versa. The main objective of this exchange is to provide mutual benefits and opportunities for the participating organizations.

Hence, the concept served as an inspiration to achieve this dissertation's aim of investigating viable possible symbioses of solar park projects with other industries or local communities. To this end, the case study methodology was adopted for a specific case – Start Campus' solar parks. The main purpose of these solar parks will be to supply energy to the data centers, however, there are opportunities to explore, namely the amount of necessary land to implement these structures and the excess energy that can be produced.

In the application of the methodology, we were able to identify the stakeholders with the greatest influence in a possible symbiosis with solar energy production, beyond the participating entities – Sines City Hall, the future solar panel developing company, and the local communities. The application also allowed us to identify three possible symbioses, two with the agricultural industry – ground-mounted panels with sheep farming and high-mounted panels with berries production; and one with local communities – community solar projects. This identification was based on other case studies of IS with solar parks that have been applied and implemented around the world.

Afterward, an analysis of benefits and drawbacks was performed on each alternative individually, which allowed to accurately identify what the target organization has to offer to SC and vice versa. From this analysis, we highlight the main benefits and drawbacks of each symbiosis:

- Solar parks with sheep farming – Reduction in land maintenance costs and GHG emissions for SC; Extra income for shepherds; Higher lamb welfare and wool quality; Land misuse; Possible sheep and manpower shortage for the amount of land
- Solar parks with berries production – Maximization of total land use; Positive impact on biodiversity; Reduction in electricity and water bills; Higher fruit quality; Very high initial costs for SC; High structure complexity; Relocation difficulties for target companies.

- Community solar projects – Full engagement with local communities; Best use of the excess energy produced; Reduction in electricity bills; Less reliance on fossil fuels, thus reducing carbon footprint; Land misuse; Possibility of being just a temporary project

Finally, we performed an analysis of the major drivers and barriers according to four parameters – economic, regulatory, social, and organizational to understand if these symbioses can be promoted or if too many obstacles hinder their implementation. Main drivers that stood out: contribution to sustainable development, contribution to an improved company image, reduction in consumption of natural resources, financial incentives, and funds, process innovation; job creation; higher social acceptance rate; local economy stimulation. In terms of barriers, the following caught our eye: high investment costs, high complexity projects, lack of investment in innovative projects, concern about the impact on biodiversity, lack of human and technological know-how, lack of communication and information exchange, and lack of cooperation and trust.

Combining all these results, we can conclude that it is possible to involve communities and/or industries in the implementation of solar parks. Also, important to mention that these are only three of the many different possible symbioses that can be established with the solar energy industry, as the existing research is lagging behind. One last conclusion is that, despite the high costs that the solar panel structures possess, it is possible to obtain several benefits that can contribute to a higher cause, meaning stimulation of society and the country's economy.

Note that the study has some limitations, for example, the lack of identification of stakeholders influencing the target organization since it can lead to the introduction of new key players that can generate other benefits or conflicts. Another limitation of this case study is the analysis of benefits, drawbacks, drivers, and barriers, which was based on other international projects and only had one value judgment – the author that can cause biased results.

As a recommendation for Start Campus, it is proposed to assess the real investment necessary to implement any of these alternatives and a life cycle assessment to understand the real impact on the ecosystem. After this evaluation, the next step could be to resort to a multiple-criteria decision analysis with the most important criteria and corresponding weighing to the company, in order to identify the best alternative for them.

As a suggestion for future research, it is advised to expand the practice of industrial symbiosis to other activity sectors, through the exploration of new case studies. These should involve materials, products, energy, or by-products from other industries and different applications should be explored for their commercialization in other areas.

7. References

Ali Bekhet, H., & Yasmin, T. (2014). Assessment of the global financial crisis effects on energy consumption and economic growth in Malaysia: An input–output analysis. *International Economics*, *140*, 49–70. https://doi.org/10.1016/J.INTECO.2014.07.003

Al-Karkhi, Z., & Fadhel, J. (2020). *Implementation of Industrial Symbiosis - How can a collaborative network improve waste management?* https://www.diva-portal.org/smash/get/diva2:1458312/FULLTEXT01.pdf

Amador, J. (2010). Produção e Consumo de Energia em Portugal. *Boletim Económico | Banco de Portugal*, 71–86.

Aviso, K. B., Laddaran, A., & Ngo, J. S. (2022). Modelling Stakeholder Goals in Industrial Symbiosis. In *Process Integration and Optimization for Sustainability* (Vol. 6, Issue 2, pp. 543–558). Springer. https://doi.org/10.1007/s41660-022-00226-6

Azevedo, J., Henriques, J., Estrela, M., Dias, R., Vladimirova, D., Miller, K., & Iten, M. (2021). Guidelines for Industrial Symbiosis—a Systematic Approach for Content Definition and Practical Recommendations for Implementation. *Circular Economy and Sustainability*, *1*(2), 507–523. https://doi.org/10.1007/s43615-021-00006-3

Bacudio, L. R., Benjamin, M. F. D., Eusebio, R. C. P., Holaysan, S. A. K., Promentilla, M. A. B., Yu, K. D. S., & Aviso, K. B. (2016). Analyzing barriers to implementing industrial symbiosis networks using DEMATEL. *Sustainable Production and Consumption*, *7*, 57–65. https://doi.org/10.1016/j.spc.2016.03.001

Badawy, N. M., El Samaty, H. S., & Waseef, A. A. E. (2022). Relevance of monocrystalline and thin-film technologies in implementing efficient grid-connected photovoltaic systems in historic buildings in Port Fouad city, Egypt. *Alexandria Engineering Journal*, *61*(12), 12229–12246. https://doi.org/10.1016/J.AEJ.2022.06.007

Baldassarre, B., Schepers, M., Bocken, N., Cuppen, E., Korevaar, G., & Calabretta, G. (2019). Industrial Symbiosis: towards a design process for eco-industrial clusters by integrating Circular Economy and Industrial Ecology perspectives. *Journal of Cleaner Production*, *216*, 446–460. https://doi.org/10.1016/J.JCLEPRO.2019.01.091

Bay Journal. (2022). *Sheep and Solar Panels: Using Solar Sites for Pastureland*. Maryland Matters. https://www.marylandmatters.org/2022/05/05/sheep-and-solar-panels-using-solar-sites-for-pastureland/

Bayod-Rújula, Á. A., Lorente-Lafuente, A. M., & Cirez-Oto, F. (2011). Environmental assessment of grid connected photovoltaic plants with 2-axis tracking versus fixed modules systems. *Energy*, *36*(5), 3148–3158. https://doi.org/10.1016/J.ENERGY.2011.03.004

Blaydes, H., Potts, S. G., Whyatt, J. D., & Armstrong, A. (2021). Opportunities to enhance pollinator biodiversity in solar parks. In *Renewable and Sustainable Energy Reviews* (Vol. 145). Elsevier Ltd. https://doi.org/10.1016/j.rser.2021.111065

Brodziński, Z., Brodzińska, K., & Szadziun, M. (2021). Photovoltaic farms—economic efficiency of investments in North-East Poland. *Energies*, *14*(8). https://doi.org/10.3390/en14082087

Bruel, A., Kronenberg, J., Troussier, N., & Guillaume, B. (2019). Linking Industrial Ecology and Ecological Economics: A Theoretical and Empirical Foundation for the Circular Economy. *Journal of Industrial Ecology*, *23*(1), 12–21. https://doi.org/10.1111/jiec.12745

Bryson, J. M. (2004). What to do when stakeholders matter: Stakeholder Identification and analysis techniques. *Public Management Review*, *6*(1), 21–53. https://doi.org/10.1080/14719030410001675722

Butturi, M. A., Lolli, F., Sellitto, M. A., Balugani, E., Gamberini, R., & Rimini, B. (2019). Renewable energy in eco-industrial parks and urban-industrial symbiosis: A literature review and a conceptual synthesis. *Applied Energy*, *255*, 113825. https://doi.org/10.1016/J.APENERGY.2019.113825

Casares de la Torre, F. J., Varo-Martinez, M., López-Luque, R., Ramírez-Faz, J., & Fernández-Ahumada, L. M. (2022). Design and analysis of a tracking / backtracking strategy for PV plants with horizontal trackers after their conversion to agrivoltaic plants. *Renewable Energy*, *187*, 537–550. https://doi.org/10.1016/J.RENENE.2022.01.081

Chertow, M., & Ehrenfeld, J. (2012). Organizing Self-Organizing Systems: Toward a Theory of Industrial Symbiosis. *Journal of Industrial Ecology*, *16*(1), 13–27. https://doi.org/10.1111/j.1530-9290.2011.00450.x

Chertow, M. R. (2000). Industrial symbiosis: Literature and taxonomy. *Annual Review of Energy and the Environment*, *25*(November 2000), 313–337. https://doi.org/10.1146/annurev.energy.25.1.313

Clean Energy Regulator. (2022). *Combining sheep farming and solar panels at Numurkah*. https://www.cleanenergyregulator.gov.au/Infohub/case-studies/Pages/ret-case-studies/Combining-sheep-farming-and-solar-panels-at-Numurkah.aspx

Colvin, R. M., Witt, G. B., & Lacey, J. (2016). Approaches to identifying stakeholders in environmental management: Insights from practitioners to go beyond the "usual suspects." *Land Use Policy*, *52*, 266–276. https://doi.org/10.1016/j.landusepol.2015.12.032

DataCenterDynamics. (2022). *Interview to Afonso Salema (Start Campus)*. https://www.datacenterdynamics.com/br/análises/afonso-salema-start-campus-sines-40-será-um-dos-maiores-campi-de-data-center-da-europa/

de Vries, W. (2021, September). "Solar panels above raspberry crops benefit everyone." *Horti Daily*. https://www.hortidaily.com/article/9354893/solar-panels-above-raspberry-crops-benefit-everyone/

Demir Duru, S., & Kechichian, E. (2021). n International Framework For Eco-Industrial Parks. *World Bank Publications*.

Dinheiro Vivo. (2021). Ambientalistas pedem legislação que regule instalação de centrais fotovoltaicas. *Dinheiro Vivo*. https://www.dinheirovivo.pt/economia/ambientalistas-pedem-legislacao-que-regule-instalacao-de-centrais-fotovoltaicas-13891393.html

Dubey, S., Sarvaiya, J. N., & Seshadri, B. (2013). Temperature Dependent Photovoltaic (PV) Efficiency and Its Effect on PV Production in the World – A Review. *Energy Procedia*, *33*, 311–321. https://doi.org/10.1016/J.EGYPRO.2013.05.072

Dusonchet, L., & Telaretti, E. (2015). Comparative economic analysis of support policies for solar PV in the most representative EU countries. *Renewable and Sustainable Energy Reviews*, *42*, 986–998. https://doi.org/10.1016/j.rser.2014.10.054

ECO. (2022). *Start Campus inicia construção de mega centro de dados em Sines*. https://eco.sapo.pt/2022/04/26/start-campus-inicia-construcao-de-mega-centro-de-dados-em-sines/

Ehrenfeld, J., & Gertler, N. (1997). Industrial ecology in practice. *Journal of Industrial Ecology*, *1*(1), 67–79.

Eilering, J. A. M., & Vermeulen, W. J. V. (2004). Eco-industrial parks: toward industrial symbiosis and utility sharing in practice. *Progress in Industrial Ecology*, *1*(1–3), 245–270. https://doi.org/10.1504/pie.2004.004681

Elamri, Y., Cheviron, B., Lopez, J. M., Dejean, C., & Belaud, G. (2018). Water budget and crop modelling for agrivoltaic systems: Application to irrigated lettuces. *Agricultural Water Management*, *208*, 440–453. https://doi.org/10.1016/J.AGWAT.2018.07.001

El-Haggar, S. M. (2007). Sustainable Development and Environmental Reform. *Sustainable Industrial Design and Waste Management*, 125–148. https://doi.org/10.1016/B978-012373623-9/50006-X

Elia, V., Gnoni, M. G., & Tornese, F. (2017). Measuring circular economy strategies through index methods: A critical analysis. *Journal of Cleaner Production*, *142*, 2741–2751. https://doi.org/10.1016/J.JCLEPRO.2016.10.196

Erkman, S. (1997). Industrial ecology: An historical view. *Journal of Cleaner Production*, *5*(1–2), 1–10. https://doi.org/10.1016/S0959-6526(97)00003-6

EU. (2008). Renewable energy directive. *Official Journal of the European Union*, *1*, 32–38.

EU. (2018). Directive (EU) 2018/2001 of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. *Official Journal of the European Union*, *2018*(L 328), 82–209.

Eurostat. (2020). *Energy data 2020 edition*.

Expresso. (2022, February). Produção de energia solar em Portugal atinge novo máximo histórico. *Expresso*. https://expresso.pt/economia/2022-02-22-producao-de-energia-solar-em-portugal-atinge-novo-maximo-historico

Fedoseeva, S., & Zeidan, R. (2018). How (a)symmetric is the response of import demand to changes in its determinants? Evidence from European energy imports. *Energy Economics*, *69*, 379–394. https://doi.org/10.1016/J.ENECO.2017.12.009

Feuerbacher, A., Herrmann, T., Neuenfeldt, S., Laub, M., & Gocht, A. (2022). Estimating the economics and adoption potential of agrivoltaics in Germany using a farm-level bottom-up approach. *Renewable and Sustainable Energy Reviews*, *168*, 112784. https://doi.org/10.1016/J.RSER.2022.112784

Finn, T., & McKenzie, P. (2020). A high-resolution suitability index for solar farm location in complex landscapes. *Renewable Energy*, *158*, 520–533. https://doi.org/10.1016/J.RENENE.2020.05.121

Fraunhofer Institute for Solar Energy Systems, & PSE Projects GmbH. (2022). *Photovoltaics Report -2022- Fraunhofer ISE*. *February*, https://www.ise.fraunhofer.de/conte%0Ant/dam/ise/d.

Gan, C. K., Lee, Y. M., Pudjianto, D., & Strbac, G. (2014). Role of losses in design of DC cable for solar PV applications. *2014 Australasian Universities Power Engineering Conference, AUPEC 2014 - Proceedings*, *October* 2–6. https://doi.org/10.1109/AUPEC.2014.6966594

Geng, Y., Zhang, P., Côté, R. P., & Fujita, T. (2009). Assessment of the national eco-industrial park standard for promoting industrial symbiosis in China. *Journal of Industrial Ecology*, *13*(1), 15–26. https://doi.org/10.1111/j.1530-9290.2008.00071.x

Gerbinet, S., Belboom, S., & Léonard, A. (2014). Life Cycle Analysis (LCA) of photovoltaic panels: A review. *Renewable and Sustainable Energy Reviews*, *38*, 747–753. https://doi.org/10.1016/J.RSER.2014.07.043

Gibbs, D., & Deutz, P. (2005). Implementing industrial ecology? Planning for eco-industrial parks in the USA. *Geoforum*, *36*(4), 452–464. https://doi.org/10.1016/J.GEOFORUM.2004.07.009

Glick, A., Smith, S. E., Ali, N., Bossuyt, J., Recktenwald, G., Calaf, M., & Cal, R. B. (2020). Influence of flow direction and turbulence intensity on heat transfer of utility-scale photovoltaic solar farms. *Solar Energy*, *207*(November 2019), 173–182. https://doi.org/10.1016/j.solener.2020.05.061

Gong, Q., Kou, F., Sun, X., Zou, Y., Mo, J., & Wang, X. (2022). Towards zero energy buildings: A novel passive solar house integrated with flat gravity-assisted heat pipes. *Applied Energy*, *306*, 117981. https://doi.org/10.1016/J.APENERGY.2021.117981

Grant, G. B., Seager, T. P., Massard, G., & Nies, L. (2010). Information and communication technology for industrial symbiosis. *Journal of Industrial Ecology*, *14*(5), 740–753. https://doi.org/10.1111/j.1530-9290.2010.00273.x

GroenLeven. (2020). *The perfect dual role for the sustainable farmer*. https://groenleven.nl/zonneparken/agri/

Guoqing, L., Hernandez, R. R., Blackburn, G. A., Davies, G., Hunt, M., Whyatt, J. D., & Armstrong, A. (2021). Ground-mounted photovoltaic solar parks promote land surface cool islands in arid ecosystems. *Renewable and Sustainable Energy Transition*, *1*, 100008. https://doi.org/10.1016/j.rset.2021.100008

Harris, S., & Pritchard, C. (2004). Industrial Ecology as a learning process in business strategy. *Progress in Industrial Ecology*, *1*(1–3), 89–111. https://doi.org/10.1504/pie.2004.004673

He, X. H., Ding, H., Jing, H. Q., Wu, X. P., & Weng, X. J. (2021). Mechanical characteristics of a new type of cable-supported photovoltaic module system. *Solar Energy*, *226*, 408–420. https://doi.org/10.1016/J.SOLENER.2021.08.065

Heeres, R. R., Vermeulen, W. J. V., & de Walle, F. B. (2004). Eco-industrial park initiatives in the USA and the Netherlands: First lessons. *Journal of Cleaner Production*, *12*(8–10), 985–995. https://doi.org/10.1016/j.jclepro.2004.02.014

Henriques, S. T. (2011). *Energy Transitions, Economic Growth and Structural Change: Portugal in a Long-run Comparative Perspective*. Lund University.

Henriques, S. T., & Borowiecki, K. J. (2014). The Drivers of Long-Run CO2 Emissions: A Global Perspective Since 1800. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.2486501

Hitchin, R. (2019). Primary Energy Factors and the primary energy intensity of delivered energy: An overview of possible calculation conventions. *Building Services Engineering Research and Technology*, *40*(2), 198–219. https://doi.org/10.1177/0143624418799716

Horbach, J., & Rammer, C. (2018). Energy transition in Germany and regional spill-overs: The diffusion of renewable energy in firms. *Energy Policy*, *121*, 404–414. https://doi.org/10.1016/j.enpol.2018.06.042

Idealista. (2022). Apoios energias renováveis: tudo sobre os incentivos ao autoconsumo. *Idealista*. https://www.idealista.pt/news/financas/economia/2022/10/20/54564-apoios-energias-renovaveis-tudo-sobre-os-incentivos-ao-autoconsumo

International Energy Agency. (2009). *Portugal 2009 Review - Energy Policies of IEA Countries*.

Jacobsen, N. B. (2006). Industrial symbiosis in Kalundborg. *VGB PowerTech*, *79*(10), 52–54.

Jäger-Waldau, A. (2007). Photovoltaics and renewable energies in Europe. *Renewable and Sustainable Energy Reviews*, *11*(7), 1414–1437. https://doi.org/10.1016/j.rser.2005.11.001

Jahid, A., Monju, K. H., Hossain, S., & Hossain, F. (2019). Hybrid power supply solutions for off-grid green wireless networks. *International Journal of Green Energy*, *16*(1), 12–33. https://doi.org/10.1080/15435075.2018.1529593

Johansen, K. (2021). Blowing in the wind: A brief history of wind energy and wind power technologies in Denmark. *Energy Policy*, *152*, 112139. https://doi.org/10.1016/J.ENPOL.2021.112139

Jose, H., & Calver, O. (2022, May 30). *Solar farm trial shows improved fleece on merino sheep grazed under panels*. ABC Rural News. https://www.abc.net.au/news/rural/2022-05-30/solar-farm-grazing-sheep-agriculture-renewable-energy-review/101097364

Kapur, A., & Graedel, T. E. (2004). Industrial Ecology. *Encyclopedia of Energy*, 373–382. https://doi.org/10.1016/B0-12-176480-X/00533-7

Korhonen, J., Honkasalo, A., & Seppälä, J. (2018). Circular Economy: The Concept and its Limitations. *Ecological Economics*, *143*, 37–46. https://doi.org/10.1016/J.ECOLECON.2017.06.041

Kørnøv, L., Lyhne, I., Schlüter, L., & Nors, B. (2020). Sustainable Synergies: Experiences from facilitating Industrial Symbiosis in Aalborg East 2017-2020. In *Aalborg University*.

Landes, D. S. (1969). Unbound Prometheus. In *Technological change and industrial development in Western Europe from 1750 to the present*. Cambridge University Press. https://doi.org/10.7551/mitpress/8906.003.0006

Lee, M., Hong, T., Yoo, H., Koo, C., Kim, J., Jeong, K., Jeong, J., & Ji, C. (2017). Establishment of a base price for the Solar Renewable Energy Credit (SREC) from the perspective of residents and state governments in the United States. *Renewable and Sustainable Energy Reviews*, *75*(November 2016), 1066–1080. https://doi.org/10.1016/j.rser.2016.11.086

Lehtoranta, S., Nissinen, A., Mattila, T., & Melanen, M. (2011). Industrial symbiosis and the policy instruments of sustainable consumption and production. *Journal of Cleaner Production*, *19*(16), 1865–1875. https://doi.org/10.1016/J.JCLEPRO.2011.04.002

Lim, C., & Lee, J. (2020). An analysis of the efficiency of the oil refining industry in the OECD countries. *Energy Policy*, *142*, 111491. https://doi.org/10.1016/J.ENPOL.2020.111491

Maguire, B., Potts, J., & Fletcher, S. (2012). The role of stakeholders in the marine planning process-Stakeholder analysis within the Solent, United Kingdom. *Marine Policy*, *36*(1), 246–257. https://doi.org/10.1016/j.marpol.2011.05.012

Majewski, P., Al-shammari, W., Dudley, M., Jit, J., Lee, S. H., Myoung-Kug, K., & Sung-Jim, K. (2021). Recycling of solar PV panels- product stewardship and regulatory approaches. *Energy Policy*, *149*, 112062. https://doi.org/10.1016/J.ENPOL.2020.112062

Martínez, M. V., Ahumada, L. M. F. De, García, M. F., García, P. F., & Torre, C. De. (2022). Characterization of an experimental agrivoltaic installation located in a educational centre for farmers in Cordoba (Spain). *University of Cordoba*, *20*, 111–115.

Mavrokefalidis, D. (2021). *Can berries grow better under solar panels?* Energy Live News. https://www.energylivenews.com/2021/04/06/can-berries-grow-better-under-solar-panels/

Miguel, C. V., Mendes, A., & Madeira, L. M. (2018). An overview of the Portuguese energy sector and perspectives for power-to-gas implementation. *Energies*, *11*(12). https://doi.org/10.3390/en11123259

Mirata, M., & Emtairah, T. (2005). Industrial symbiosis networks and the contribution to environmental innovation: The case of the Landskrona industrial symbiosis programme. *Journal of Cleaner Production*, *13*(10–11), 993–1002. https://doi.org/10.1016/J.JCLEPRO.2004.12.010

Mirzaei, M., & Mohiabadi, M. Z. (2017). A comparative analysis of long-term field test of monocrystalline and polycrystalline PV power generation in semi-arid climate conditions. *Energy for Sustainable Development*, *38*, 93–101. https://doi.org/10.1016/J.ESD.2017.01.002

Morseletto, P. (2020). Targets for a circular economy. *Resources, Conservation and Recycling*, *153*, 104553. https://doi.org/10.1016/J.RESCONREC.2019.104553

Mortensen, L., & Nors, B. (2020). *Industrial Symbiose Nord*. https://industrielsymbiosenord.com/?lang=en#vand

Nealon, S. (2021, April). Combining solar panels and lamb grazing increases land productivity, study finds. *Oregon State University*. https://today.oregonstate.edu/news/combining-solar-panels-and-lamb-grazing-increases-land-productivity-study-finds

Neves, A., Godina, R., Azevedo, S. G., Pimentel, C., & Matias, J. C. O. (2019). The Potential of Industrial Symbiosis: Case Analysis and Main Drivers and Barriers to Its Implementation. *Sustainability (Switzerland)*, *11*(24), 1–68. https://doi.org/10.3390/su11247095

Omrany, H., GhaffarianHoseini, A., GhaffarianHoseini, A., Raahemifar, K., & Tookey, J. (2016). Application of passive wall systems for improving the energy efficiency in buildings: A comprehensive review. *Renewable and Sustainable Energy Reviews*, *62*, 1252–1269. https://doi.org/10.1016/J.RSER.2016.04.010

Pacca, S., Sivaraman, D., & Keoleian, G. A. (2007). Parameters affecting the life cycle performance of PV technologies and systems. *Energy Policy*, *35*(6), 3316–3326. https://doi.org/10.1016/J.ENPOL.2006.10.003

Palmer, D., Gottschalg, R., & Betts, T. (2019). The future scope of large-scale solar in the UK: Site suitability and target analysis. *Renewable Energy*, *133*, 1136–1146. https://doi.org/10.1016/J.RENENE.2018.08.109

Park, J., Duque-Hernández, J., & Díaz-Posada, N. (2018). Facilitating business collaborations for industrial symbiosis: The pilot experience of the sustainable industrial network program in Colombia. *Sustainability (Switzerland)*, *10*(10). https://doi.org/10.3390/su10103637

Pearce, J. M. (2008). Industrial symbiosis of very large-scale photovoltaic manufacturing. *Renewable Energy*, *33*(5), 1101–1108. https://doi.org/10.1016/j.renene.2007.07.002

Peng, H.-K., Zhao, H.-Y., Zhang, X.-F., Li, T.-T., Wang, Y., Lou, C.-W., & Lin, J.-H. (2022). Fabric composites inspired by the structure of polar bear hair for collecting solar thermal energy. *Sustainable Energy Technologies and Assessments*, *52*, 102205. https://doi.org/10.1016/J.SETA.2022.102205

Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). Circular economy: Measuring innovation in the product chain. *PBL Netherlands Environmental Assessment Agency*, *2544*, 42.

Prada, M. (2022, October). Novas regras para acelerar instalação de centrais solares entram em vigor esta quinta-feira. *Jornal Expresso*. https://expresso.pt/economia/2022-10-19-Novas-regras-para-acelerar-instalacao-de-centrais-solares-entram-em-vigor-esta-quinta-feira-535c10c0

Puig, R. F. (2019). *The roles of industrial ecology and circular economy: a literature review and a classroom application*. *October*.

Rahman, M. M., Khan, I., Field, D. L., Techato, K., & Alameh, K. (2022). Powering agriculture: Present status, future potential, and challenges of renewable energy applications. *Renewable Energy*, *188*, 731–749. https://doi.org/10.1016/J.RENENE.2022.02.065

RTP. (2017, April). *Alentejo é a região do país com maior criação de ovinos*. RTP. https://www.rtp.pt/noticias/pais/alentejo-e-a-regiao-do-pais-com-maior-criacao-de-ovinos_v992839

Saavedra, Y. M. B., Iritani, D. R., Pavan, A. L. R., & Ometto, A. R. (2018). Theoretical contribution of industrial ecology to circular economy. *Journal of Cleaner Production*, *170*, 1514–1522. https://doi.org/10.1016/J.JCLEPRO.2017.09.260

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., & Kim, H. (2020). How circular economy and industrial ecology concepts are intertwined? *University of Illinois*.

Sánchez-Lozano, J. M., García-Cascales, M. S., & Lamata, M. T. (2016). Comparative TOPSIS-ELECTRE TRI methods for optimal sites for photovoltaic solar farms. Case study in Spain.

Journal of Cleaner Production, *127*, 387–398. https://doi.org/10.1016/J.JCLEPRO.2016.04.005

Schlüter, L., Mortensen, L., & Kørnøv, L. (2020). Industrial symbiosis emergence and network development through reproduction. *Journal of Cleaner Production*, *252*, 119631. https://doi.org/10.1016/J.JCLEPRO.2019.119631

Sharma, A. (2011). A comprehensive study of solar power in India and World. *Renewable and Sustainable Energy Reviews*, *15*(4), 1767–1776. https://doi.org/10.1016/J.RSER.2010.12.017

Silva, B. (2021). Comunidades de energia prometem poupança até 30% na conta da luz. *Eco Sapo*. https://eco.sapo.pt/2021/02/10/comunidades-de-energia-prometem-poupanca-ate-30-na-conta-da-luz/

Sodhi, M., Banaszek, L., Magee, C., & Rivero-Hudec, M. (2022). Economic Lifetimes of Solar Panels. *Procedia CIRP*, *105*, 782–787. https://doi.org/10.1016/j.procir.2022.02.130

Stahel, W. R. (2016). The circular economy. *Nature*, *531*(7595), 435–438. https://doi.org/10.1038/531435a

Szczygielski, J. J., Brzeszczyński, J., Charteris, A., & Bwanya, P. R. (2021). The COVID-19 storm and the energy sector: The impact and role of uncertainty. *Energy Economics*, 105258. https://doi.org/10.1016/J.ENECO.2021.105258

Toledo, C., & Scognamiglio, A. (2021). *Agrivoltaic Systems Design and Assessment: A Critical Review, and a Descriptive Model towards a Sustainable Landscape Vision*. https://doi.org/10.3390/su13126871

Topić, D., Knežević, G., & Fekete, K. (2017). The mathematical model for finding an optimal PV system configuration for the given installation area providing a maximal lifetime profit. *Solar Energy*, *144*, 750–757. https://doi.org/10.1016/J.SOLENER.2017.02.011

Trommsdorff, M., Kang, J., Reise, C., Schindele, S., Bopp, G., Ehmann, A., Weselek, A., Högy, P., & Obergfell, T. (2021). Combining food and energy production: Design of an agrivoltaic system applied in arable and vegetable farming in Germany. *Renewable and Sustainable Energy Reviews*, *140*, 110694. https://doi.org/10.1016/J.RSER.2020.110694

Tumilo, R. (2022, March). *Agrivoltaics - harnessing the sun for both food and electricity.* Ignitis | Innovation Hub. https://ignitisinnovation.com/agrivoltaics-harnessing-the-sun-for-both-food-and-electricity/

Uyan, M. (2013). GIS-based solar farms site selection using analytic hierarchy process (AHP) in Karapinar region, Konya/Turkey. *Renewable and Sustainable Energy Reviews*, *28*, 11–17. https://doi.org/10.1016/J.RSER.2013.07.042

Virgílio, R. P., & Robalo, P. A. (2009). Solar energy in Portugal - Development perspectives based on a comparison with Germany. *ISCTE Business School*, *Master in* (September), 105.

Vodã, A. M. (2018). *ISPM - A framework Industrial Symbiosis Promotion Model Integrated Master' s in Environmental Engineering Examination Committee :*

Wang, Q., Deutz, P., & Chen, Y. (2017). Building institutional capacity for industrial symbiosis development: A case study of an industrial symbiosis coordination network in China. *Journal of Cleaner Production*, *142*, 1571–1582. https://doi.org/10.1016/J.JCLEPRO.2016.11.146

Wang, Y. (2022). *How Agriculture and Renewable Energy Can Work Together: The Case for Sheep and Solar Panels*. College of Agriculture and Life Sciences. https://smallfarms.cornell.edu/2022/06/how-agriculture-and-renewable-energy-can-work-together-the-case-for-sheep-and-solar-panels/

Wüstenhagen, R., & Menichetti, E. (2012). Strategic choices for renewable energy investment: Conceptual framework and opportunities for further research. *Energy Policy*, *40*(1), 1–10. https://doi.org/10.1016/J.ENPOL.2011.06.050

Yue, S., Guo, M., Zou, P., Wu, W., & Zhou, X. (2021). Effects of photovoltaic panels on soil temperature and moisture in desert areas. *Environmental Science and Pollution Research*, *28*(14), 17506–17518. https://doi.org/10.1007/s11356-020-11742-8

Zhang, Y., Zheng, H., Su, M., & Liu, G. (2008). A review of industrial symbiosis research: theory and methodology. *Journal of Industrial Ecology*. https://doi.org/10.1007/s11707-014-0445-8

Zhu, Q., Lowe, E. A., Wei, Y. A., & Barnes, D. (2007). Industrial symbiosis in China: A case study of the Guitang Group. *Journal of Industrial Ecology*, *11*(1), 31–42. https://doi.org/10.1162/jiec.2007.929

Zou, C., Zhao, Q., Zhang, G., & Xiong, B. (2016). Energy revolution: From a fossil energy era to a new energy era. *Natural Gas Industry B*, *3*(1), 1–11. https://doi.org/10.1016/J.NGIB.2016.02.001