Soiling Index Modeling for Photovoltaic Systems

Vitor Henrique Pagani - 39807

Dissertation presented to the School of Technology and Management of Bragança to obtain the Master Degree in Industrial Engineering.
Within the scope of the double diploma with the Federal University of Technology - Paraná.

Work oriented by:
Prof. Dr. Paulo Leitão
Prof. Dr. Marcio Mendes Casaro

Bragança
2019-2020

Soiling Index Modeling for Photovoltaic Systems

Vitor Henrique Pagani - 39807

Dissertation presented to the School of Technology and Management of Bragança to obtain the Master Degree in Industrial Engineering.
Within the scope of the double diploma with the Federal University of Technology - Paraná.

Work oriented by:
Prof. Dr. Paulo Leitão
Prof. Dr. Marcio Mendes Casaro

Bragança
2019-2020

Dedication

To my Parents, Jeferson and Regina, for all the support they gave me during the graduation period, and the effort they made so that i could participate in the double degree program.

To my fiancée, Amanda S. Minucci, for the support during graduation, and for her important companionship during this year in Portugal.

To my supervising teachers who were extremely important for the development of this dissertation.

To my friends and family, for all the support and companionship during this journey.

Acknowledgment

First, I would like to thank my Parents, Jeferson and Regina, for all the support they gave me during the graduation period, and the effort they made so that i could participate in the double degree program.

I also thank my fiancée Amanda S. Minucci, for the support during graduation, and mainly for the companionship during this year in Portugal.

A special thanks to my Mother Drª. Regina Negri Pagani, who is always willing to help and clarify any and all doubts I encountered during this trajectory.

I thank my advisor Professors, Dr. Paulo Leitão and Dr. Marcio M. Casaro, for the time and dedication given so that this dissertation could be developed. I also thank me Professor Jeferson Gomes, that had an important participation in my academic life!

Big thanks to the Federal University of Technology, Paraná (UTFPR), and the Polytechnic Institute of Bragança, for the opportunity I had to experience this amazing program overseas.

And last, but not least my flatmate, Ana Luiza, who was always there for me and Amanda during our journey, so we could achieve our goals in a pleasant and ease way.

Abstract

This work has as general objective the creation of a soiling index modeling for photovoltaic systems. The specific objectives are: To characterize the functioning of photovoltaic cells, to simulate the photovoltaic system utilizing the PVSyst software to analyze the production capacity of the system, to identify how these variables affect the production of solar energy and to characterize the conditions of energy production based on simulations. To accomplish these objectives, it is necessary to perform a systematic literature review aiming at the soiling impact and the tilted angle in photovoltaic systems. To perform the modeling, a mathematical formula was adapted to calculate the output current of photovoltaic systems. The differences of this approach regarding the other on the extant literature are the facilities to implement this technology using a reduced number of sensors and demanding less processing power. To validate the proposed soiling index model and achieve the objectives, it was performed a simulation of the photovoltaic system, where the theoretical production values of the photovoltaic system were acquired which were used as a database to analyze the results obtained by modeling the soiling index. From these steps, it was possible to realize the relative error for the modeling varies from 0.33% to 2.48%, with a consistent behavior for most of the scenarios. It is possible to conclude that the behavior presented by the modeling is similar to the simulated. The modeling can contribute to photovoltaic systems as a tool to create better and cleaning schedules.

Keywords: Soiling Index Modeling, Photovoltaic system, PVSyst, Energy Production

Resumo

Este trabalho tem como objetivo geral a criação de uma modelagem de índice de sujidade para sistemas fotovoltaicos. Os objetivos específicos são: Caracterizar o funcionamento das células fotovoltaicas, simular o sistema fotovoltaico utilizando o software PVSyst para analisar sua capacidade de produção, identificar como essas variáveis afetam a produção de energia solar e caracterizar as condições de produção de energia com base em simulações. Para atingir esses objetivos, é necessário realizar uma revisão sistemática da literatura, visando estimar o impacto da sujidade e o ângulo de inclinação nos sistemas fotovoltaicos. Para realizar a modelagem, uma fórmula matemática foi adaptada para estimar a corrente de saída dos sistemas fotovoltaicos. A diferença desta abordagem em relação a outras na atual literatura, caracteriza-se pela redução do número de sensores ao se implementar essa tecnologia, o que exige menor poder de processamento. Para validar o modelo de índice de sujidade proposto, foi realizada uma simulação do sistema fotovoltaico. Para isto, foram adquiridos os valores teóricos de produção fotovoltaica, a fim realizar uma análise comparativa aos resultados obtidos através da modelagem do índice de sujidade. A partir disto, foi possível perceber que o erro relativo para a modelagem varia de 0,33% a 2,48%, com um comportamento consistente na maioria dos cenários. É possível concluir que o comportamento apresentado pela modelagem é semelhante ao simulado. Podendo contribuir para os sistemas fotovoltaicos como uma ferramenta, auxiliando na otimização das escalas de limpeza.

Palavras-chave: Modelagem do Índice de Sujidade, Sistema Fotovoltaico, PVSyst, Produção de Energia.

Contents

List of Tables

List of Figures

Acronyms

a-Si Amorphous Silicon. 11, 13

APREN Portuguese Association of Renewable Energies. 1, 2, 18

CdTe Cadmium Telluride. 11, 14

CIS/CIGS Copper Indium Gallium Selenide. 11, 13, 14

EU European Union. 1, 17

GHG Greenhouse Gases. 1, 4, 17

IEA International Energy Agency. 1, 4

Isc Short Circuit Current. 38

mono-Si Monocrystalline Silicon. 11–13

MPPT Maximum Power Point Tracking. 42

NREL National Renewable Energy Laboratory. 14

PECVD Plasma Enhanced Chemical Vapor Deposition. 13

PNEC National Energy and Climate Plan. 1, 2, 4, 17, 20, 71, 73

poly-Si Polycrystalline Silicon. 11, 41, 46

pp percentage points. 18

PV Photovoltaic. 2–5, 7–11, 15, 17, 19–23, 26, 28, 30, 32, 35–37, 39–44, 46, 47, 49–53, 63, 71–75

SLR Systematic Literature Review. 5, 6, 21, 22

UPAC Self-consumption Production Units. 46

Vco Open-Circuit Voltage. 38

Chapter 1

Introduction

This first chapter presents the introduction of the work, based on a general analysis of PV energy. It describes how much this energy source has growth in recent years according to Portuguese Association of Renewable Energies (APREN), and how it will be further promoted. It takes into account the Greenhouse Gases (GHG) data, referring to the need to expand renewable energy sources, and the objectives stipulated by the National Energy and Climate Plan (PNEC), based on the Paris agreement made by the EU, in which countries must reduce their GHG emission rates and spread new sources of energy production to improve a sustainable energy growth. Finally, the question for the development of this work is raised, the objectives are listed, and the work structure is presented.

1.1 Framework

The world is currently experiencing a phase of readjusting energy sources due to the increasingly emission of GHG and a growing in energy demand reported by the International Energy Agency (IEA) [1]. With these problems occurring, the Paris agreement was created, setting targets regarding energy consumption for the countries involved in the European Union (EU). Having this scenario as background, Portugal created the PNEC, which focuses on increasing energy generation rates from renewable sources.

The implementation of the PNEC brought for Portugal as goals for the next decade an increase in the consumption of final energy from renewable sources, with an amount of 47%, which represents 80% of the national energy balance, coming only from these sources [2]. To achieve the goals presented by PNEC, it is necessary that he government follow the incentive to implement renewable energy sources, among which the focus on the production of Photovoltaic (PV) energy is the main one, which by 2030 is intended to have a total installed potential between 8.1 to 9.9 GW [2].

Currently, Portugal faces another problem - the external energy dependence –, being solved with the implementation of more renewable energy sources. During the last 20 years, the country has presented rates of energy dependence around 70% and 90% [3], consequences of the low or even non-existent national production of fossil energy sources, which have been kept below 80% [3] due to the country's commitment to the implementation of renewable sources, demonstrating Portugal's potential on the production of renewable energies.

The APREN has stored the growth data of renewable energy production, showing that, from 2008 to 2018, the growth of PV systems increased 11 times, reaching a total installed of power of 673 MW only in continental Portugal [4]. The values tend to grow 15 times in the next decade, as shown by the projected of the PNEC to attain a total power around 8.1 and 9.9 GW [2].

The PV generation comes as the main source of energy, to assist in meeting the goals set by the Portuguese government [2]. Due to this growth, it is necessary to develop methods that can assist in the maintenance of systems that already exist and will emerge over time. Within the factors that most influence the generation of PV energy, the accumulation of debris is one of the main factors affecting energy generation [5], [6].

A way to assist in monitoring this index would be to create a model that can collect these data, since the dirt index does not have a standard behavior. Currently, no methodology for data analysis is being used to determine the soiling levels in practice, even with the existence of this technologies, because of the high costs and complexity of implementation as presented in [6], making it difficult to create more efficient cleaning scales. Because of the complexity presented in current models, the presented in [7]–[9] were analyzed, which demand a high number of sensors and a complex mathematical calculation to determine the dirt index, which coincides with the statements presented above.

The creation of a soiling index modeling for PV systems could improve the energy production capacity, and deliver a more satisfactory performance in energy production as it works as a tool that informs the percentage of energy possibly lost due to the accumulation of debris.

Furthermore, this model provides the soiling index, which can be use as a tool to facilitate the development of the cleaning cycles by the companies that offered a cleaning service, or for the owner of the system to analyze the percentage of energy lost by soiling, and thus help Portugal's energy growth and being more independent.

Given the above about the need to increase the supply of energy from renewable sources, and because of the possibilities of this increase coming from the production of PV energy, it is possible to ask the following question-problem: How to improve and optimize the energy supply PV systems?

From this starting question, the objectives of this research were originate, and are presented below.

1.2 Objectives

The objectives of this work were defined based on Bloom's taxonomy [10], where a general objective and specific objectives were established, with the general objective being the focus of the work and the specific objectives being the necessary steps to carry out this research.

1.2.1 General Objective

The general objective is the creation of a soiling index modeling for PV systems.

1.2.2 Specific Objectives

The complimentary objectives to support the research are:

- To present and describe the characteristics of PV energy production.
- To simulate, using the PVSyst software, implementing the tilted angle, tracking and soiling loss.
- To analyze the energy production capacity of a PV structure with a solar tracker using the PVSyst software.
- To identify how these variables affect the production of solar energy.
- To characterize the conditions for the production of PV energy from the structure analyzed in the work.

1.3 Justification

According to reports issued by the IEA [1] in recent years, the world has been going through a phase of readjusting energy sources, because of the increase in GHG emissions and energy demand is growing.

At the end of 2019, presenting the final version of the PNEC [2], and setting out the targets for Portugal, concerning GHG emissions and the use of energy, determining the increase in the use of renewable sources for production as 47%, where the focus for the 2030 horizon for the electricity generation sector is, above all, solar energy. Other goals of the plans are to increase energy efficiency by 35% and reduce energy dependency by 65%.

Based on the PNEC goals, observing that the focus of this plan for the production of renewable energy will be the solar source. Based on the studies [5], [6], [11], [12], which portray the impact caused by the soiling index and the importance of this variable to improve the efficiency of PV energy, the soiling index modeling was developed.

This modeling can estimate the percentage of the soiling index, which impacts the PV system. Making it possible to improve cleaning cycles, increasing energy efficiency and solar energy production.

Analyzing the literature models present in [7]–[9], it is possible to observe they address the use of extremely complex systems, which demands a high processing power and a high number of sensors. Thus justifying the development of simplified modeling, as proposed in this work.

1.4 Work Structure

The composition of this work was made up of six chapters and one annex.

The first chapter presents the introduction of the study, the research question for the development of this work, the objectives, the justification and the structure of this work.

The second chapter approaches the state of the art introducing the history of PV technology. Subsequently, describe how the PV system works and introduce the technology employed to the modules and solar trackers.

After the technologies and the history of PV systems, present an analysis of the energy balance and the scenario of the solar sources in Portugal. Furthermore, this chapter brings a Systematic Literature Review (SLR) based on Methodi Ordinatio, the methodology used to study energy production drop.

The third chapter describes the approach used in the research, structured by the modeling flowchart, presenting all the steps to reach the mathematical modeling, and then presenting the simulation of the PV system.

The fourth chapter presents the application of the methodology developed in the previous chapter.

The fifth chapter consists of presenting the results together with their analysis. The first part refers to the analysis of the results obtained in the simulation. The second part was the presentation of the results obtained from the application of the soiling index modeling for the scenarios related to the output current and the irradiation. Finally, the analysis of the modeling behavior in relation to the simulated values was made.

In the sixth and last chapter, conclusions were presented regarding the results obtained, the limitations that were observed during the work, and the future work that can be done to contribute to the evolution of this theme.

The annexes present in this work correspond to the detailed table on the values, obtained in the simulations and application of the soiling index modeling, and the SLR articles final results.

Chapter 2

State of the Art

This second chapter deals with the state of the art, presenting the history of PV technology, its discovery in 1839 by Edmond Becquerel, and all its development during the 19th and 20th centuries. The second part describes the technologies used in PV modules, detailing the material used to build different types of modules. Solar trackers are also presented, revealing their importance to increase the energy production. The Portuguese Energy System is contextualized, bringing details related to governmental laws. Finally, a systematic literature review on Energy Efficiency in PV using Methodi Ordinatio is built.

2.1 Photovoltaic Energy

2.1.1 History

The origin of the Solar energy is not so recent as one might assume. It emerged in the 19th Century from the analysis of the French physicist Edmond Becquerel, who had seen this phenomenon for the first time in 1839 when he converted solar energy into electricity by placing some electrolytic cells into an acid solution and then exposing to light. With this experiment he could produce voltage and current[13].

During the 19th century, solar energy effects were studied and witnessed by other people like the professor Willian Grylls Adams and his student Richard Evans Day in

1876, when they exposed some selenium to light and produced energy. The amount of energy generated by the sunlight was not enough to power electrical equipment but proved that solid materials can produce energy without moving parts and just using the Sun. From this experiment the idea of PV cells as we know was born[14].

In 1883 the inventor Charles Fritts from the USA created the first solar cells made with selenium. Coating the selenium with gold, and this first model of a solar function cell had a conversion efficiency of 1%, and they were used to build the first rooftop solar array in New York in 1884. Because of the high price materials, it was not possible to produce the cell in a large scale production[14].

In the 20th century, the improvement of solar cells had the most important discovery. At the beginning of the century, Max Planck studied how to explain the nature of light emission from hot bodies, for example, the Sun, and we know this today as Planck's Law [13]. This study impulsion Albert Einstein to postulate that the light was composed of small particles named Photons, these particles contain amounts of energy and the amount is determined by the color. As he had studied the amount of energy in a blue photon has twice the energy as a red photon[15].

Einstein's suggestion led to the formulation and development of quantum mechanics, culminating in Edwin Schrödinger's wave equation, and this formulation was responsible to explain the difference between metals, good conductors of electricity and insulators, and also the properties of semiconductors. The electrons in metals are free, so they can let the current flow easily. In insulators, they are closed in connections making the atoms stay together, demanding a high amount of energy to make them free from those connections, this way they can flow the current. This principle is the same for semiconductors, but the amount of energy to free the electrons is less than regarding the insulators case.

In 1940 [14] Russel Ohl accidently discovered the first solar cell made with silicon. He had measured a large amount of electrical voltage coming from a silicon rod, that he had thought were pure, exposing it to the light of a flashlight. Deeply investigation showed that the rod contains small parts of impurities making the material gaining some "negative" characteristics. Nowadays, we know that these characteristics are deriving out of an excess of mobile electrons with a negative charge, and the other part had the opposite properties called "positive". It is known that it became from the lack of mobile electrons causing the effect of a positive charge.

From the discovers of Russel Ohl, William Shockley was capable to develop the theory of the material build from junctions between "positive" and "negative" regions in 1949 [13] and then used this theory to build the first practical transistors.

Deriving out of the "positive" and "negative" junctions Bell Labs scientists Daryl Chapin, Calvin Fuller, and Gerald Pearson developed the first commercial silicon PV cell, reaching the efficiency of 6% with this first cell [14]. Soon they were using solar panels to fuel satellites and in 1958 the Vanguard was launched with the among of 6 solar cells, capable to produce 1W [14].

In the 1970s, because of the oil crisis, people started to invest in solar research and Dr. Elliot Berman, in partner with Exxon, was responsible to make the price of solar panel raise down one fifth. He found that using multiple crystals from silicon was cheaper than just one, but was lost.

The timeline that represents the historical evolution of PV technology, can be seen in the Figure 2.1.

2.1.2 Photovoltaic Technologies

This section will present a brief explanation about how the light is converted into electricity, the equivalent circuit of a PV cell and the diverse types of materials used in PV modules.

For the conversion of light into electricity, it is necessary to analyze the theory proposed by Einstein, based on the study by Max Planck, where light is composed of energy packages, called photons. Depending on the energy of the photons, it is possible to break the electron bond out of the material. Being possible to quantify the energy of the photon by the frequency of the light as shown in equation 2.1. Where E corresponds to the energy of a photon, h the Planck Constant and f the light's frequency.

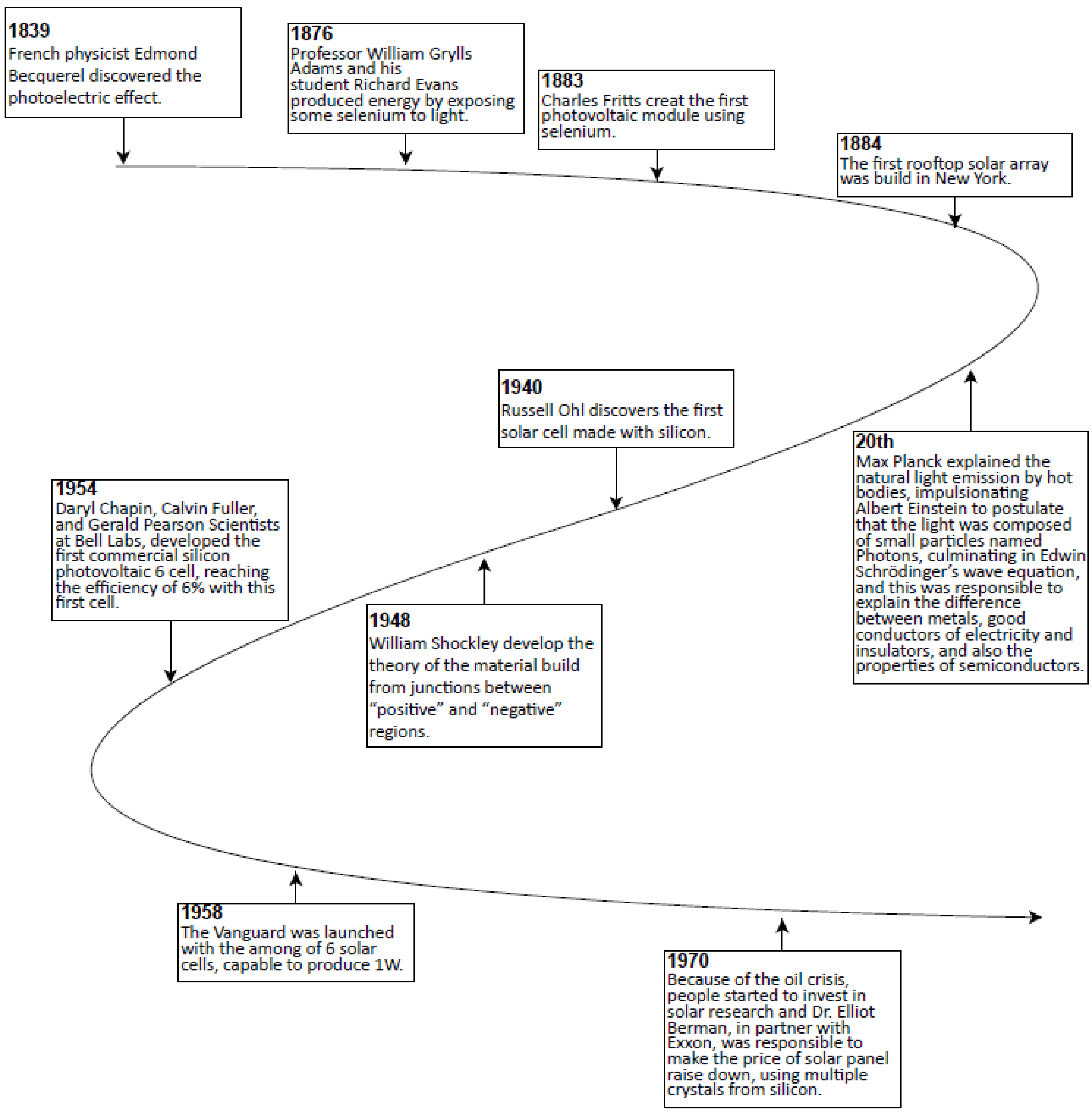


Figure 2.1: History Timeline.

$$E = h.f \tag{2.1}$$

In a PV cell, because of the doping differences on each layer P and N, when the photon releases an electron, this electron flows as electric current, producing a hole in the layer N being filled by another electron from the layer P producing the electrical cycle that flows through the connections.

According to the representation on Figure 2.2, which shows the equivalent circuit of a PV cell and the theory of PV effect, it is possible to determine that the PV cell works as a current source, varying according to the intensity of the light, making the circuit more dependent on the current than the voltage.

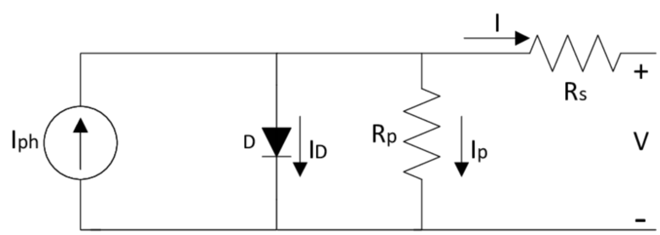


Figure 2.2: Equivalent Circuit of a Photovoltaic Cell.

As cells can be made of different materials, it is necessary to study which material would be the most efficient for the development of PV modules. These materials are divided into different types of technologies. According to Lynn (2010) silicon modules have led the PV energy market to represent 80% of world production, and manufacturers using this material can offer guarantees that last up to 20-25 years [16]. The main modules that use silicon may vary between Monocrystalline Silicon (mono-Si) and Polycrystalline Silicon (poly-Si).

To complement the variety of modules, there are other existing technologies, such as thin film, Amorphous Silicon (a-Si), Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIS/CIGS).

Next, the different types of technologies that constitute the photovoltaic cells presented above will be described, following the following sequence: mono-Si, poly-Si, a-Si, CIS/CIGS and CdTe.

Monocrystalline Silicon

Monocrystalline silicon module is the most efficient on the market with an efficiency above 25% [17]. It is composed of a thin layer of silicon obtained by crystallizing a single piece of pure molten silicon [16]. It has a pseudo square shape with a unique and smooth coloration as shown in Figure 2.3. The manufacture of this type of module is time-consuming and expensive due to the need to crystallize a single piece of pure silicon, which also demands a lot of more care in the process. Furthermore, to present the necessary electrical characteristics it is necessary to dope the material with small quantities of other elements.

Figure 2.3: Mono-Si Cell[18]

Polycristalline Silicon

This technology is also known as multicrystalline silicon. Similarly to the mono-Si cell, the production of this module is made by casting a piece of pure silicon, but with a different process [16]. The main difference is that the casting of several crystals is done in a single block, and when this block is cut it is possible to see the different crystals, as it can be observed in Figure 2.4. Due to this process, the silicon residue generated is reduced and the manufacturing process is faster, but the efficiency of this module is reduced in relation to the mono-Si module, being around 17% [19].

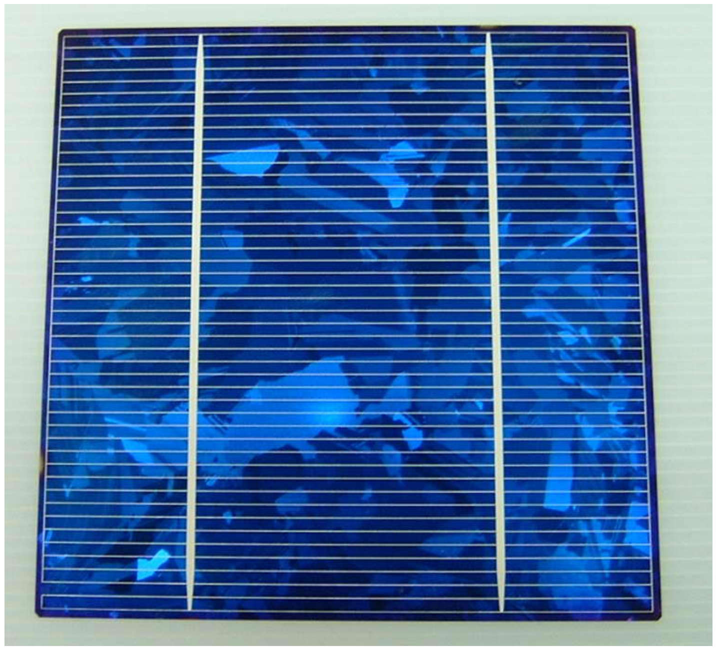


Figure 2.4: Poly-Si Cell [18]

Amorphous Silicon

Amorphous Silicon Modules, as shown in Figure 2.5, are also known as thin-film modules. The manufacturing process of this module is based on the Plasma Enhanced Chemical Vapor Deposition (PECVD) roll-to-roll method [20]. The result of this process is a flexible, non-expensive material, with low silicon demand. It is a slow method and the conductive glass layer has a high cost, so the final manufacturing cost is slightly lower than the crystal modules [16], [20]. Besides the cost problem, this technology has very low efficiency, presenting 13.5% in laboratory tests and 4-8% for commercial modules [16], [20].

Copper Indium Gallium Selenide

The CIS/CIGS modules have the same manufacturing method as a-Si. As they are part of the thin-film category, which is produced by spraying materials onto a surface that can

Figure 2.5: A-Si Cell[21]

be flexible. According to [16], [22], it was noted that this composition has a higher light absorption. There are some disadvantages of this technology. The scarcity of the material used in its manufacture turns it to be expensive. Furthermore, it is besides being a heavy metal, and it ends up emitting a lot of toxic waste. Yet, it has a reduced efficiency and, according to certification by the National Renewable Energy Laboratory (NREL), the efficiency of this material is around 16.1% [22].

Cadmium Telluride

The CdTe cell is considered a thin-film cell. Just as CIS/CIGS, it is also considered a great light-absorbing material [16]. The components in its constitution are abundant and produce a low toxicity to the environment, if compared to the current production. Nevertheless, the efficiency of the cell in relation to the most used technologies in the market is low, being around 11% [16].

Even with all these diverse types of material that develop solar modules, various types of structure also help in solar energy production like solar trackers. The solar tracker subject was presented because the parallel project of this work represents the development of a solar tracker with the technology of the soiling index modeling. When combined it is possible to improve the energy production with the soiling index analysis with a solar tracker working together.

2.1.3 Solar Trackers

Solar trackers consist of a technology that helps the movement of PV systems using motors or linear actuator, with a central that controls how much the system should be moved. By using a solar tracker, the PV systems have the possibility of making movements, following the Sun light, with a similar movement of sunflower. This movement allows the Sun's rays to strike perpendicularly on the surface of the modules, thus increasing the amount of radiation absorbed and, consequently, increasing the production of energy.

The cost to implement this technology increases in approximately 20% the final cost of a project. Nevertheles, as presented by [23], the increase in generation can reach 40%.

This technology, as shown in Figure 2.6, can be classified into two groups with the division between single-axis and double-axis trackers. For the single-axis, it is possible to notice the different ways to perform this kind of tracker. In sequence, we will describe the categories of solar trackers' positions, as in [24].

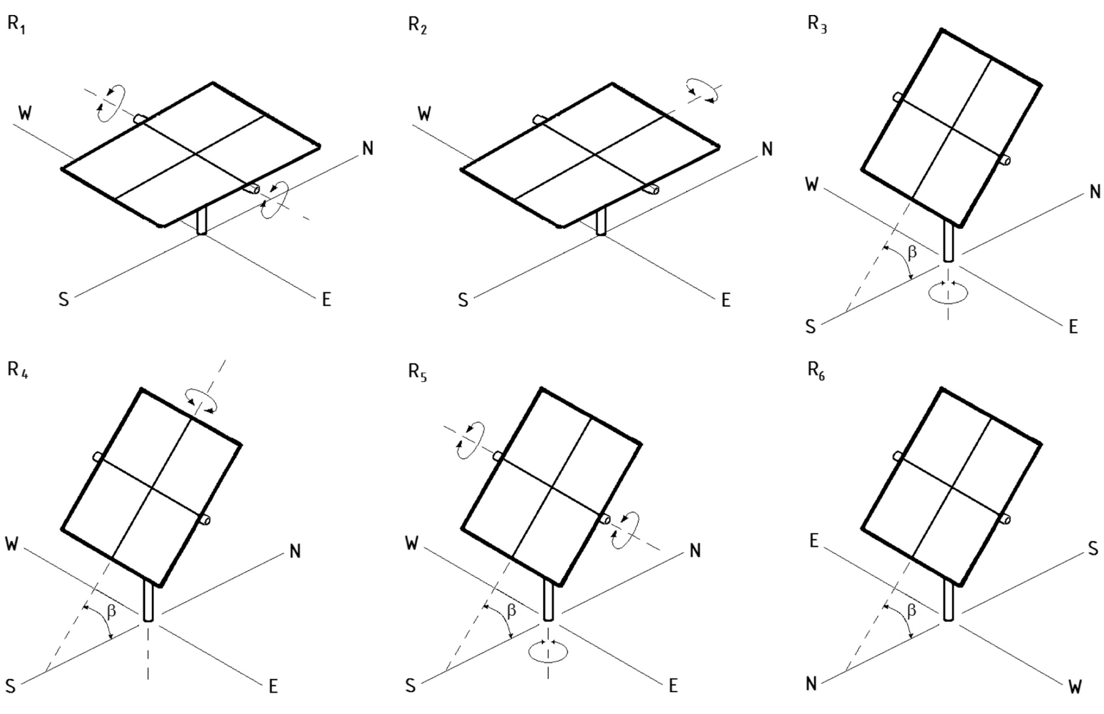


Figure 2.6: Solar Trackers [24].

- R1: a single-axis tracker parallel to the ground, parallel to the east-west axis. This tracker performs the adjustment of the module's tilt angle in relation to the height of the Sun, minimizing the vertical incidence angle for the system.
- R2: a single-axis tracker parallels to the ground like R1, but parallel to the north-south axis. This tracker monitors the horizontal trajectory of the Sun, minimizing the angle of incidence of the system for this axis.
- R3: single-axis tracker, however its operation differs from the previous ones, in which the system is connected to a vertical bar, which on its turn supports the module at an angle of inclination; its segment occurs by monitoring the horizontal path of the Sun.
- R4: Single-axis tracker, with its layout equal to R2, changing only that it has a tilt angle in the base axis, and the movement is the same as R2, following the horizontal movement of the Sun.
- R5: a double-axis tracker, with its fixation similar to R3, but it does the vertical and horizontal monitoring of the Sun's path, maximizing the absorption of solar radiation.
- R6: fixed system, with a predetermined inclination angle.

Among the studies analyzed in [24] on tracker technologies, it is possible to note that researches in the two-axis trackers segment represent 42.57% of the total. Searches on single-axis trackers represent 41.58% and the remaining 15.84% are studies that analyze the two types of trackers, revealing that the interest in the development and research on the two methods are practically equivalent, showing a small difference between them.

Presenting the study carried out in Chengdu/China was performed the comparison of various technologies of solar trackers. In which was concluded that the trackers of the N-S tilted tracking obtained an absorption of 93.2% [25] about the result obtained in a dual-axis tracker. The results are satisfactory for this technology, considering that the dual-axis tracker is more complex and demands a lengthier amount of space and material. Helping to choose the N-S inclined single-axis tracker as the object of study for this work.

2.2 Portguese Energetic System

In this section, the energetic scenario in Portugal will be described, presenting all the data of the country's energy balance. Also, the PV scenario in Portugal will be described, with the goals for this technology and the national plans on how to achieve them.

2.2.1 Energetic Scenario

Currently, Portugal, together with the EU, focuses on reducing the emission of GHG and, consequently, increasing the production of energy from renewable sources. The European Union's target for 2030 in the gross final consumption of renewable energy sources is at 32%, while Portugal stipulated its target for the same period at 47%. This goal is equivalent to the balance of electricity production to a percentage of 80% from renewable sources, as shown in Figure 2.7 from the PNEC [2].

Among the focus for the implementation of renewable energy new sources, it solves the problem that Portugal has been facing, about the issue of energy dependence from abroad. According to government data for the last 20 years, the country has presented values between 70-90% [3], as shown in Figure 2.8, a consequence of the low national energy production from fossil sources, such as oil and natural gas, which represent a significant portion in the final consumption of primary energy. Due to the incentive in the production of renewable energies and energy efficiency, Portugal has managed to keep its dependency rates below 80% [3], which reveals a high dependency on external sources.

Despite this dependence on external sources and with the implementation of the PNEC, as presented in Figure 2.9, Portugal has been showing a very optimistic trajectory to achieve the goals set by the EU and the government itself, which are above the goals of the EU. It is possible to observe a small drop in 2017 in the verified trajectory. However, the values were still above the objectives as presented in Figure 2.9, which is 0.8

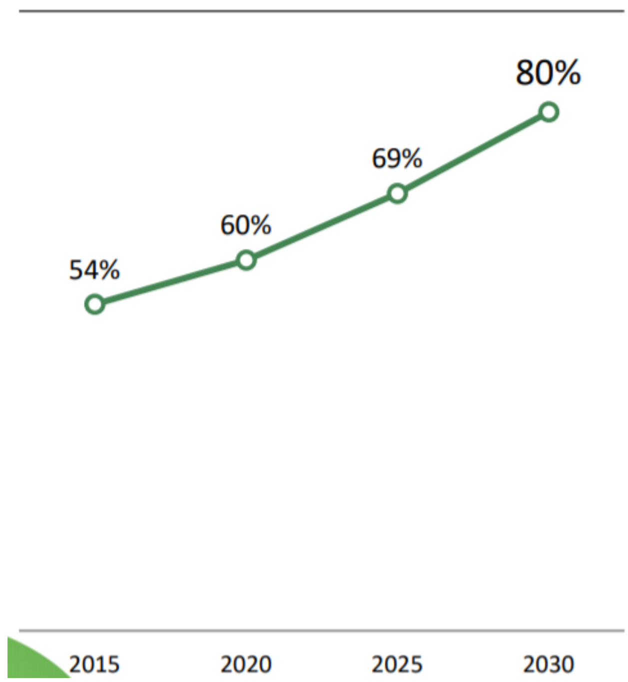


Figure 2.7: Renewable Energy Equivalent in the Balance of Electricity [2]

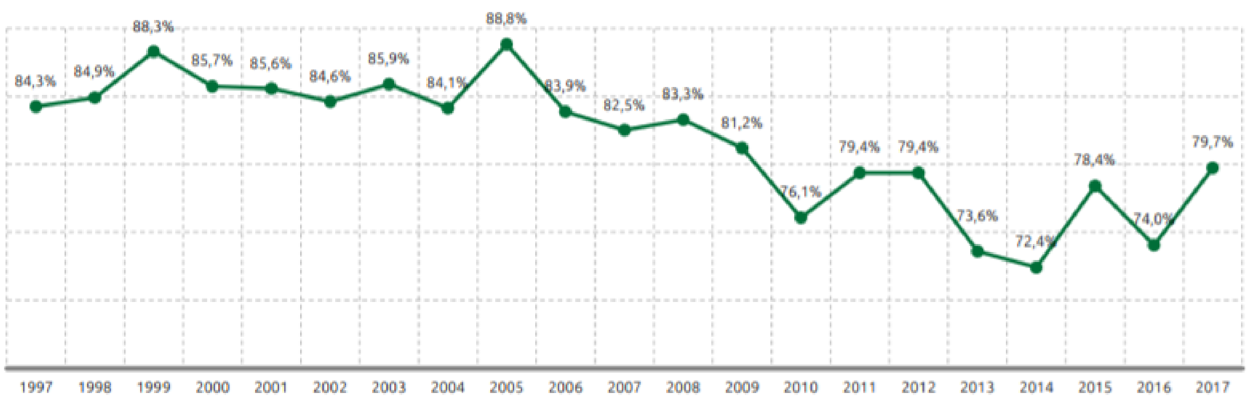


Figure 2.8: Portugal's Scenario on Energetic Dependence [3]

percentage points (pp) above the goals for 2017 and 2.9 pp below the target stipulated for 2020. According to [2], with the increase in the enforcement of renewable energies, it can suffer a positive impact on energy prices, greater maturity and liquidity in the energy market.

According to APREN, it is possible to observe the growing history of energy production

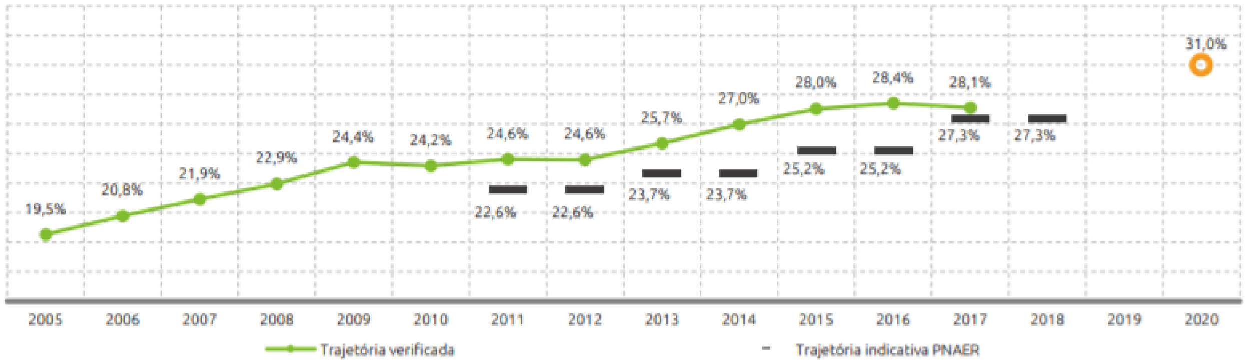


Figure 2.9: Evolution of the Incorporation of Renewable Energies [3]

data in mainland Portugal. In 2019 Portugal had mostly a source of energy from renewable sources, as shown in Figure 2.10, demonstrating that the commitment and established goals are bringing the expected results to the country.

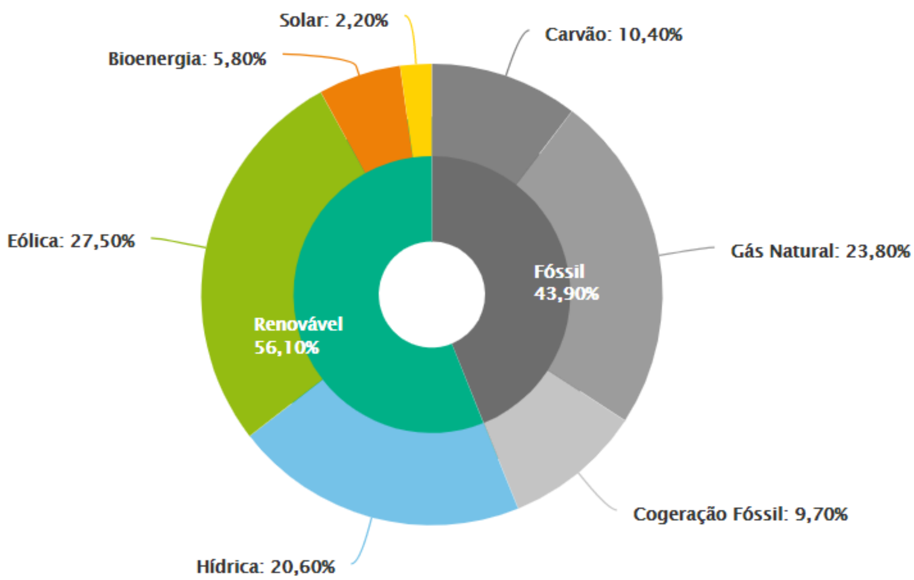
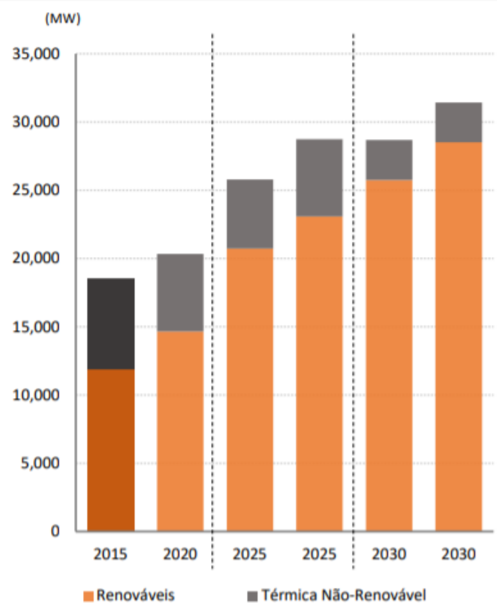


Figure 2.10: Portugal Continental Energy Balance [4]

2.2.2 Photovoltaic Energetic Scenario

The scenario of PV power generation in Portugal shows a strong increase in self production, signaling a self sufficiency. It was observed that in 2018 the installed power of PV energy had a value 11 times greater than back in 2008, reaching 673 MW [3]. Possibly, this growth may come from the cost of implementing this technology, which according to PNEC data, has a cost of 0.7 €/W in 2016 [2], while the production leader has a cost of 1 €/W. However, with all this growth, PV energy represented 2.2% in 2019 [4] of the continental energy matrix, as shown in Figure 2.10.

However, the goals imposed by the Portuguese government in the PNEC and the focus on PV energies [2], present an estimate growth of this branch to be even greater for the next decade, with the objective of surpassing the current leader, wind energy, of renewable generation and reaching a total installed power between 8.1 to 9.9 GW [2], making it the largest source of energy among renewable ones, as shown in Figure 2.11.



	2015	2030
Térmica NFER	6,7 GW	2,9 GW
Hídrica	6,0 GW	9,0 GW
Eólica	5,0 GW	8,0 - 9,2 GW
Solar	0,5 GW	8,1 - 9,9 GW
Outras FER	0,3 GW	0,6 - 0,7 GW
TOTAL	**18,5 GW**	**28,6 – 31,7 GW**
TOTAL FER	**11,8 GW**	**25,7 – 28,8 GW**

Figure 2.11: PV Expectation Increase in Portugal [2]

The Government of Portugal has set objectives and goals for the next decade focused on renewable energies, with an emphasis on PV energy, and a focus on improving the country's energy efficiency.

This governmental strategic policy has given rise to a demand for the development of methods that can mitigate the reduction of energy production due to external effects, such as the drop in PV electricity generation and the direct relationship with the dirt index mentioned above, bringing even more importance to these matters. Therefore, this study intends to contribute with this subject, of great importance for the region right now.

In this sense, it is important to notice that PV systems have many variables that can cause changes in energy generation, compromising the efficiency of the system. The impacts may come from internal factors of the system, such as the materials used in the composition of the module and its connections, presenting losses due to effects on energy conduction, or if any cell is damaged and it is compromising the performance of the others, bypass diodes are used, which somehow cancel out a series of cells, and even the issue of loss due to the conversion of AC / DC energy in the system inverter [16].

The energy losses with the greatest impact may come from issues external to the PV system. Among them, we can mention the system project itself with inadequate tilt angle in the region, which may considerably reduce generation [26], [27], and possible shading by the environment around the modules, which it can occur due to the accumulation of dust on the modules. It important to point out that the soiling index is one of the factors that cause greater loss in the system [5], [6].

Therefore, when it comes to the energy production of PV systems, two factors highly impact its generation: the soiling impact and the tilted angle of the system, to better understand these two phenomena. We performed a SLR to build this section, aimed to present the state of art of the existing literature. Exploring deeply how these two factors significantly impact the production of the system, compromising the performance of the module and, consequently, their efficiency.

Thus, the next topic will explain how the systematic literature review was developed.

2.3 Energy Efficiency in PV: A Systematic Literature Review

In order to identify the relation between the soiling index with the output current and performance, and between the tilted angles with the performance in the energy efficiency of the PV system, a SLR was performed. To reach this purpose, the methodology Methodi Ordinatio, proposed by [28], [29] was implemented.

Methodi Ordinatio, as well as other SLR methodologies, was based on the Cochrane Collaboration Model [30]. From the Cochrane protocol, other protocols for SLR have been developed [31]–[34].

Although Cochrane's model has been at the heart of the development of the Methodi Ordinatio, this model first has particularities specific to the health area. While the proposed methodology by [28], [29] can be applied in the most diverse areas, being generic. Another particularity of the Methodi Ordinatio is its multicriteria character, that is, from three criteria of scientific interest, it arranges the articles, being the impact factor of the Journal; the citation number of the article and the year of publication. Sorting is performed using the InOrdinatio equation, an index that indicates the scientific relevance of the work, facilitating the researcher's work by prioritizing and selecting the works without compromising the quality of the research.

The scientific community considers the combination of these relevant criteria as described in [28], [29], being validated by different researchers [35]–[40]. Thus, this work will use Methodi Ordinatio in order to build the portfolio of scientific articles that will be the subject of analysis of this research.

2.3.1 Methodi Ordinatio Steps

To perform the literary search using Methodi Ordinatio to assist in the composition of the bibliographic portfolio, following the steps stipulated by the methodology, as shown by the flowchart in Figure 2.12.

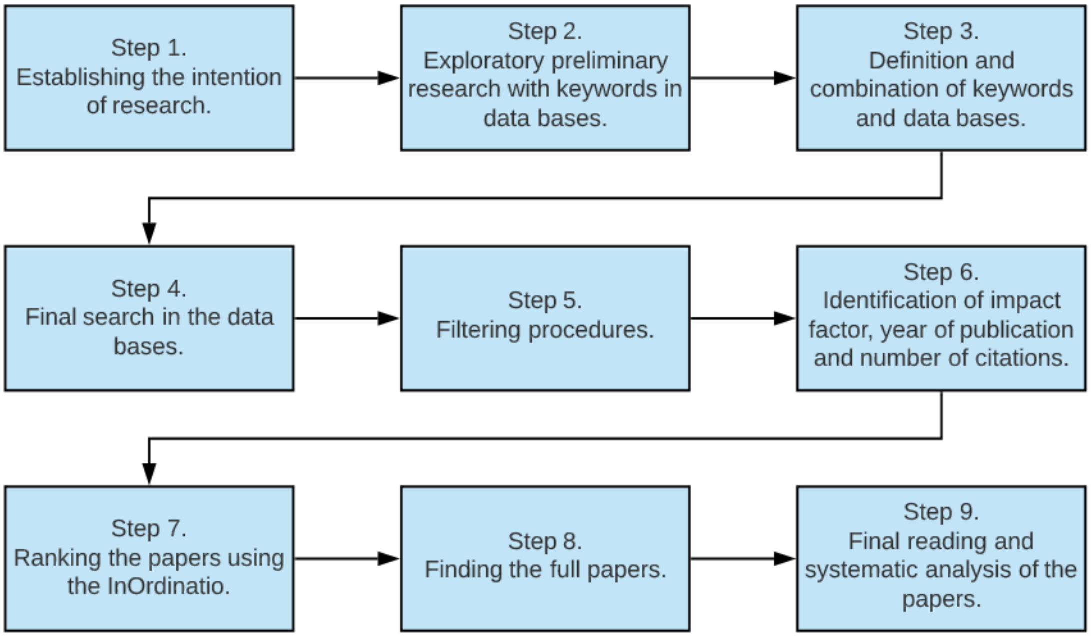


Figure 2.12: Methodi Ordinatio Flowchart

Step 1 - Establishing the intention of research: This systematic review methodology aims to assist in the search for work, regarding the impact of the dirt index, and the variation of the angle of inclination in the performance of PV systems. In this way, the intention of the research for this work fits in the general objective, to create a modeling of the dirt index, and fitting in the variation of the angle of inclination of the system that also causes loss in the performance of the system.

Step 2 - Exploratory preliminary research with keywords in data bases: In the second step, a preliminary research was carried out with the keywords that fit the theme of the study, ranging from “Photovoltaic”, “dust” and “Tilted Angle” in the databases of Scopus and Science Direct. Selecting these two databases by the relevant impact factor found in the works that constitute these databases.

Step 3 - Definition and combination of keywords and data bases: The third step was based on identifying variants to define the keywords. This way the term “Photovoltaic” was used in all searches to focus the searches. To compose the combination of keywords were varied between the uses of two or three words, to vary the results within of the subject. Founding the combinations and variations used in Table 2.1.

Step 4 - Final search in the data bases: The final search was carried out using the combinations of keywords defined in the previous step in the Science Direct and Scopus databases. Presenting the results obtained through all combinations and the different databases in Table 2.1, containing the partial results for each combination.

	Keywords and Combinations	A	B	Gross Total
		Science Direct	Scopus	
1	“Photovoltaic” AND “Energy Generation” AND “Cleaning Forecast”	0	0	0
2	“Photovoltaic” AND “Modules Angulation” OR “Modules Generation”	31	0	31
3	“Photovoltaic” AND “Dust”	243	0	243
4	"Photovoltaic" AND "Generation" AND "Angulation"	1	0	1
5	“Photovoltaic” AND “Tilted Angle”	229	0	229
6	“Photovoltaic” AND “Dust” AND “Tilted Angle”	26	0	26
7	“Photovoltaic” AND “Energy Generation” AND “Dust”	4	0	4

Table 2.1: Number of Articles Found.

Therefore, the searches raised a gross total of 534 articles to carry out the study. The information from these articles extracted in BibTex format was taken to the reference management software JabRef Desktop ©, where the filtering process started.

Step 5 - Filtering procedures: The gross number of articles was then filtered according to the following criteria: "Exclusion of duplicates", "Exclusion of books and book chapters", "Exclusion by reading titles and abstract".

In the process of filtering by the “Exclusion of duplicates” criterion, the number of articles was reduced to 522, using a tool from the JabRef Desktop© software. Now with the number of articles reduced by the reduction of duplicates, filtering was done by the criterion of “Exclusion of books and book chapters”, which resulted in 467 articles. In the third and last stage of filtering, used the criterion of “Exclusion by reading the titles and abstract”, where the remaining number of articles resulted in 210 articles. It is possible to better observe the results of the filtration in table 2.2.

After that, the 210 articles were extracted from the reference manager and washed into the Excel® software, so that they could be tabulated and analyzed in the next step.

Step 6 - Identification of impact factor, year of publication and number of citations: In this step, extracting information from the 210 articles, necessary for carrying out Step

Step	Excluded Articles	Quantity
Gross Number of Articles	-	534
Exclusion of Duplicates	12	522
Exclusion of Books and Book Chapters	55	467
Exclusion by Reading Titles and Abstract	257	210
Total	-	210

Table 2.2: Filtering Steps

7. The year of publication was already contained in the files when extracted in BibTex format in Step 4. Consulting the impact factor through the list available on the Scopus website, and acquiring the number of citations for each article through Google Scholar.

Step 7 - Ranking the papers using the InOrdinatio: In order to rank the papers according to their scientific relevance, the inOrdinatio Equation 2.2 is applied, using the software Excel®.

$$InOrdinatio = (IF/1000) + \alpha \text{Ö}[10(ResearchYearPublishYear)] + (Ci)(1) \qquad (2.2)$$

The elements of the equation are: IF (impact factor); α (alfa value, ranging from 1 to 10, to be defined by the researcher according to the importance of the newness of the theme; for this study, the value of was defined to be 10, since the theme is the object of the study in very recent papers); ResearchYear (year in which the research was developed); PublishYear (year in which the paper was published); and Ci (number of times the paper has been cited).

Step 8 - Finding the full papers: the 210 article was full obtained, to be analyzed in the step 9.

Step 9 - Final reading and systematic analysis of the papers: The articles were analyzed following the decreasing order established by the ranking of the value of the InOrdinatio index.

However, during the reading of the articles, identifying that among the selected articles, many of them did not have the necessary information to study the impact caused by the soiling index and the tilted angle of the system. Thus, after analyzing the 210 articles, the number used was reduced, with only 5 articles related to the impact caused by the soiling index and 3 articles related to the impacts caused by the system tilted angle being selected, as presented in Appendix B. Studying these articles to form the theoretical basis used for the elaboration of this work as a whole. The Table 2.3 will present a short presentation of each one of the selected articles, and after presenting a brief description of the subject studied for each one following the order of the Table.

The article “[11]” reports the performance analysis of two PV systems, one fixed and the other with a solar tracker. This work demonstrated how the solar tracking system accumulated less dirt and had less impact on energy production, and how much the accumulation of debris can impact PV systems, reaching a loss greater than 50% of production in relation to the studied region in this work.

The article “[12]” studied different types of dirt that can be found on the PV modules, analyzing how much each one affects the production of PV energy, carrying out experiments in the laboratory with artificial deposition of dust and in the field with the natural deposition of dust, for different values of solar irradiation.

The article ”[41]” made a study on how the different types and sizes of debris affect the transmittance of solar irradiation on the modules, it was also studied how the tilted angle of the PV system and the occurrence of rain helps in cleaning, and coatings were analyzed which can further assist in reducing the accumulation of debris.

The article “[6]” makes a review, which describing the different effects, caused by the environment in which the modules are exposed and the accumulation of debris in PV systems. Portraying the effects that different types of climates can cause, such as the case of works "[11]" and "[41]", which showed different behaviors for the same problem depending on the environment in which they found themselves. In addition, this work also presented different technologies to perform self-cleaning, reporting the importance of cleaning for PV systems and the lack of systems that are able to model the soiling index in a simplified way and with a greater feasibility for practical application.

The article “[9]”, as previously presented, deals with the development of a soiling index

Authors	Title	Year
Adinoyi, M.J. and Said, S.A.M.	Effect of dust accumulation on the power outputs of solar photovoltaic modules	2013
Darwish, Z.A., Kazem, H.A., Sopian, K., Al-Goul, M.A. and Alawadhi, H.	Effect of dust pollutant type on photovoltaic performance	2015
Appels, R., Lefevre, B., Herteleer, B., Goverde, H., Beerten, A., Paesen, R., Medts, K.D., Driesen, J. and Poortmans, J.	Effect of soiling on photovoltaic modules	2013
Said, S.A.M., Hassan, G., Walwil, H.M. and Al-Aqeeli, N.	The effect of environmental factors and dust accumulation on photovoltaic modules and dust-accumulation mitigation strategies	2018
Hammad, B., Al-Abed, M., Al-Ghandoor, A., Al-Sardeah, A. and Al-Bashir, A.	Modeling and analysis of dust and temperature effects on photovoltaic systems' performance and optimal cleaning frequency: Jordan case study	2018
Hafez, A.Z., Soliman, A., El-Metwally, K.A. and Ismail, I.M.	Tilt and azimuth angles in solar energy applications – A review	2017
Al-Sayyab, A.K.S., Al Tmari, Z.Y. and Taher, M.K.	Theoretical and experimental investigation of photovoltaic cell performance, with optimum tilted angle: Basra city case study	2019
Ali Morad, A.M., Al-Sayyab, A.K.S. and Abdulwahid, M.A.	Optimization of tilted angles of a photovoltaic cell to determine the maximum generated electric power: A case study of some Iraqi cities	2018

Table 2.3: Final 8 Articles Selected

modeling using artificial neural networks to analyze the effects caused by the soiling and temperature on the performance of the PV system, and carries out a study on the ideal frequency of cleaning for PV system, in the study region.

The article "[42]" carries out a review involving the determination of the tilted angle and the azimuth angle for applications aimed at solar energy, describing an overview on the design of parameters, applications, simulations and mathematical techniques used to carry out the determination of these angles, with different models and tests, which has been developing since 1956.

The article "[43]" makes a theoretical and practical study, collecting data of the effect caused by the variation of the tilted angle with a mathematical model, without the use of solar tracker systems, varying the angle of inclination of the system between 0º and 90º.

The article "[26]" studies the forecast of the ideal monthly and the ideal annual tilted angle for PV systems. To perform the prediction of the angles, mathematical models were used and were programmed to find the ideal angle, based on the maximum intensity of solar energy obtained, varying the angle of the system between 0º and 90º.

The next subsections, 2.3.2 Soiling Effect and 2.3.3 Tilted angle, will bring the results from the SLR.

2.3.2 Soiling Effect

Taking into account the external factors that most impact PV power generation, the dust accumulation proved to be one of the most important to be considered [5], [6]. Observing the impact caused by soiling as a progressive loss in the generation of energy.

As shown in Figure 2.13 the difference between a clean and dirty PV system. Because of the shading that the accumulation of debris causes on the modules, as was observed in [6], which presents values of loss by dirt between 40-70% for systems with an exposure of 6 months, in environments with arid climates and with low incidence of rain.

Nevertheless, in contradiction to this fact, observing that climates with a higher relative humidity of the air might end up increasing the adhesion of dirt on the surface of the modules. Considering this fact when cleaning the system, since dirt with greater adherence and without a careful cleaning, can damage the surface of the module [11].

Figure 2.13: Difference Between a Clean and Dirty PV System. [44]

To understand the impact caused by the dirt on PV modules, performing several studies, analyzing the difference between the types of dust that affect the surface of the modules, being an important factor in the literature. Since the different sizes and compositions of the dirt can cause different impacts on the modules, as analyzed in [12]. Among the impacts treated in this article, we can mention the drop in light transmittance to the cells, caused by the different sizes of debris. In addition, the tilt angle of the system can affect the reduction of dirt, causing the accumulation of debris to be reduced due to the greater ease of self-cleaning with the help of the external environment.

Modeling the soiling index is the most efficient way of identifying this drop in PV generation, helping to maintain the system, which improves the system's operating conditions and increases its generation rates. According to the literature review, models were found where they measure the level of dirt from climatic factors as a base [7], [8].

Being this one the method that presents the best results as was concluded in [6]. There are also models that use the electrical behavior of the modules as a base [9].

The model presented in [7] calculated using an artificial neural network that estimates the dirt index, using as a data source the climatic factors, such as solar radiation, wind speed, wind direction, ambient temperature, relative humidity and rain, as showed in Figure 2.14. Due to the high number of necessary inputs and the complexity of operation of this model, it ends up being unfeasible for practical applications, as it needs several sensors and the processing required in calculating the soiling index estimate is very high, making the application cost more expensive.

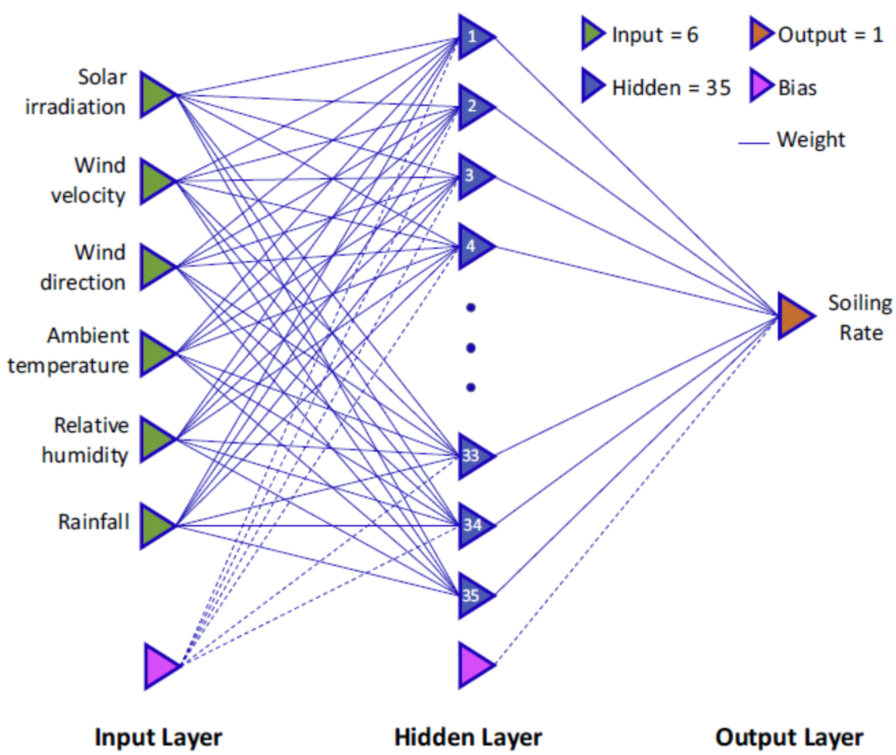


Figure 2.14: Artificial Neural Network Architecture for Soiling Rate Estimation. [7]

The model presented in [8] calculated using an artificial neural network, using climatic factors, such as wind speed, wind direction, air temperature, relative humidity and, in addition to climatic factors, the concentration of mass of dust. The architecture of this artificial neural network as shown in Figure 2.15. This model has undergone two modifications evaluated in the study. The first network named as ANN-5 because it contains five variables. Then three more variables were implemented, corresponding to the average observed on the previous day of wind speed, concentration of dust mass and relative humidity, corresponding to the ANN-8 model.

Finally, implementing two more variables, referring to the frequency of gust winds and the cumulative exposure time, corresponding to the ANN-10 model. To assess the accuracy of the artificial neural network, implementing a multiple linear regression model was, as present in Figure 2.15.

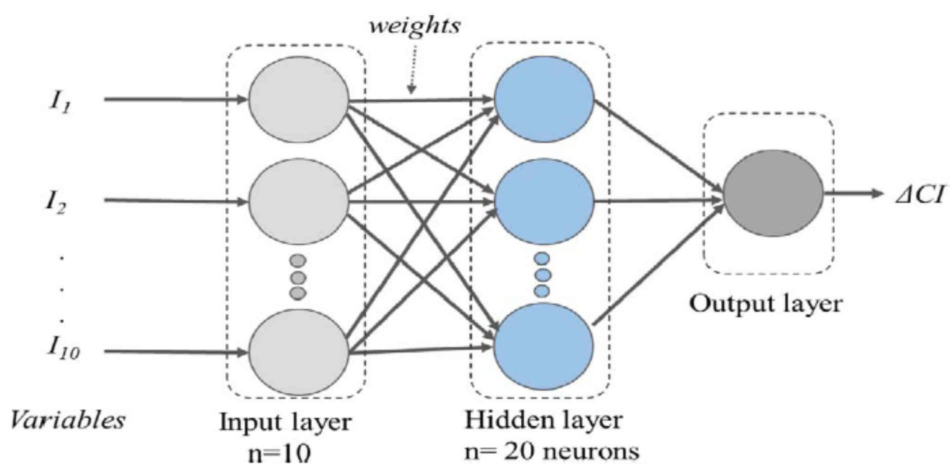


Figure 2.15: Structure of the Employed Neural Network Model. [8]

As seen in the previous model present on Figure 2.15, the need for several sensors and the complexity of processing the calculation to determine the soiling index. Make it difficult to apply this model in practice, due to the cost that the sensors may incur in conjunction with the need for hardware, with high processing, and the final cost of using the developed software.

The model presented in [9] calculated using an artificial neural network in conjunction with a multivariate linear regression model, with the objective of estimating the current efficiency conversion of the PV system, as a dependent variable, based on the accumulation of debris, the ambient temperature, and the number of days of exposure, as independent variables. A Feed-forward-layer networks architecture with a linear input layer, two hidden layers, and using a linear output layer to predict the target value, as shown in Figure 2.16. This model presented as a limiter for its application In practice, the complexity required to calculate the dirt index, implying the need for more powerful hardware, to carry out the necessary analyzes for the two proposed models to work together.

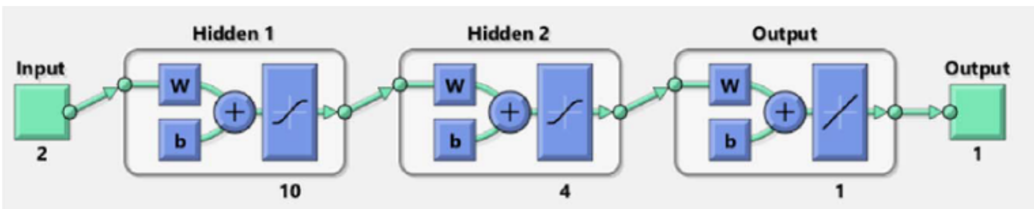


Figure 2.16: Feed-forward Networks with Two Hidden Layers and an Output Layer. [9]

As presented, the analyzed models have a very complex monitoring model, which can make their application difficult. As they may have a high cost of application due to the number of sensors required, and the demand for high data analysis processing since neural networks and very complex calculations compose them, making these methods economically unfeasible [6] and making it difficult to insert this technology into the practical environment.

2.3.3 Tilted Angle

The tilted angle of PV systems is one of the factors that can cause a decrease in the performance of a PV system [27], [42]. This loss caused by the angle of incidence of solar radiation with the surface of the module, because when the rays do not they strike perpendicularly, a part of the light is reflected, so that there is no total absorption of the potential that affects the modules [16]

As the year goes by, the Sun's trajectory changes, as shown in Figure 2.17, making it possible to identify that the duration of the system's exposure for some seasons will be longer than in others. Furthermore, the maximum height that the sun reaches varies for each day, causing the angle of incidence of sunlight on the modules' surface to change over time.

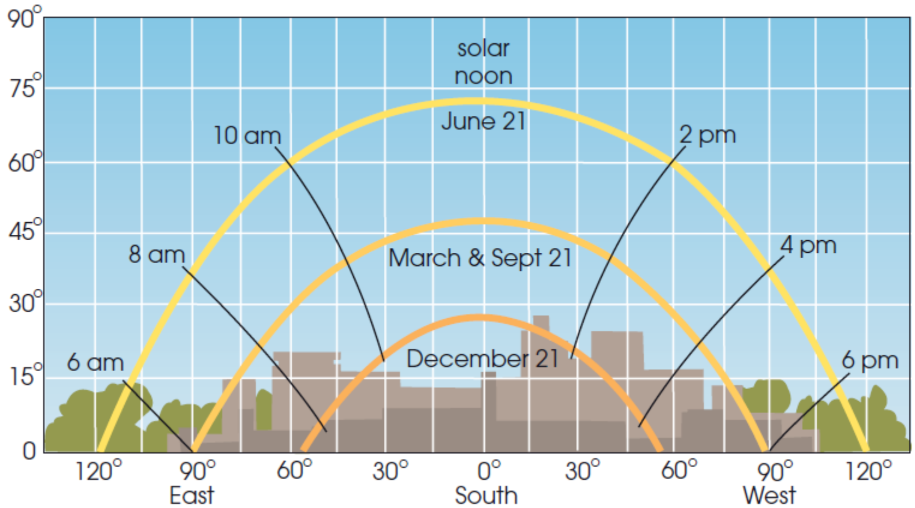


Figure 2.17: Solar Path [16]

The variation of the sun's trajectory during the year causes fluctuation in the generation of energy, as it is possible to notice in Figure 2.18. It was studied in [26], [27], [42], [43] that these fluctuations can be reduced with the projection of the system with the analysis of the annual optimum angle, as stipulated in [26], [27], [42], [43], or causing the system to suffer a variation in the angle of inclination over time to reduce the generation drop, as presented in [27], [43].

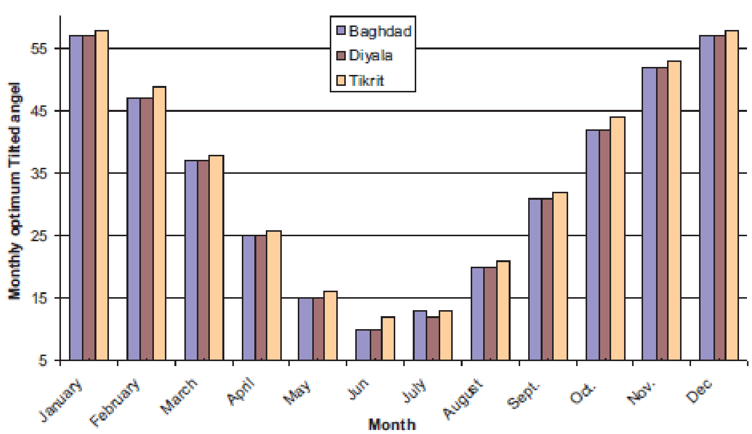


Figure 2.18: Variation in Energy Production [26]

In order to identify the ideal angle for the system, it is necessary to perform simulations of the behavior of annual energy generation for different slopes, or to analyze the behavior of the sun during the year. Due to the fact that this trajectory does not present a significant variation over the years, it is possible to perform mathematical calculations based on the geographic position of the installation, and define the ideal angle, as was done in [43] comparing with real values, as shown in Figure 2.19.

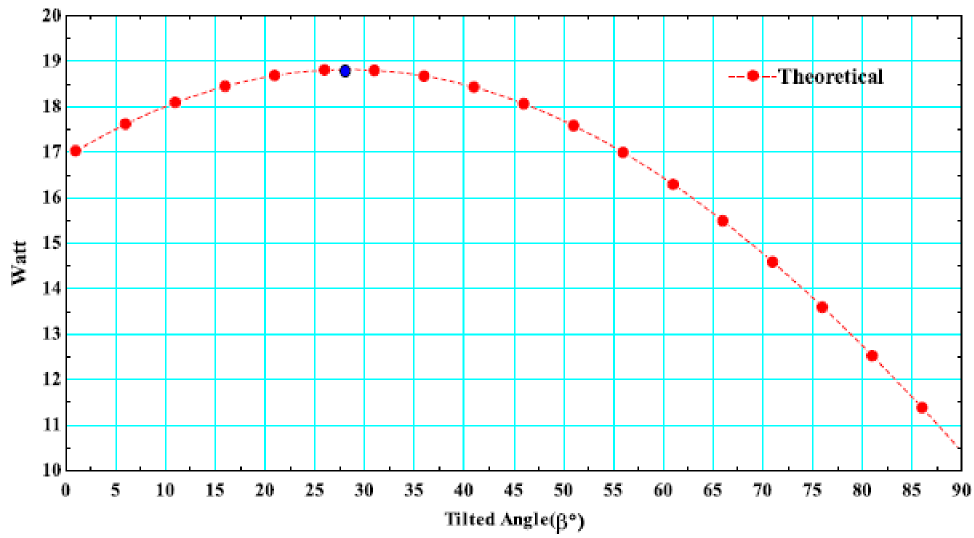


Figure 2.19: Tilt Angle Theoretical Calculation [43]

2.4 Closing Remarks on Energy Efficiency

With the soiling effect and the tilted angle presented in this section, it is possible to analyze the impact that this variables can cause in the PV systems. Concluding the importance in realizing this SLR, to acquire more knowledge in these subjects and perform a better soiling index modeling. In addition, the points raised through the analyze of the existing modeling's, shows different approaches that can be improved in a future study of the soiling index modeling proposed in this work.

The next section will present the steps necessary to perform the soiling index modeling proposed by this work, and the simulations.

Chapter 3

Definition of the Soiling Index Modeling

The objective of this chapter is to define the soiling index model. Considering the reduced number of sensors, it makes this modeling an essential tool for analyzing the impact of the soiling index on PV systems, assisting maintenance companies and PV system owners to create a cleaning routine based on the index provided by the modeling.

For the development of this section, a flowchart was made, describing the entire process of theoretical application of the soiling index modeling for PV systems, presented in Figure 3.1. In section 3.1 it will be presented the necessary steps for the elaboration of the soiling index modeling and the percentage error calculation used for validation. In section 3.2 the *bottom-up* methodology was used to assist in the organization and following the necessary steps to develop the simulations in the software. From the simulations, it was possible to collect the data that constitute the database, the specifications of the modules and the collection of irradiation in real-time.

The *bottom-up* methodology characterize the used for the simulation of the PV systems by the analysis of the current behavior. An individual model was determined for each part, correlated all to form a complete set. That is to say that this model starts from the detailing of several variables from the base to the top, being the answer of the whole

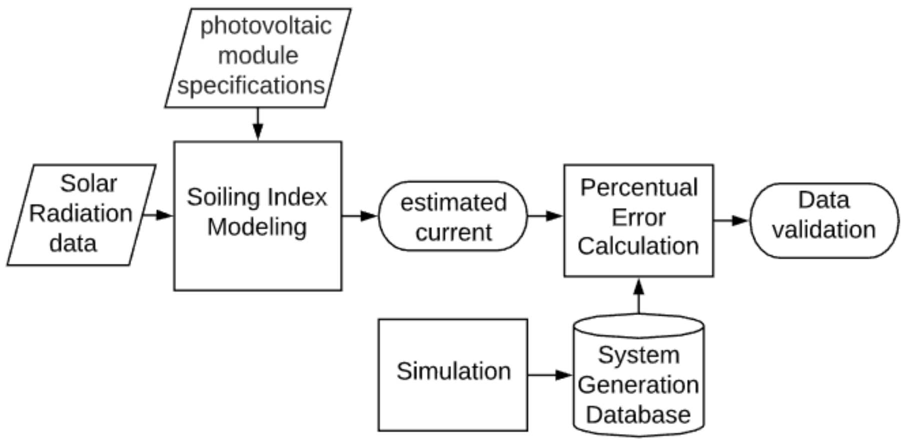


Figure 3.1: Flowchart of the Functioning of the Soiling Index Modeling

analysis.

The application of this model can be made from different scenarios, where the effect occurred for each branch is analyzed, causing the final analysis to have more data from different functioning, being able to be applied to different modes of operation.

The next section will approach the Soiling Index Modeling, detailing the whole process.

3.1 Soiling Index Modeling

Presenting the development of the soiling index modeling. For the modeling, it is necessary to create a mathematical model that allows the determination of the PV system soiling index. For the modeling, the mathematical models brought in [45], [46] were used as the basis, which uses mathematical formulas to estimate the output current, based on technical data from the PV system, which are found in the module's datasheet. Along with this development, taking the models already developed as a reference as well, which was found in the literature in [7]–[9].

For a better understanding of this section, subsections were made, showing the development of the mathematical part of the soiling index modeling, describing how the solar radiation data used for this work was collected and the estimated current calculation, as shown in the flowchart in the Figure 3.1.

3.1.1 Model Mathematical Elaboration

With the focus on developing a simplified form of monitoring the impact caused by the accumulation of debris, for the soiling index modeling for PV systems, it is necessary to study other methodologies on this very purpose already developed, such as the models [7]–[9] previously presented. It was also necessary to study the mathematical formulas presented in [45], [46], as these studies use the equation 3.1, being part of the main equation the calculus in 3.2 and 3.3 to determine the output current of the system, as previously presented.

$$I_{out} = I_{sc} * \left[1 - C1 * (e^{\frac{V_{out} - \Delta V}{C2 * V_{oc}}} - 1)\right] + \Delta I \tag{3.1}$$

$$C2 = \frac{(\frac{V_{mp}}{V_{oc}}) - 1}{ln(1 - \frac{I_{mp}}{I_{sc}})} \tag{3.2}$$

$$C1 = (1 - \frac{I_{mp}}{I_{sc}}) * e^{\frac{-V_{mp}}{C2 * V_{oc}}} \tag{3.3}$$

Based on equation 3.1 and the studies presented in section 2.1.2 and 2.3.2, it is possible to conclude that the accumulation of debris causes a reasonably high negative impact on the power generation of the modules. Furthermore, as seen that the PV cells work as current sources from the incidence of solar radiation, it was determined that the variables analyzed for this study would be current and irradiation.

Thus, in order to be able to make the equation meet the expected values, the analysis of equation 3.4 carried out, observing where the need for temperature and irradiation data.

However, when analyzing that the constant α is part of the product with the temperature, it may end up canceling this constant, and because of the number of α is very small, the impact of this constant in this part of the equation would be very small to the final result.

$$\Delta I = \alpha * \frac{S}{S_{ref}} * \Delta T + [\frac{S}{S_{ref}} - 1] * I_{sc} \tag{3.4}$$

The changes previously expressed can be replicated for equation 3.5, because in the same way as the previous one, the multiplied values result in a low impact on the final result, as β and the variable R_s are very low values.

$$\Delta V = -\beta * \Delta T - R_s * \Delta I \tag{3.5}$$

3.1.2 Data Acquisition

Considering that, this research work is a theoretical application and a simulation, data collection use the software PVSyst software. Selecting this software because it provides information from a meteorological database for the region of the study. Therefore, we were able to collect data on solar radiation for each simulation performed, under ideal conditions. The ideal conditions are a sunny day without shading by clouds, and with the radiation value at high potential. Collecting the data when the sun was at its maximum height during its daily trajectory. With the conditions for collection presented, the date for data collection is 15th of June, at noon, time of the day when the Sun reaches the maximum height.

As the radiation value that affects the modules can vary according to the system's angle of inclination. Collecting the solar radiation data from the cleaned modules surface simulation only, having the same performance on the collected solar radiation data as a pyranometer should do, being inserted to the soiling index modeling for each of the simulations.

To collect the specification of the PV module, it is required to analyze the datasheet, which contains all the necessary constants the modeling needs, like the Open-Circuit Voltage (Vco) and Short Circuit Current (Isc). Considering that the datasheet present only fixed values, it is possible to input all the values in the modeling as default.

3.1.3 Calculus of the Soiling Index and Percentage Error Calculation

With the entire calibration process made to the formulas 3.1, 3.2 and 3.3, done in section 3.1.1 and the collected data made in section 3.1.2, making it possible to perform the mathematical operation idealized in this work. That will calculate the estimated current of the system in ideal condition.

After calculating the current in ideal conditions, it is applied the same percentage of dirt used for the simulations. Then, it was possible to identify what the current estimated by the modeling would be for the same percentage of soiling. With the estimated current response, molded to the values used in the simulation, it was possible to calculate the percentage error between the simulated values with the values modeled from the system responses, using the relative error, equation 3.6, as the mathematical method to calculate. The I_m refers to the estimated current, and I_s refers to the output current from the simulation PV system.

$$E_r = (I_m - I_s)/I_s \tag{3.6}$$

After calculating the percentage error, it is possible to validate the soiling index modeling, using as a base the percentage error presented in [7]–[9].

Since the tariff of the energy varies among the companies operating in the region, and there is no concrete information about the cleaning costs of the PV system and the efficiency of low-cost autonomous cleaning. These factors prevent a review of the autonomous cleaning trigger, considering this issue as a limitation of this study and a topic to be studied in the future as a way of improving the application of this modeling.

3.2 Simulation

The simulation is used in this work to generate the database of the solar radiation and the output current for the application of the soiling index modeling. Making this because this is a theoretical application of the proposed modeling, as we mentioned above, there is no real system for the collection of this data.

To carry out the simulations in a more organized way, it was used the *bottom-up* methodology, which stipulated the necessary procedures to be taken, to obtain all the information necessary for the simulation, taking into account the necessary data to be added to the soiling index modeling. For greater understanding, two diagrams were elaborated, represented by the Figures 3.2 and 3.3.

The Figure 3.2 represent the diagram with the components needed to be evaluated in the simulation software, to reach out the data of the energy produced.

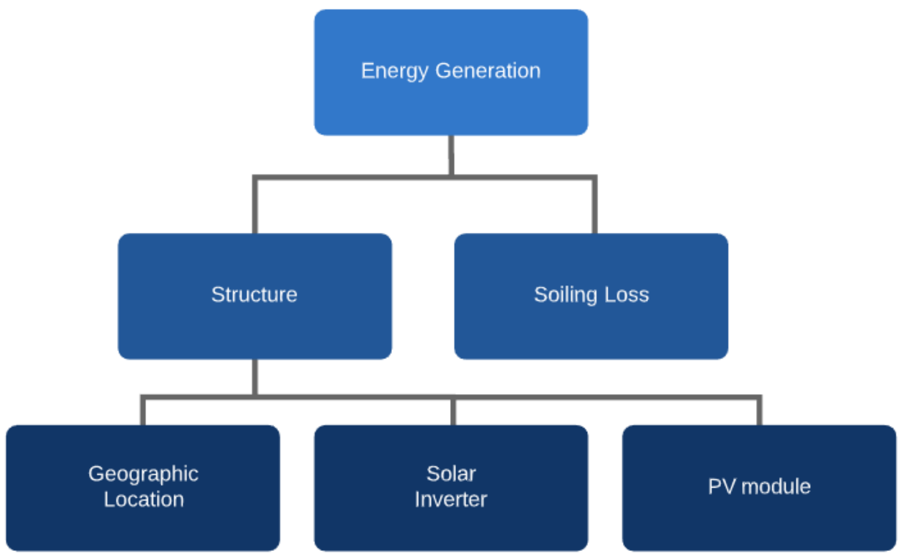


Figure 3.2: *Bottom-up* Methodology Structure for Energy Generation.

The Figure 3.3 represent a diagram similar to the one used for the energy produced, the difference in this diagram is that this one collect the data of output current and solar radiation.

3.2.1 Determination Of The Annual Energy Generated

Taking the energy generated from the systems as a parameter, collecting this data as a way of quantifying the energy that will be lost by a PV system. According to the application of variables that may cause a drop in the optimization of generation, with all

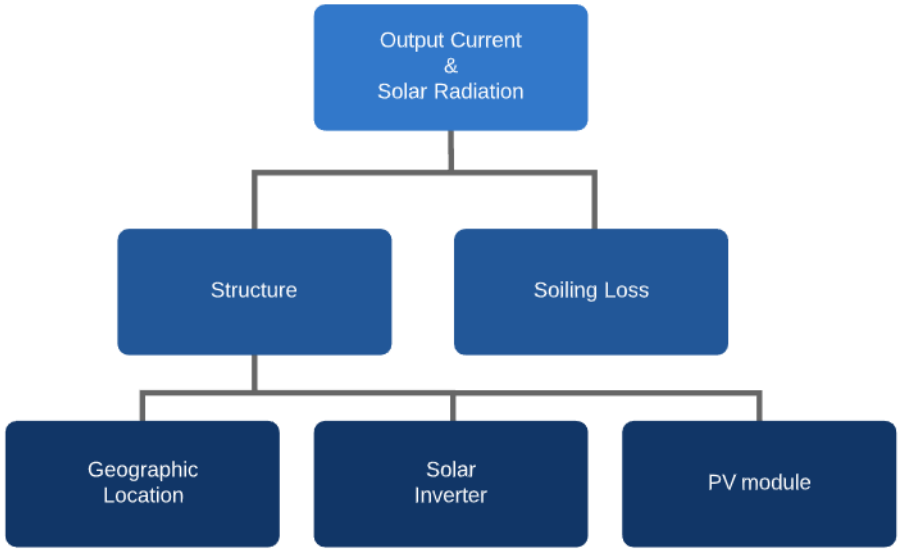


Figure 3.3: *Bottom-up* Methodology Structure for Output Current and Solar Irradiation.

this analysis performed in simulation software that presents the values as close to reality as possible.

Based on the energy drop and analyzing the necessary components, it enables the ideal condition for each simulation to collect the amount of annual energy produced by the system. Besides, making the comparison of these values in the future for a possible drop in system performance.

Below we highlighted the necessary components and the parameters established for the selection of each simulation, as shown by the structure of the *bottom-up* methodology in Figure 3.2.

Photovoltaic Module

As mentioned in section 2.1.2, there are several technologies for making PV modules, with silicon as the main material, which represents 80% of the PV systems market [16]. For this reason, the poly-Si is the technology used for this current study.

However, as there is a variation in the peak power of each panel, estimating the number of modules, and the power of each one, to fit with the characteristics offered in the market, based on law 162/2019 [47]. The estimation took into account the Portuguese legislation since the study was performed in Bragança, Portugal. When replicating in other global regions, must be analyzed the local legislation and consider it.

Solar Inverter

PV inverters are found in two types for connections with the electric system, which are responsible to convert the energy, giving a protection support to the system and some of the have the Maximum Power Point Tracking (MPPT), which the name suggest is responsible to track the best point to produce energy to the whole system.

The first type of inverter is responsible to connect a big amount of solar modules, the modules can be connected in strings or parallel. The string is the connection of the modules in series, while the parallel, as the name suggest, the modules are connected in parallel, the connections depend on the limitations that this inverter had, such as the power, the current and voltage that it supports.

The second type are called micro-inverters, which are responsible for the energy inversion of a limited number of modules, having a slightly higher cost and requiring the application of many micro-inverters if the system is very large.

Based on this information and seeking the practicality of installation, minimizing the components and reducing the complexity of the system, deciding in use only one inverter for the entire system.

Geographical Location

As some locations, do not have weather stations to store this data, but only present estimates. Thus, to obtain a collection of climatic data with greater precision, it is essential to define the location to carry the simulation. So that it will be possible to correctly dimension the estimated potential that a system may present, allowing a more coherent estimate of reality.

Structure

To install the PV systems is necessary a previously dimension and determining the type of structure. The structure may vary between various types presented in Section 2.1.3, represented in Figure 2.6. Among the structures already presented, two structures will compound as the object of this present study.

The selected structures are the fixed model and the single-axis tracker with inclined NS axis type. The fixed model because it enables to analyze the amount of energy produced by the equivalent system without the use of any tracker. The single-axis tracker with inclined NS axis type, because this tracker can absorb an equivalence of 93.2% of a double-axis tracker [25], demands less complexity structure, fewer components to compose it and having a great energy production.

3.2.2 Determination of Instantaneous Current and Irradiation

With the current and the solar radiation parameters, it is possible to create a database with these values, being able to identify the behavior of the PV system. As presented in section 2.1.2, the PV cells function as sources of currents, being the main parameters of the module that serving as the base for the determination of the soiling index modeling for PV systems. To evaluate this behavior in the best way, it is necessary to determine some parameters such as PV modules, inverter, geographic location, and the structure, mentioned previously in section 1.2.1, it is essential to apply the variation in the soiling index and solar radiation via software.

Below will be highlighted the necessary components and the parameters used stipulated for the selection of each one, as shown by the structure of the *bottom-up* methodology by the Figure 3.3.

Soiling Loss

The determination of the soiling index for PV systems represents the crucial point of the work. Since this is the variable that causes impacts on the energy production of the PV system, and does not maintain a uniform behavior for the different regions with a different climate [6].

To accomplish it is necessary to utilize a varying amount of soiling index, enabling the analysis of the PV system behavior, which can be a uniform or not.

Solar Radiation

The solar radiation data have enormous importance to the project, as already mentioned in section 2.1.2, the PV system produces energy because of the PV effect, which converts the light energy into electrical energy, working as a current source fueled by the solar radiation. This analysis reinforces the importance of this variable and serves as the principal source of the modeling, because of the variation in absorption impact directly the energy production.

Chapter 4

Case Study: Simulation with the Soiling Index Modelling Application

This fourth chapter presents the application of the methodology described in the previous chapter. The initial configuration for the application is presented. In the sequence, the PVSyst software with his features, characteristics and operationality is explained, as well as the reasons for using it. Next, the Simulation Scenarios and Modeling Application is presented.

4.1 Initial Configuration

This fourth Section divides into two main topics. The first topic, 4.1.1 Components Definition, will present the necessary components to perform the system simulation, as described in Section 3.2, which also detailed the selection of the components and variables.

The second topic, 4.1.2 Soiling Index Modeling Parameters Definition, presents the variables used to build the soiling index modeling, as described in section 3.1, depicting how each variable was analyzed.

4.1.1 Components Definition

Based on the needs in determining the values of annual energy generation and the instantaneous values of output current and irradiation, previously presented, we will make the analysis of the components that will be part of the composition of the PV system and the simulation variations.

Using all these components to compose the simulation in the PVSyst software, which will be essential to generate the database for this study. Since there was no application in real systems, making It is important to point out that the definition of the components very important due to its high similarity factor mentioned above and because it is a theoretical development, . In order to obtain the best results based on the components, and taking into account the Portuguese legislation, more specifically the Decree-Law nº153 / 2014 of 20 October [47], to choose the power of the system.

PV Module

For the choice of the module to reflect the reality of the Portuguese energy system, the Self-consumption Production Units (UPAC) were used as the basis, which are energy generation systems for own consumption. In addition, limiting the total power of the system according to the decree-law nº153 / 2014 of 20 October [47], it was decided to analyze the systems with a maximum of 1.5 kWp, which manage to produce a satisfactory amount of energy. Furthermore, for the installation of a system with up to that power, charges are not applicable, requiring only prior notice of exploitation.

Thus, making a search on self-consumption kits, with a power of up to 1.5kWp. Among the modules found for this category and the database of the PVSyst software, analyzing the manufacturers of the modules and their operating characteristics. Being possible to observe the kits mostly had modules consisting of poly-Si cells, with a peak power of around 275 Wp, which resulted in the choice of the JAP6-72-275 model from the company JA Solar, which has similar operating characteristics to the models found. Finally, to achieve the expected total power, using six modules.

Solar Inverter

Similar to the PV modules, the inverter choice is based on the auto consume components kits, comparing with the inverters presented in PVSyst software databases.

With the power defined as 1,5kWp, because of the law bureaucracy [47], the characteristics of the inverter need to match with the PV modules, this way, the simulation would produce better results if compared to real systems.

From these statements, it opted to select a single inverter. This type of inverter is the most found among the auto consume kits. Comparing the characteristics of the other inverters found, the result of the search indicated that the model Omniksol-1.5k-TL2-M, from Omink, was the more compatible inverter with the PV modules used.

Geographical Location

The geographic location chosen was Bragança, Portugal. Making this choice for two reasons: first, the researcher study at the Polytechnic Institute of Bragança, making it more accessible to the author to collect data concerning the weather. Second, the data concerning the weather on Bragança city already registered on the MeteoNorm database, which is the database that the software PVSyst uses to make the simulations.

The precision of the weather information is very important not just because of the sun, but also the temperatures and the wind velocity. These factors can change the amount of energy produced by the system.

To present the data of the weather, MeteoNorm collect them from weather stations located all around the world. One of the stations that feed the database is located in Bragança, making the information more accurate and trustable. It is important to point out that when the software is used to collect data for a random city that do not contain a weather station that feeds the information on the MeteoNorm, the software makes an interpolation with the data collected from the station presented around the geographic point [48].

Structure

The structure utilized takes into account the two types of structure selected in the previous section. Implementing a fixed structure with the annual ideal tilted angle and another with a solar tracker using various tilted angles. Using the PVSyst to establish the annual ideal tilted angle for Bragança, and shaping the simulation steps to perform the data survey.

These two models studied because the modeling proposed for this work is implemented in a solar tracker, requiring this performance comparison to be made and also to perform the tests of the functioning of the soiling index modeling for fixed systems.

To establish the ideal angle, considering that the system has only one tilt angle for the continuous year of operation.

Considering the annual tilted angle, the suggestions to dimension the inclination as using the same angle as the latitude of the system location, as shown by studies conducted in Iraq [26], [43].

To analyze the applicability of this suggestion, performing simulations of the system used in the study, varying the system's inclination from 0 to 90 degrees, with the analysis of the amount of kWh/year generated.

This simulation in the PVSyst software resulting in the construction of a graph based on the results obtained, shown in Figure 4.1.

From the data obtained by the simulation, the suggestion of using the system location latitude value, 41 degrees, is not the ideal annual angle for the system, since the 34 degrees of tilted angle had a more satisfactory performance, as present in Figure 4.1, refuting the latitude angle suggestion.

To establish the steps taken to simulate, considering the production graph presented by Figure 4.1. This way, the simulation of the system's angle inclination with the solar tracker varies from 0 to 90 degrees, as previously done, but with a simulation step of 5 degrees. Considering the behavior presented in the previous simulation, enabling the reduction of the simulations, but maintaining the production varies according to the

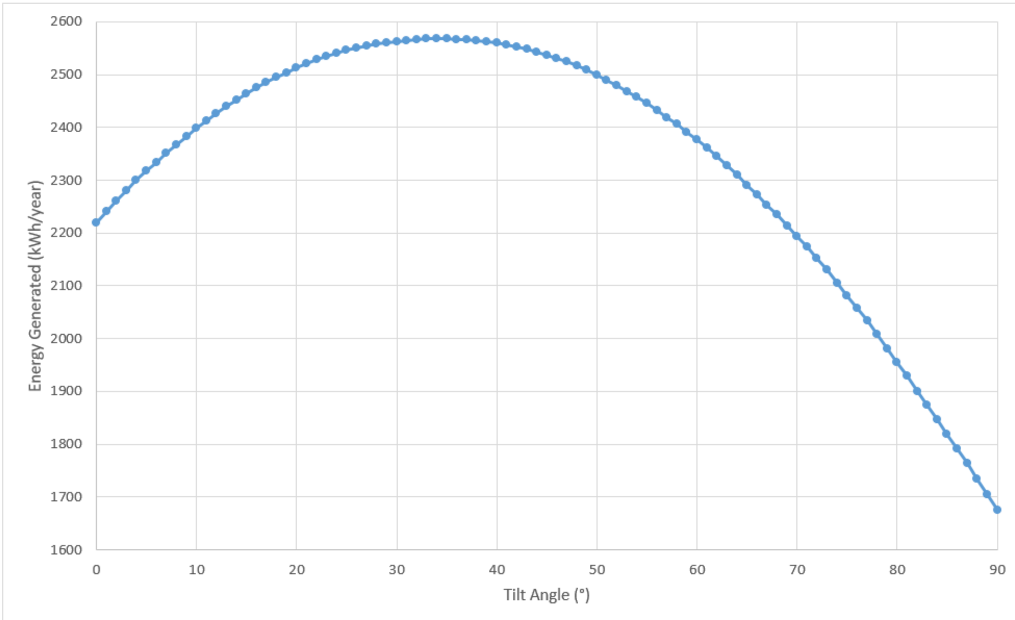


Figure 4.1: Analysis to Determine the Best Tilted Angle.

behavior obtained with a reduced step.

Soiling Loss

The impact on the PV system caused by the soiling index justifies its selection. This interferes with energy production, affecting the current, which can express a pattern, by the growth of the amount of dust accumulation.

To establish the steps to this variable performing a previous simulation, utilizing the equivalent system as the utilized before for the tilted angle. Where the values vary from 0% to 50% with a 5% step with a Yearly Soiling Loss Factor. From this simulation, a tendency line expresses an R^2 of 98,68%, as presented in Figure 4.2. This value represents a significant correlation, enabling to determine a 10% step, without losing reliability.

4.1.2 Parameters Definition for the Soiling Index Modeling

Based on the presentation of the soiling index modeling in Section 3.1, which present the adaptation of the equations, by reducing the input variables to simplify the system,

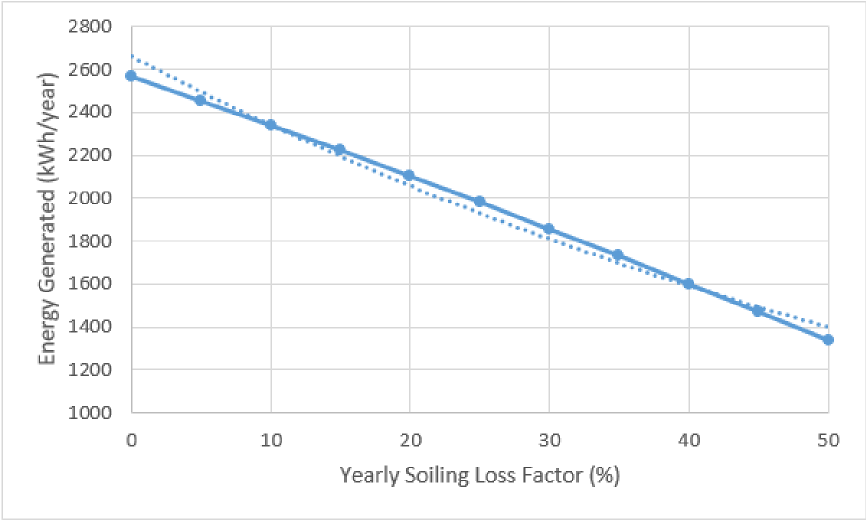


Figure 4.2: Analysis to Determine Correlation for Soiling Effect.

replacing the variables taken of by standard values.

In this way, describing the output current and irradiation variables, and which value will be used instead of the Voltage and Temperature.

Output Current

As previously discussed, the operation of a PV system makes it possible to determine the current as one of the most important values to the PV system. This situation shown in Figure 4.2 occurs because energy production is greatly affected by the soiling index, as presented in the studies [6], [11], [12].

With the study carried out in [44], it is possible to correlate that the energy drop expressed in Figure 4.2 can be the same for the output current of PV systems. Besides, it possible to observe how solar radiation affects the PV system energy production, directly affecting the output current.

Solar Radiation

To establish a correlation between the output values of the system with the values that the system should produce under ideal conditions, the solar radiation data collected just under ideal conditions. Therefore, the modeling calculates the output current that the system should produce, making it is possible to estimate the system soiling index.

By doing it, all the output current estimates from the solar radiation absorption. This evaluation corresponds to the amount of output current the system should produce with no soiling on the modules, this way estimating the soiling index.

Voltage

Switching the output voltage on the formula, by the maximum power voltage value of the module, present in the datasheet. Using maximum power voltage value, the formula still presents the desired response, with a flawless calculation, allowing a consistent result, and reducing the inputs, simplifying the model as expected.

Temperature

Similarly to the voltage, the temperature of the modules was replaced to reduce the number of sensors applied to the system. The temperature values used in the modeling equations were replaced by the reference temperature value, in which temperature is used to perform testing on PV equipment at 25 degrees Celsius.

4.2 PVSyst

The version used for this work is the PVsyst 6.8.5, a free trial version, founded at the official website for download. This software is a computational tool developed for the study, sizing and simulation of PV systems. This software was created by the University Of Geneva, Switzerland. Due to the specifications for the PV area, the software provides the designer a comprehensive modeling, including several technologies of modules, inverters, loss, 3D modeling, shading models and economics/financial analysis. This software is very flexible and very intuitive. Can adding different data to the database, being capable to develop projects for PV systems grid-connected, stand alone, pumping and DC grid. Actually, PVSyst is one of the most used software in the world for a range of projects, either for residential with a small number of modules, or big generation fields with lots of complexity [49]

4.2.1 How the Software Works

In order to perform a simulation in the software it is necessary to follow a sequence of data to be inserted in the software until the end, where is possible to get a report from the system simulated. At the initial stage for a simulation, it is necessary to indicate the geographical location. In the case of Bragança, the data is already set in the database. If the location does not exist in the database of the software, it is possible to create the new location. Adding it manually or by the MeteoNorm. The difference between these two options is the source of the data.

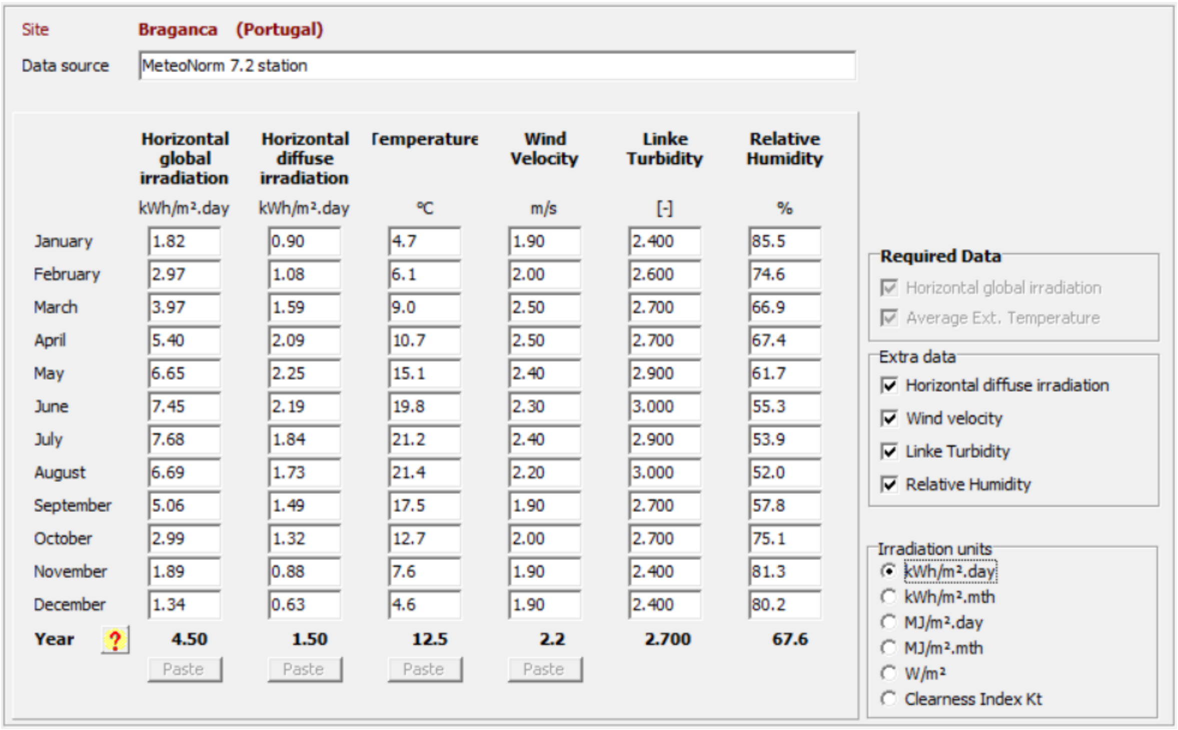
MeteoNorm is a software founded already installed in PVSyst. It provides the data from weather station around the world. When a city does not contain a weather station, the software interpolates the data from others station to provide some data. However, if the user has data provided by a local weather station, it is possible to insert this data manually. Presenting the page for the data insertion in the Figure 4.3, with all the parameters that are possible to introduce.

As soon as the geographical location and the weather data set in the software, the next step is defining the orientation of the PV system.

PVsyst is capable to simulate different types of systems. There are three types of orientation: fixed, single-axis and double-axis.

Once selected the type, it is possible to set your kind of orientation in other subtypes, in the area presenter. Presenting the configurations in Figure 4.4.

With the type of orientation select, the next step is to choose the components that integrate the system in the simulation, as shown in Figure 4.5. PVSyst has a variety of PV modules and inverters, from different brands, to enable the selection. The database is filled with the data provided by the manufacturer's datasheet. If the component is not found in the database, the user can add it manually.


Site Braganca (Portugal)
Data source MeteoNorm 7.2 station

	Horizontal global irradiation	Horizontal diffuse irradiation	Temperature	Wind Velocity	Linke Turbidity	Relative Humidity
	kWh/m².day	kWh/m².day	°C	m/s	[-]	%
January	1.82	0.90	4.7	1.90	2.400	85.5
February	2.97	1.08	6.1	2.00	2.600	74.6
March	3.97	1.59	9.0	2.50	2.700	66.9
April	5.40	2.09	10.7	2.50	2.700	67.4
May	6.65	2.25	15.1	2.40	2.900	61.7
June	7.45	2.19	19.8	2.30	3.000	55.3
July	7.68	1.84	21.2	2.40	2.900	53.9
August	6.69	1.73	21.4	2.20	3.000	52.0
September	5.06	1.49	17.5	1.90	2.700	57.8
October	2.99	1.32	12.7	2.00	2.700	75.1
November	1.89	0.88	7.6	1.90	2.400	81.3
December	1.34	0.63	4.6	1.90	2.400	80.2
Year	4.50	1.50	12.5	2.2	2.700	67.6

Figure 4.3: Irradiation Window [49]

The software has some pre sizing modes to help the designer in the dimension of the project. Using the data of the available area or the estimated power, the software can help to choose the amount of the PV module and inverter. In the area of the PV module, it is possible to filter the components by the year of manufacture, if the component is bifacial and if the max voltage is 1500V, for instance. In the area of the inverter, it is possible to filter by the year of manufacture as well, and whether or not the frequency of the energy is 50 or 60 hertz. To complement, it is possible to determine the number of strings and the number of modules in each one. With all this data selected it is possible to have feedback from the choices. A sample interface of the software can be seen in Figure 4.5.

Using just this information is possible to run the software and simulate a PV system in PVSyst.

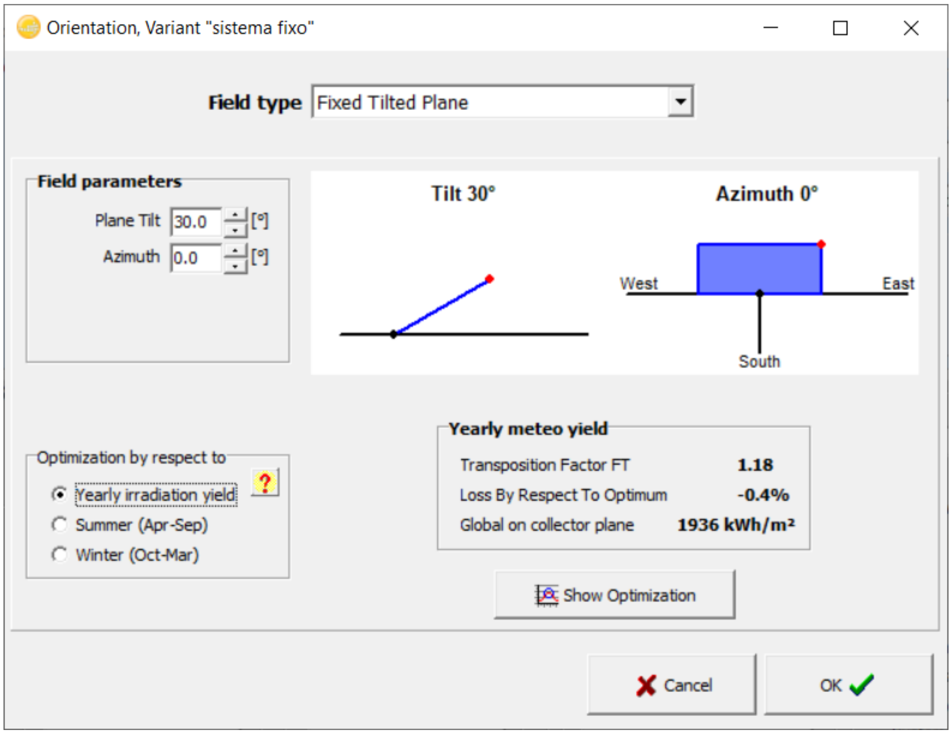


Figure 4.4: Orientation Window. [49]

4.2.2 Software Selection

As previously described, PVSyst software has a vast database and reliable sources of information for composing PV simulations and can be adapted to different real projects and theoretical simulations based on the analysis of system performance data. In addition, to have a detailed area of loss analysis, it addresses all variables that may present some significant energy loss. However, the most important for this decision is the analysis performed by several works. When comparing the simulation systems existing in the market and showing what PVSyst contains, we can notice that PVSyst presents the closest results to a real PV system, bringing greater reliability to the results obtained [49], [50].

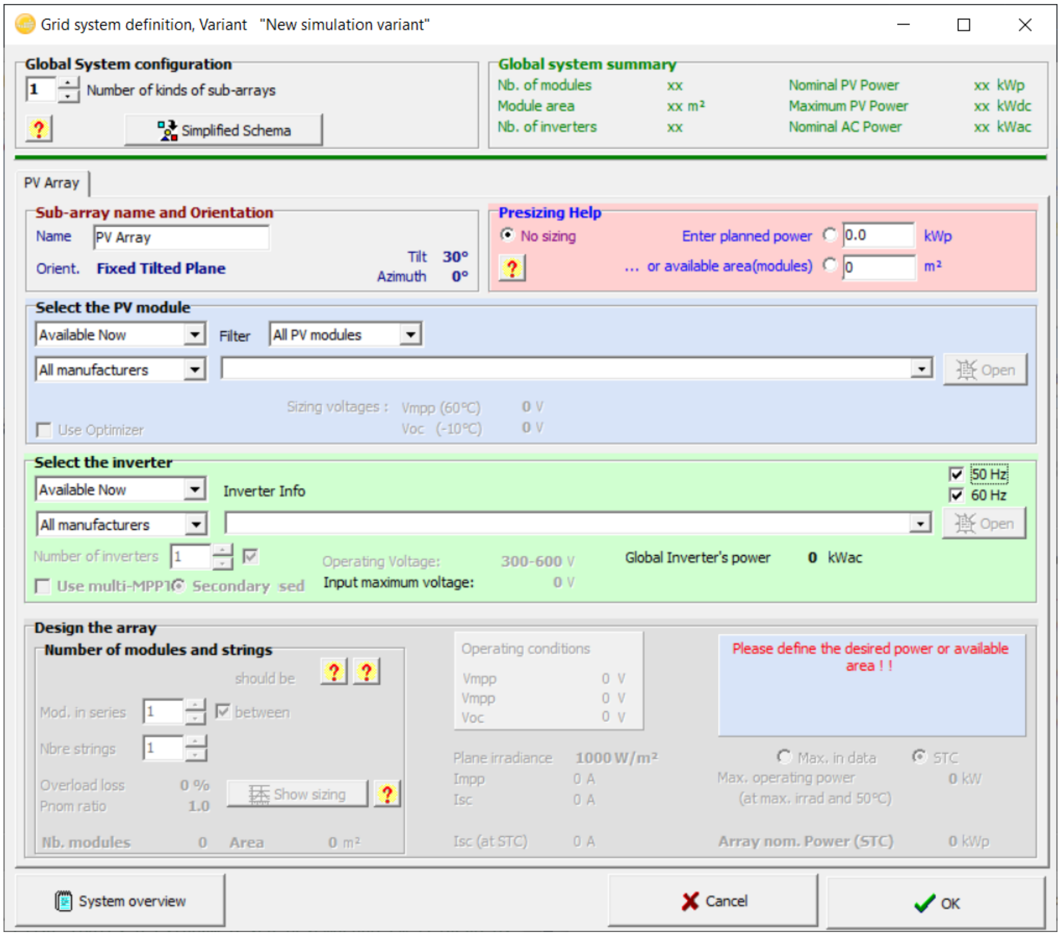


Figure 4.5: System Window. [49]

4.3 Simulation Scenarios and Modeling Application

To collect the data from the simulation, it was necessary to divide it into two main scenarios. The first scenario is responsible to collect the data of annual energy production. The second scenario is responsible for the collection of the output current and solar radiation data on June 15th. This date was chosen for being the day with the highest solar power, and the best solar radiation values, corresponding to a day without occurrence of shading by clouds, as shown in Figure 4.6. Within each scenario, simulating three different sub-scenarios, as described below:

- Scenario Fixed System with Ideal Annual Angulation: In this scenario, simulating the system without changing the angle, and without solar tracking. However, in

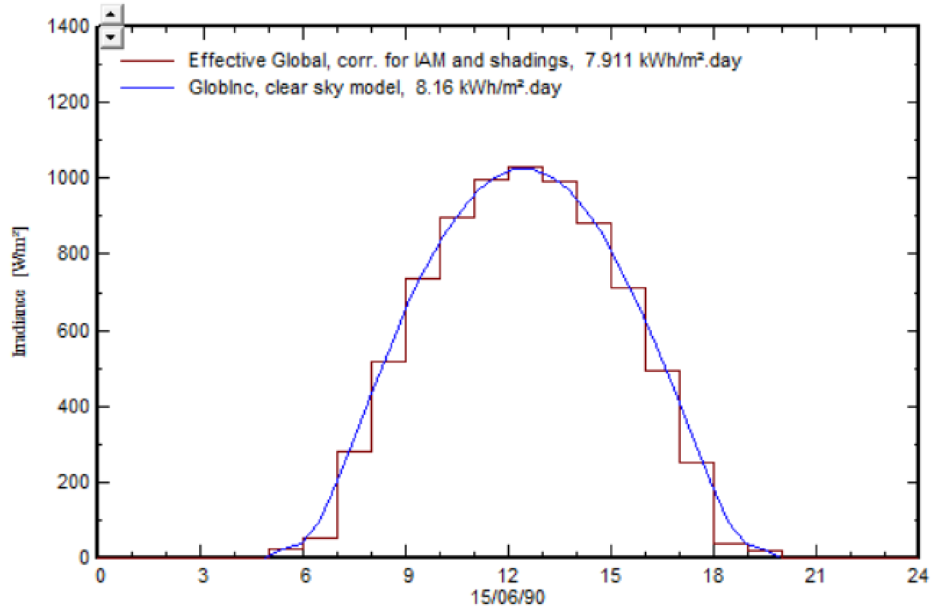


Figure 4.6: Behavior of the Best Day to Simulate [49].

order to visualize the energy drops needed for each main scenario, applying different values of the soiling index, as previously presented.

- Solar Tracker Scenario with Ideal Annual Angulation: In this scenario, simulating a system with solar tracking at the ideal annual tilted angle, but the soiling index variation was made, allowing the comparison of the system's performance in relation to the tracking and the system's behavior in relation to debris.

- Solar Tracker Scenario with Varied Angulations: In this scenario, performing the simulation in a system with tracking for different angles, and the various soiling indices presented above, allowing the comparison of the performance of the system in relation to the angulation and making it possible to see the system's behavior regarding the accumulation of debris.

Chapter 5

Results Discussion

This fifth section consists of presenting the results together with their analysis. In this section, the results obtained through the simulation and modeling will be presented, and what was possible to observe about the system's behavior for the different scenarios will be discussed. The first part refers to the analysis of the results in an annual perspective obtained from the simulation. The second part was the presentation of the results obtained from the application of the soiling index modeling. Finally, at the end, the results will be presented together in order to compare both results. The analysis of the modeling behavior in relation to the simulated values was made, making it possible to identify that the simulation modeling presented similar patterns for most cases.

5.1 Simulation Results

5.1.1 Annual Energy Generated

This first part aims to present the behavior of the PV system in relation to the variations to which it was exposed, and how this behavior demonstrates the functioning of the system. The results are presented in an annual perspective.

Fixed System with Optimal Annual Tilted Angle

The variation of the annual energy production for the fixed system with an ideal annual inclination with the incidence of the soiling index is represented in Figure 5.1.

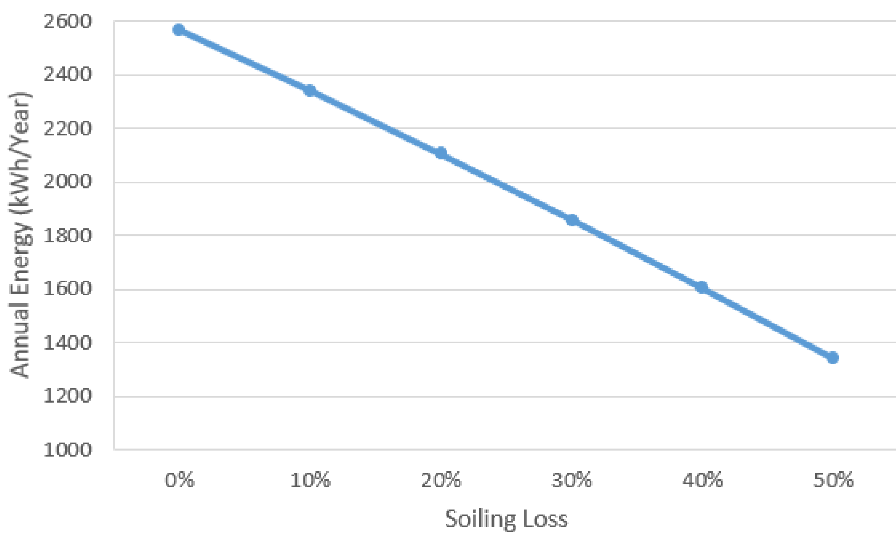


Figure 5.1: Energy Generated by the Fixed System with the Annual Tilted Angle.

As it is possible to observe in Figure 5.1, the energy production had a progressive drop, while the soiling index increase. This result confirms what was studied in section 2.3.2, that the soiling index can be observe as a progressive loss in the energy production [5], [6].

Solar Tracker With Optimal Annual Tilted Angle

The variation of the annual energy production for the system with solar tracking, with the ideal annual slope, and with the variation of the soiling index represented in Figure 5.2.

As it is possible to observe in Figure 5.2, the energy production present the same progressive drop as the previous analysis made to the fixed system. Proving again that the soiling index can be observed as a progressive loss.

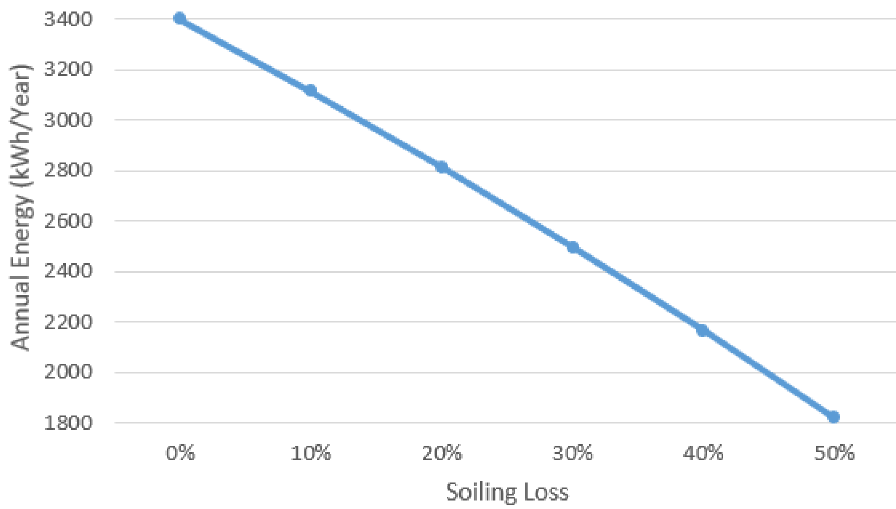


Figure 5.2: Energy Generated by the Solar Tracker System with the Annual Tilted Angle.

Solar Tracker With Various Tilted Angles

The variation of the annual energy generated for the system with solar tracking with variable angles. Because it contains several angles, the graph presented in Figure 5.3 contains a small portion of the values to facilitate the visualization, containing the highest and lowest value, showing the same pattern found in the other scenarios.

As it is possible to observe in Figure 5.3, the energy production present the same progressive drop as previous analysis made. Proving that the theory present in [5], [6] was true.

5.1.2 Instantaneous Current and Irradiation

This second part aims to present the behavior of the PV system in relation to the variations to which it was exposed, and how this behavior demonstrates the functioning of the system. The results are presented in an moment perspective, corresponding to June 15th at noon.

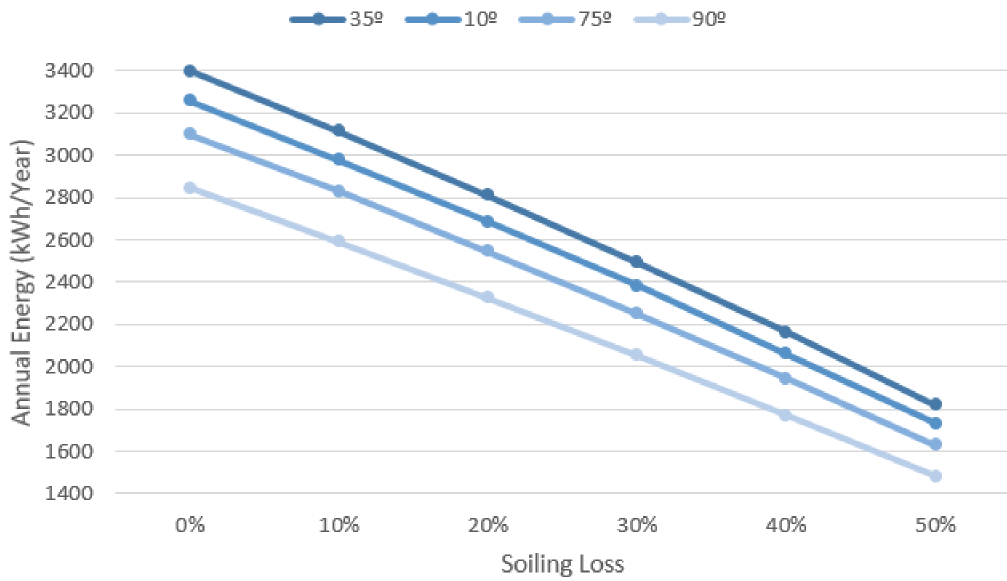


Figure 5.3: Energy Generated by the Solar Tracker System with Variable Tilted Angle.

Fixed System with Optimal Annual Tilted Angle

The variation in the output current of the fixed system with the ideal annual tilt angle is shown in Figure 5.4, and the irradiation value under ideal conditions, 0% soiling loss, for this analysis was $1031.79 Wh/m^2$.

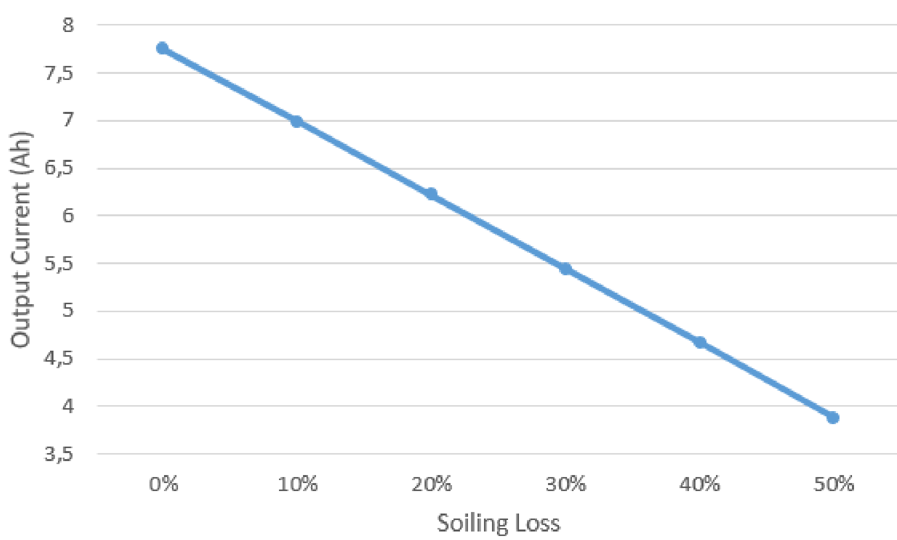


Figure 5.4: Output Current by the Fixed System with the Annual Tilted Angle.

As it is possible to observe in Figure 5.4, the output current present the same progressive drop as the energy production, being able to observe the direct correlation the current have with the energy.

Solar Tracker with Optimal Annual Tilted Angle

The variation of the output current for the system with solar tracking at the ideal annual tilt angle is shown in Figure 5.5, the irradiation value under ideal conditions, 0% dirt, for this analysis, was $1031.8304 Wh/m^2$.

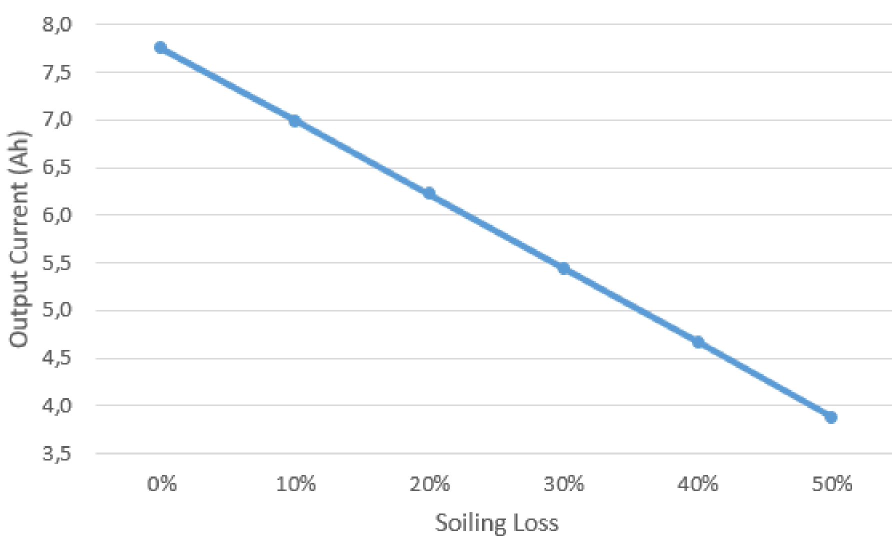


Figure 5.5: Output Current by the Solar Tracker System with the Annual Tilted Angle.

As it is possible to observe in Figure 5.5, the output current present the same progressive drop as the previous analysis made to the fixed system. Proving again that the soiling index can be observed as a progressive loss to the output current, used as a parameter to measure the soiling index in [44].

Solar Tracker with Various Tilted Angles

The variations in the output current for the system with solar tracking at different angles are shown in Figure 5.6, however, as occurred for scenario 5.1.1, the numbers represented were limited to facilitate visualization, containing the highest and lowest value, making it possible to observe the limits, and how the system behaves. For the values represented below, the radiation in ideal conditions was $1058.402 Wh/m^2$, $931.7712 Wh/m^2$, $714.8285 Wh/m^2$ and $419.3143 Wh/m^2$ respectively.

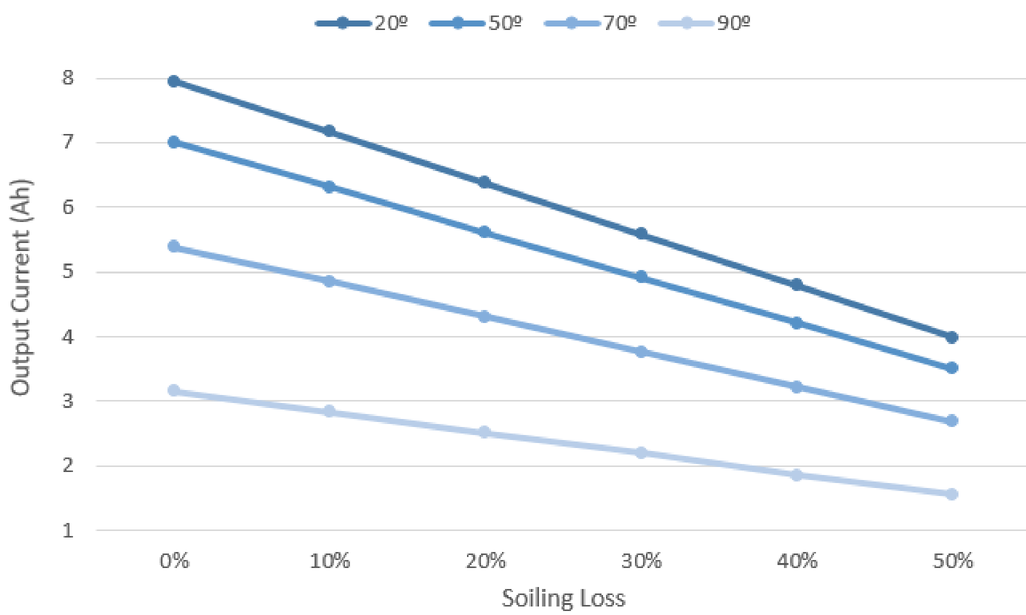


Figure 5.6: Output Current by the Solar Tracker System with Variable Tilted Angle.

As it is possible to observe in Figure 5.6 the same progressive loss on the output current happen to all of the cases in this section. Proving that the current is directly connected to the solar radiation, and from this variables is possible to estimate the soiling index.

5.1.3 Correlation of Both Scenarios

With the combination of the results of the output current and energy production, of the fixed system in the same graph, presented in Figure 5.7, it is possible to notice the patterns described above even more clearly, by limiting themselves to the maximum and minimum values of each variable.

For the results of the system with a solar tracker, it is possible to observe a similar

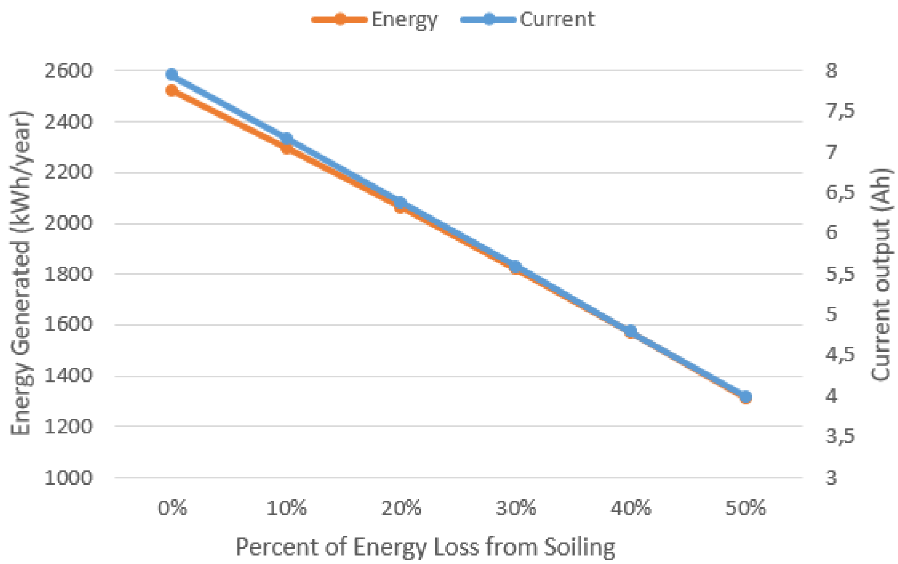


Figure 5.7: Output Current and Energy Generation for the Fixed System.

pattern. However, the energy production drop is greater than the fixed system. Demonstrating the importance of having a soiling index modeling system for PV systems with solar trackers. Since the increase of dirt in this type of application results in a greater loss energy loss, as shown in the graph in Figure 5.8.

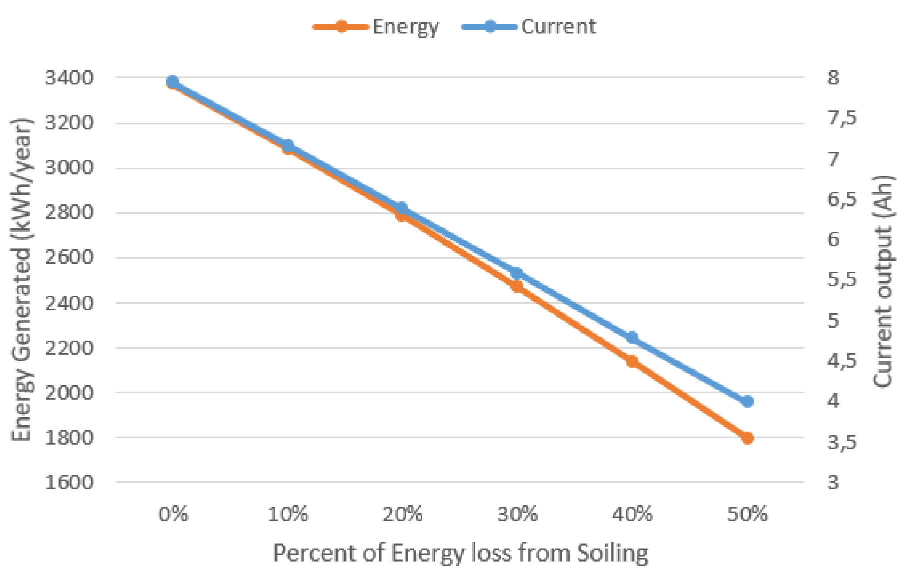


Figure 5.8: Output Current and Energy Generation for the Solar Tracker System.

5.2 Soiling Index Modeling Results

To facilitate the visualization, the values resulting from the application of the modeling are present in Annex A. in a table showing the values for each index, system, and slope.

In this section, the values presented in the graphs originate from the application of the soiling index modeling, presented in section 3.1.

5.2.1 Fixed System with Optimal Annual Tilted Angle

The results obtained for the fixed system, with a fixed tilt angle from the estimation of the output current, are represented by the graph in Figure 5.10.

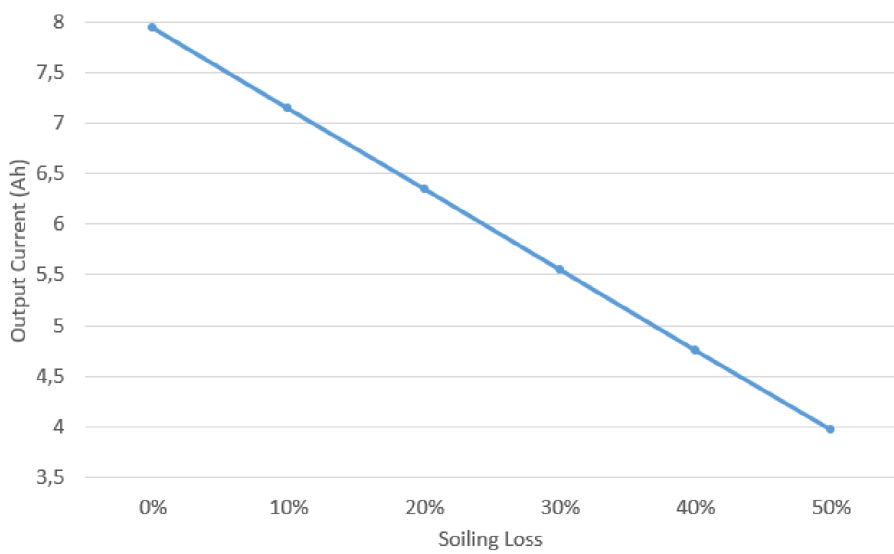


Figure 5.9: Output Current for a Fixed System with Annual Ideal Tilted Angle.

As it is possible to observe in Figure 5.9, the estimated output current presents a progressive drop similar to the simulation.

5.2.2 Solar Tracker with Optimal Annual Tilted Angle

The results obtained for the system with solar tracking, with a fixed tilt angle from the estimation of the output current, are represented by the graph in Figure 5.10.

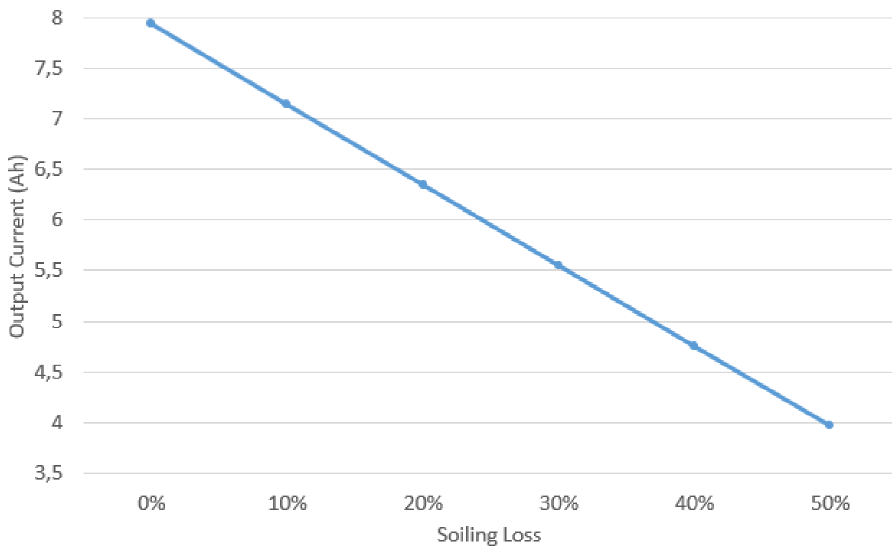


Figure 5.10: Output Current for a Solar Tracker System with Annual Ideal Tilted Angle.

As it is possible to observe in Figure 5.10, the progressive drop in the output current to this system, is similar to the simulation system and the previous analysis.

5.2.3 Solar Tracker with Various Tilted Angle

To present the values obtained for this scenario a graph was composed with a part of the values, represented by Figure 5.11, containing the highest and lowest value for this analysis, to facilitate the visualization of the system behavior, and as previously mentioned the complete data are available in Annex A.

As it is possible to observe in Figure 5.11, the same progressive loss on the output current happen to all of the cases in this section. Proving again, that the current is directly connected to the solar radiation, and it is possible to estimate the soiling index using this values as reference.

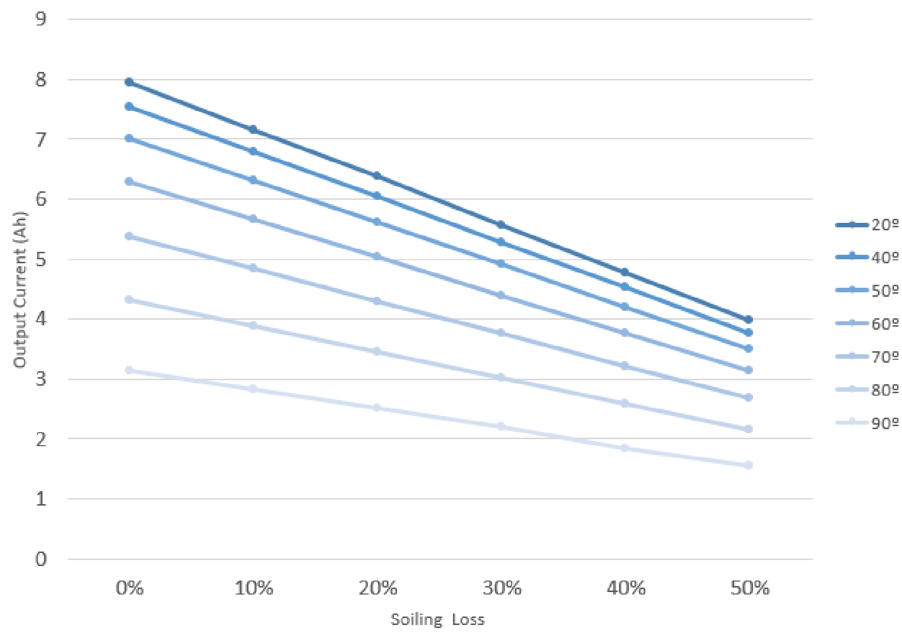


Figure 5.11: Output Current for a Solar Tracker System with Varied Angle.

5.3 Correlation and Discussion Between Results and Simulation

The correlation between the values presented in the simulation performed to create the database and the values generated from the soiling index modeling is an important exercise, because allows to analyze whether the values have any relation with each other and present a valid error.

When plotting the values for the fixed system at an ideal annual angle, represented in Figure 5.12, it is possible to notice that the response obtained by the modeling is similar to the current decay behavior, presenting only a slight difference, which can be easily arranged, showing how accurate the results obtained through modeling for this configuration were.

Plotting the values for the system with solar tracker in ideal annual angulation, as shown in the graph in Figure 5.13, the behavior of the current for both is similar, as well as for the fixed system. This situation demonstrates that variation in energy production may show a decay greater, as presented in Figure 5.8, because the annual production of the

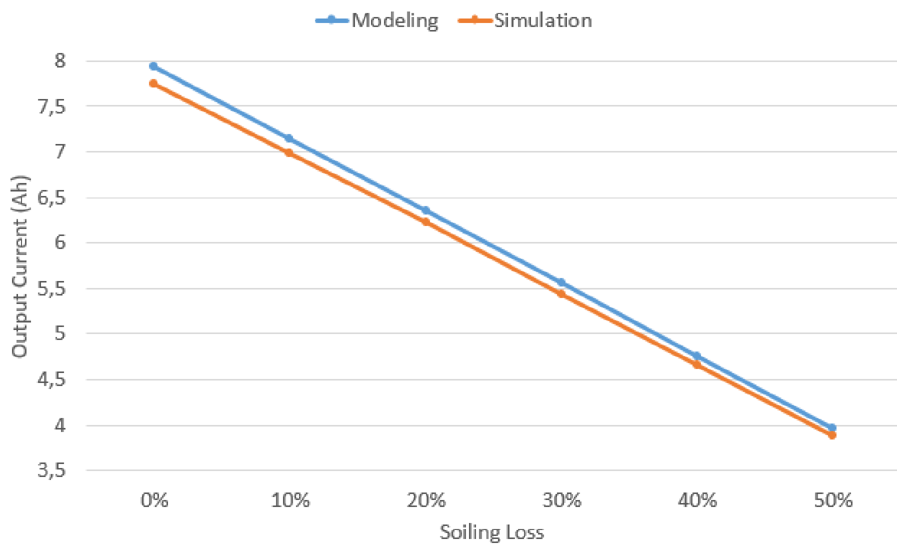


Figure 5.12: Correlation between Simulated and Modeling Values for Fixed System.

system with solar tracking is greater and suffers more intensely from this loss. However, as expected, the behavior remains the same for different systems, which demonstrates the model's versatility, and how the answers obtained by the modeling are accurate, making it more reliable.

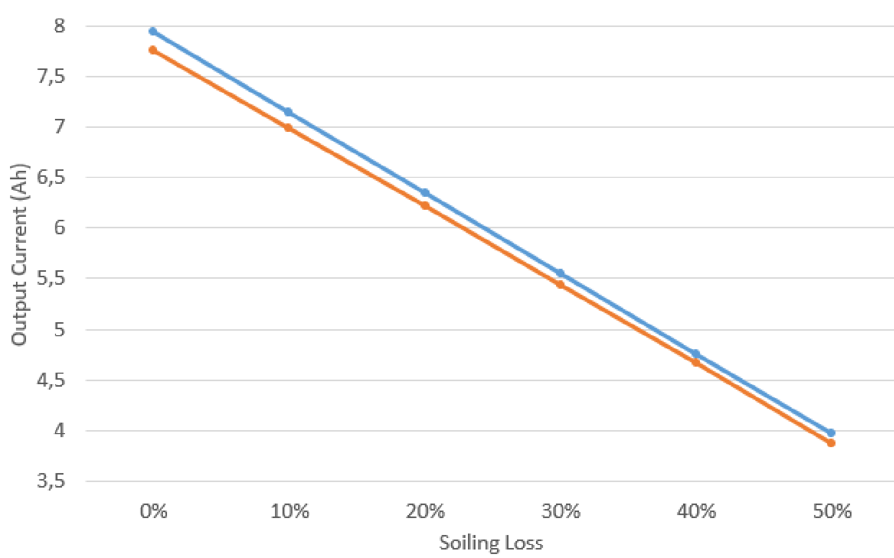


Figure 5.13: Correlation between Simulated and Modeling Values for Solar Tracker System.

The values plotted for the system with solar tracker with varying angles, as before, presents a reduced portion of its values to facilitate visualization, represented in Figure 5.14. As with previous systems, the decay behavior maintains the same pattern observed in the simulation, showing that the system simulation confirms the theory raised above about the possible behavior.

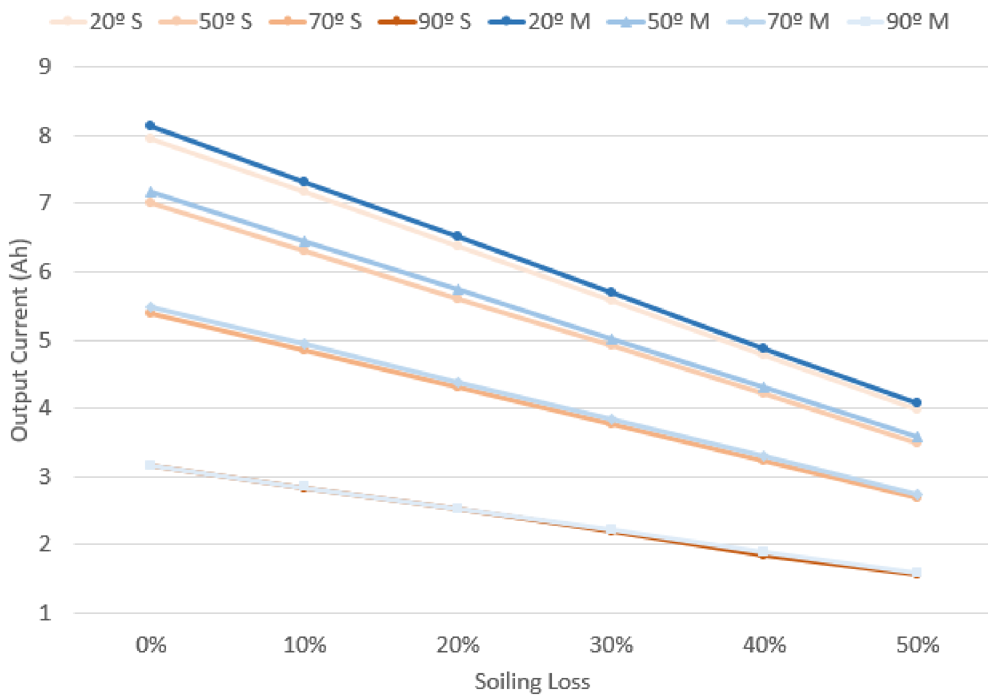


Figure 5.14: Correlation between Simulated and Modeling Values for Solar Tracker System with Varied Tilted Angle.

With the results it can be seen that there is actually a gradual decay in the current, as well as the decay that occurs in energy production, presented by [6], making the study simplify the analysis to just two variables, which have a greater impact in the final response.

From the results, it is possible to calculate the relative error between the values obtained through modeling and simulation, as shown in Figure 5.15. Based on these values, it was possible to notice a standard error behavior for the largest angle interval, and with a margin of error lower than that reported in the studies presented in [7]–[9], showing how accurate was this modeling.

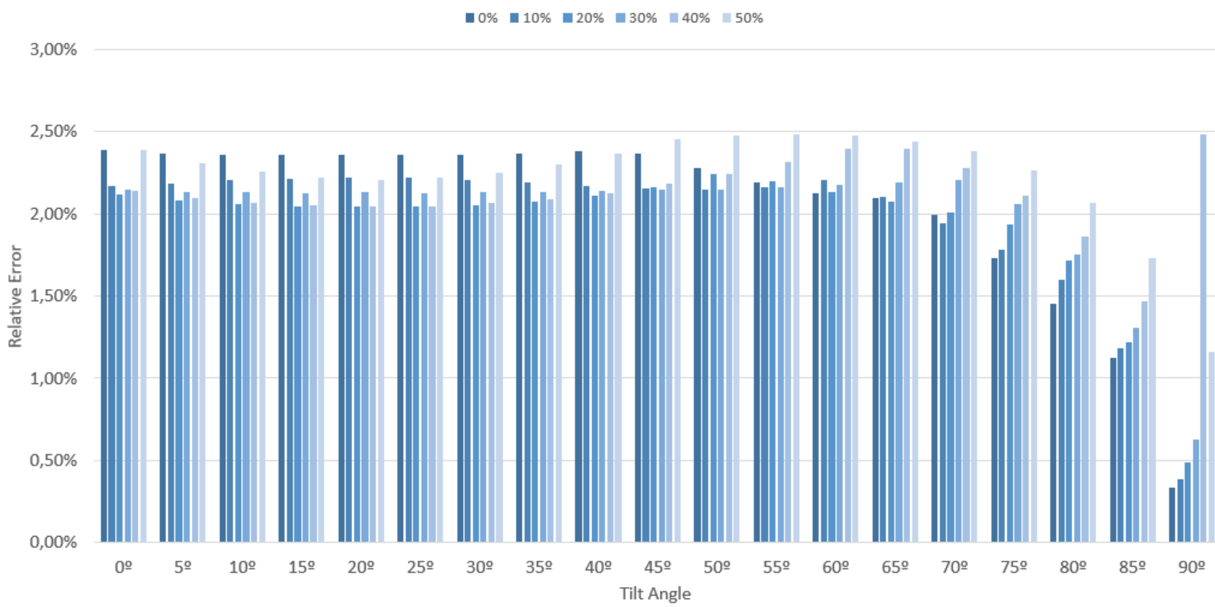


Figure 5.15: Relative Error.

The behavior shown in Figure 5.15, demonstrates that for the largest range of angulation, the error can be easily corrected taking into account the behavior of it. As for the less usual angulation, such as the system at 90 degrees of inclination, this behavior can be corrected, but with a lower degree of reliability, by the variation observed for 40% of soiling loss.

Even the variation outside the standards tilted angle, the error is still accurate, not exceeding the maximum 2.50%, a value close to those found in some of the experiments of the studies [7]–[9]. Comparing those studies with the application of the modeling developed in this work, the results had a more consistence response for different scenarios of application, demonstrating the accuracy of the soiling index modeling developed, using a simplified solution, less sensors and being easy to implement in embedded systems with less processing capacity.

Therefore, it is possible to conclude that the soiling index modeling can provide reliability estimation when analyzed the behavior of the error and the similarity of the simulation values with the estimated values. Then, this research has proved to be valid and useful.

Chapter 6

Conclusions

The analyzed goals of the PNEC for Portugal show the importance of developing research and implementation on renewable energy sources, making it possible to obtain energy growth in the country, reducing its dependence on foreign energy sources, not to mention the benefits that these implementations can bring to the environment. The production of PV energy has gained a great prominence in recent years as seen its growth between 2008 and 2018, and with the guidelines presented, it has been receiving even more prominence to present an even greater growth.

Basing the development of this work on the question-problem: How to improve or how to optimize the energy supply PV systems? To improve the production of energy by renewable sources to optimize its operation, making the stipulated objectives to be achieved more effectively and with even better results than expected. Portugal has a strong dependence on energy from an external source and, according to government data, by implementing new sources of sustainable energy production. This problem reduces over time, making Portugal more independent and adding more positive results with this study.

This scenario proposes the creation of a soiling index modeling, a capable tool that measures the impact of the soiling index in the PV system. The advantage of this modeling against the ones found in the literature was the approach. Which focuses on reducing the number of variables and reducing the processing power necessary to the hardware. To construct this modeling it was necessary to study how the soiling affects the PV system. From this, found that the output current and the solar radiation as the most significant variables of the system. With the most significant variables analyzed, it was employed a formula that calculates the estimated current for a PV system, and in this formula have other variables not considered to be collected, making it necessary to calibrate the formula to adjust on the modeling.

After the adjustment of the mathematical formula of the modeling, it was necessary to develop the scenario for the testing and validation of the modeling. As this work is a part of a project that will develop a solar tracker, the scenario used to test and validate this modeling was comparing the efficiency of the system between a fixed system and a solar tracker system. To estimate the maximum power of the system was used the current legislation [47], which limit the power for domestic solar system with the less bureaucracy to 1,5kWp. Nevertheless, because this work was only theoretical, without the resources to implement this modeling to a real system, using all the data collected and tested from the selected software PVSyst.

The results presented by the soiling index modeling values were very close to the simulated, where the relative errors found ranged from 0.33% to 2.48%, and within the most of the tilted angle, their behavior was practically constant, demonstrating certain ease in correcting the values for real applications, which can bring a result with a high degree of reliability, becoming an application to solve the optimization problems of PV systems with the maintenance.

With the results, it is possible to conclude that the general objective of this work, in creating a modeling of the soiling index in PV systems from simulations, starts from a more simplified solution. The simplicity facilitates the insertion of this modeling in the practical scope, because of the relation cost/benefit ends up representing an economy of natural resources, when performing an adequate cleaning and the increase in the performance of PV systems.

In addition to the results, it was possible to observe the behavior of the modules, to facilitate the identification of their operation, in a more simplified way. In this way it is possible to find new solutions for PV systems, taking into account the practical perspective for problem solving, analyzes that may end up making implementations feasible that will bring many benefits in relation to energy production.

And according to the energy production data, the use of systems with solar trackers brought a relatively high gain for energy production, since the values presented for the system without this technology implemented represented almost half of the potential observed for the system with the tracking solar applied.

Objectives

Taking into account the specific objectives raised, it was possible to achieve all of them, and regarding the dependence that existed between them. The first specific objective, achieved in Section 2, was to present and describe the characteristics of PV energy production. Where the direct dependence of the current was raised for solar radiation, because the cells work as a current source and the solar radiation through the PV effect converts the light into electrical energy, as demonstrated in the graphs presented in this work, because of the behavior presented as the soiling rate was increased.

The second specific objective was to simulate, using the PVSyst software, implementing the tilted angle, tracking and soiling loss, taking into account all the bureaucratic and functioning issues of the systems found in Portugal [47]. This objective was achieved by developing Section 4. The results presented outcomes as expected, in giving support to the first specific objective.

The third specific objective was to analyze the energy production capacity of a PV structure with a solar tracker using the PVSyst software. This objective was achieved with the Section 4. Taking into account the goals imposed by the government with the implementation of the PNEC [2], Portugal has the potential necessary to carry out the implementation of this energy source. Since the gain presented when applying a solar tracker almost doubled, concerning the fixed system, which would increase the need for the idealization of a model like the one proposed in this work, to assist in obtaining the maximum performance of the systems.

The fourth specific objective was to identify how these variables affect the production of solar energy. This objective was achieved with the development of the Section 4. When the results showed how the PV systems behave with the different values applied to the variables. Since the pattern of the output current was observed while the soiling index was varied, and the difference in energy production due to the variation of the tilted angle.

The fifth and final specific objective was to characterize the conditions for the production of PV energy from the structure analyzed in the work. This objective is responded on Section 4 which presented the graphs of energy production for PV systems with ideal annual tilted angle and the PV systems with solar tracking for various inclinations, enabling the projection with the minimum loss for slope, and from modeling the identification of the soiling index for the PV systems.

With the achievement of all the objectives, and with each expected result during the work, developing the soiling index modeling, which is the general objective of the work. It presented an expected behavior for all analyses previously performed. Nevertheless, what could have improved an even more satisfactory result could have been the implementation of this analysis in a functioning system, is possible to carry out the practical validation. However, by the studies carried out in this research, it was possible to determine that the answers demonstrate initially ideal values, since in [49], [50] the values generated by the PVSyst software, have a certain similarity with reality.

Future Work

For the futures work, it is necessary to attend the points that limited the work. The lack of studies regarding the incidence of debris in Portugal, as found for other regions, could assist in improving the work. The dependence on simulation results, even if the software results are close to reality. The real systems may present some variations, which in turn may need to perform a new calibration of the modeling for a practical application. And as well as the limitation of simulated data and the lack of real data for comparison, they were also a limiting factor.

The study referring to the application of this modeling to real systems, may be an aspect that ends up confirming the results presented in the practical scope, enabling the use of this technology in order to assist in the growth of energy production in Portugal and PV technology, as being this is the source of focus for future country implementations.

The performance of studies regarding the behavior of the dirt index, determining the patterns for occurrence, could be a source of information that could greatly improve the determination of the dirt indexes for the region of the study in question, since its behavior is very particular for each region.

A study regarding the ideal cleaning point in reference to the dirt indexes in the region, which may end up in determining a cycle for carrying out a possible self-cleaning, making the system itself identify the ideal time to clean the modules.

Bibliography

[1] IEA, *World energy outlook 2019.* [Online]. Available: https://www.iea.org/reports/world-energy-outlook-2019 (visited on 01/16/2020).

[2] D. G. de Energia e Geologia, “Plano nacional energia e clima 2021-2030,” 2019.

[3] O. da Energia, *Energia em Números*, A. para a Energia, Ed. 2019, ISBN: 978-972-8646-76-9.

[4] *Balanço da produção de eletricidade de portugal continental*, Associação Portuguesa de Energias Renováveis. [Online]. Available: https://www.apren.pt/.

[5] N. Kishor, M. G. Villalva, S. R. Mohanty, and E. Ruppert, “Modeling of pv module with consideration of environmental factors,” in *2010 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe)*, IEEE, 2010, pp. 1–5.

[6] S. A. Said, G. Hassan, H. M. Walwil, and N. Al-Aqeeli, “The effect of environmental factors and dust accumulation on photovoltaic modules and dust-accumulation mitigation strategies,” *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 743–760, 2018.

[7] B. Laarabi, O. M. Tzuc, D. Dahlioui, A. Bassam, M. Flota-Bañuelos, and A. Barhdadi, “Artificial neural network modeling and sensitivity analysis for soiling effects on photovoltaic panels in morocco,” *Superlattices and Microstructures*, vol. 127, pp. 139–150, 2019.

[8] W. Javed, B. Guo, and B. Figgis, “Modeling of photovoltaic soiling loss as a function of environmental variables,” *Solar Energy*, vol. 157, pp. 397–407, 2017.

[9] B. Hammad, M. Al–Abed, A. Al–Ghandoor, A. Al–Sardeah, and A. Al–Bashir, "Modeling and analysis of dust and temperature effects on photovoltaic systems' performance and optimal cleaning frequency: Jordan case study," *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 2218–2234, 2018.

[10] L. W. Anderson and L. A. Sosniak, *Bloom's taxonomy*. Univ. Chicago Press Chicago, IL, 1994.

[11] M. J. Adinoyi and S. A. Said, "Effect of dust accumulation on the power outputs of solar photovoltaic modules," *Renewable energy*, vol. 60, pp. 633–636, 2013.

[12] Z. A. Darwish, H. A. Kazem, K. Sopian, M. Al-Goul, and H. Alawadhi, "Effect of dust pollutant type on photovoltaic performance," *Renewable and Sustainable Energy Reviews*, vol. 41, pp. 735–744, 2015.

[13] M. V. X. DIAS, "Impacto no consumo de energia elétrica e nas emissões decorrente da introdução de carros elétricos na frota de automóveis.," 2013.

[14] K. Pickerel, *The long history of solar pv*. [Online]. Available: `https://www.solarpowerworldonline.com/2018/01/long-history-solar-pv/`.

[15] J. Stachel, "Einstein's miraculous year," 1998.

[16] P. A. Lynn, *Electricity from sunlight: an introduction to photovoltaics*. John Wiley & Sons, 2011.

[17] B. E. Sørensen, *Renewable Energy: Physics, engineering, environmental impacts, economics and planning*. Academic Press, 2017.

[18] B. Zientara, *Types of solar panels – what they're made of how they work*. [Online]. Available: `https://www.solarpowerrocks.com/solar-basics/types-of-solar-panels/`.

[19] F. Calise, M. D. D'Accadia, M. Santarelli, A. Lanzini, and D. Ferrero, *Solar Hydrogen Production: Processes, Systems and Technologies*. Academic Press, 2019.

[20] D. Shi, *Nanomaterials and devices*. Elsevier, 2014.

[21] M. Newkirk, *What are monocrystalline, polycrystalline and thin film solar panels?* [Online]. Available: `https://www.cleanenergyreviews.info/blog/pv-panel-technology`.

[22] J. Ramanujam and U. P. Singh, "Copper indium gallium selenide based solar cells–a review," *Energy & Environmental Science*, vol. 10, no. 6, pp. 1306–1319, 2017.

[23] F. G. Gil, M. Martin, J. P. Vara, J. R. Calvo, L. Perlovsky, D. Dionysiou, L. Zadeh, M. Kostic, C. Gonzales-Concepcion, H. Jaberg, *et al.*, "A review of solar tracker patents in spain," *Proceedings of the Energy Problems and Environmental Engineering*, pp. 292–297, 2009.

[24] A. Hafez, A. Yousef, and N. Harag, "Solar tracking systems: Technologies and trackers drive types–a review," *Renewable and Sustainable Energy Reviews*, vol. 91, pp. 754–782, 2018.

[25] J. Wu, H. Hou, and Y. Yang, "Annual economic performance of a solar-aided 600 mw coal-fired power generation system under different tracking modes, aperture areas, and storage capacities," *Applied Thermal Engineering*, vol. 104, pp. 319–332, 2016.

[26] A. M. A. Morad, A. K. S. Al-Sayyab, and M. A. Abdulwahid, "Optimisation of tilted angles of a photovoltaic cell to determine the maximum generated electric power: A case study of some iraqi cities," *Case studies in thermal engineering*, vol. 12, pp. 484–488, 2018.

[27] H. Hussein, G. Ahmad, and H. El-Ghetany, "Performance evaluation of photovoltaic modules at different tilt angles and orientations," *Energy conversion and management*, vol. 45, no. 15-16, pp. 2441–2452, 2004.

[28] R. N. Pagani, J. L. Kovaleski, and L. M. Resende, "Methodi ordinatio: A proposed methodology to select and rank relevant scientific papers encompassing the impact factor, number of citation, and year of publication," *Scientometrics*, vol. 105, no. 3, pp. 2109–2135, 2015.

[29] R. N. Pagani, J. L. Kovaleski, and L. M. M. de Resende, "Avanços na composição da methodi ordinatio para revisão sistemática de literatura," *Ciência da Informação*, vol. 46, no. 2, 2017.

[30] J. P. Higgins, "Green s," *Cochrane handbook for systematic reviews of interventions version*, vol. 5, no. 0, p. 3, 2011.

[31] D. Tranfield, D. Denyer, and P. Smart, "Towards a methodology for developing evidence-informed management knowledge by means of systematic review," *British journal of management*, vol. 14, no. 3, pp. 207–222, 2003.

[32] B. Kitchenham, "Procedures for performing systematic reviews," *Keele, UK, Keele University*, vol. 33, no. 2004, pp. 1–26, 2004.

[33] B. Kitchenham, O. P. Brereton, D. Budgen, M. Turner, J. Bailey, and S. Linkman, "Systematic literature reviews in software engineering–a systematic literature review," *Information and software technology*, vol. 51, no. 1, pp. 7–15, 2009.

[34] C. Okoli and K. Schabram, "A guide to conducting a systematic literature review of information systems research," 2010.

[35] L. Cunha, P. Ceryno, and A. Leiras, "Social supply chain risk management: A taxonomy, a framework and a research agenda," *Journal of Cleaner Production*, 2019.

[36] L. Gao, I. Melero, and F. J. Sese, "Multichannel integration along the customer journey: A systematic review and research agenda," *The Service Industries Journal*, pp. 1–32, 2019.

[37] M. F. Muller, F. Esmanioto, N. Huber, E. R. Loures, and O. C. Junior, "A systematic literature review of interoperability in the green building information modeling lifecycle," *Journal of cleaner production*, vol. 223, pp. 397–412, 2019.

[38] ——, "A systematic literature review of interoperability in the green building information modeling lifecycle," *Journal of cleaner production*, vol. 223, pp. 397–412, 2019.

[39] J. T. de Souza, A. C. de Francisco, C. M. Piekarski, G. F. do Prado, and L. G. de Oliveira, “Mineração de dados e aprendizado de máquina no contexto de avaliação sustentável,” *IEEE Latin America Transactions*, vol. 17, no. 3, pp. 372–382, 2019.

[40] A. Corsi, R. N. Pagani, J. L. Kovaleski, *et al.*, “Technology transfer for sustainable development: Social impacts depicted and some other answers to a few questions,” *Journal of Cleaner Production*, p. 118 522, 2019.

[41] R. Appels, B. Lefevre, B. Herteleer, H. Goverde, A. Beerten, R. Paesen, K. De Medts, J. Driesen, and J. Poortmans, “Effect of soiling on photovoltaic modules,” *Solar energy*, vol. 96, pp. 283–291, 2013.

[42] A. Hafez, A. Soliman, K. El-Metwally, and I. Ismail, “Tilt and azimuth angles in solar energy applications–a review,” *Renewable and sustainable energy reviews*, vol. 77, pp. 147–168, 2017.

[43] A. K. S. Al-Sayyab, Z. Y. Al Tmari, and M. K. Taher, “Theoretical and experimental investigation of photovoltaic cell performance, with optimum tilted angle: Basra city case study,” *Case Studies in Thermal Engineering*, vol. 14, p. 100 421, 2019.

[44] Í. B. IGOR BASKOSKI, “Rendimento de sistemas de geração de energia solar com relação ao acúmulo de detritos sobre módulos fotovoltaicos.”

[45] H. S. Rauschenbach, *Solar cell array design handbook: the principles and technology of photovoltaic energy conversion.* Springer Science & Business Media, 2012.

[46] Z. M. Salameh, B. S. Borowy, and A. R. Amin, “Photovoltaic module-site matching based on the capacity factors,” *IEEE transactions on Energy conversion*, vol. 10, no. 2, pp. 326–332, 1995.

[47] “Ministério do ambiente, ordenamento do território e energia decreto-lei n.º 153/2014 de 20 de outubro,” no. 153/2014, p. 14, out. 2014.

[48] P. R. G. Torres, “Avaliação do desempenho de uma central fotovoltaica baseada em dados de exploração e em medições do recurso solar,” 2014.

[49] V. M. Mermoud A., *Pvsyst.* [Online]. Available: `https://www.pvsyst.com/help/`.

[50] L. G. M. Oliveira, "Avaliação de fatores que influenciam na estimativa da geração e operação de sistemas fotovoltaicos conectados à rede elétrica," 2017.

Appendix A

Results

System	Tilted Angle (°)	Annual Energy Generated (kWh/Year)						Output Current (Ah)						Solar Radiation (kWh/m²)
		0%	10%	20%	30%	40%	50%	0%	10%	20%	30%	40%	50%	
Fixed	34	2568	2340	2103	1856	1601	1339	7,7486	6,9854	6,2168	5,4363	4,6620	3,8774	1031,7900
Tracker	34	3398	3112	2811	2494	2162	1817	7,7488	6,9857	6,2169	5,4365	4,6621	3,8775	1031,8304
Tracker	0	3134	2863	2580	2284	1976	1657	7,4804	6,7472	6,0003	5,2489	4,4993	3,7403	995,9720
	5	3200	2925	2637	2336	2022	1696	7,6782	6,9228	6,1599	5,3870	4,6191	3,8412	1022,3380
	10	3257	2979	2687	2381	2062	1731	7,8228	7,0514	6,2768	5,4883	4,7072	3,9154	1041,7511
	15	3306	3025	2730	2420	2097	1761	7,9122	7,131	6,3492	5,5512	4,7617	3,9614	1053,8002
	20	3345	3062	2764	2452	2125	1785	7,9462	7,1613	6,3768	5,5746	4,7826	3,9790	1058,4020
	25	3375	3090	2790	2475	2146	1803	7,9258	7,1432	6,3603	5,5607	4,7700	3,9684	1055,6467
	30	3392	3107	2805	2489	2158	1814	7,8495	7,0751	6,2984	5,507	4,7234	3,9291	1045,3535
	35	3398	3113	2811	2494	2163	1818	7,7182	6,9585	6,1922	5,4151	4,6435	3,8617	1027,7191
	40	3394	3108	2807	2490	2159	1814	7,5311	6,7921	6,0410	5,2842	4,5299	3,7661	1002,7026
	45	3379	3094	2793	2478	2148	1805	7,2945	6,5787	5,8472	5,1172	4,3846	3,6440	970,793
	50	3357	3072	2773	2459	2131	1790	7,0086	6,3158	5,6089	4,9121	4,2066	3,4975	931,7712
	55	3325	3042	2745	2433	2108	1770	6,6741	6,0086	5,339	4,6733	3,9997	3,3276	886,5370
	60	3283	3002	2707	2398	2077	1743	6,2884	5,6551	5,0302	4,3997	3,7631	3,1335	834,9429
	65	3229	2951	2659	2355	2038	1710	5,8541	5,2684	4,6842	4,0940	3,5022	2,9171	777,5261
	70	3169	2894	2606	2306	1995	1672	5,3809	4,8452	4,304	3,7587	3,2195	2,6803	714,8285
	75	3099	2828	2545	2251	1945	1630	4,8735	4,3841	3,8911	3,4005	2,9133	2,4241	647,1100
	80	3022	2755	2478	2190	1891	1583	4,3281	3,8898	3,4535	3,0208	2,5865	2,1511	575,0350
	85	2938	2677	2406	2124	1834	1534	3,7484	3,3717	2,9960	2,6191	2,2414	1,8631	499,0401
	90	2846	2591	2326	2053	1770	1480	3,1474	2,8311	2,5141	2,1967	1,8488	1,5608	419,3143

Figure A.1: PVSyst Simulation Results.

System	Tilted Angle (°)	Model Output Current (Ah)						Relative Error						Solar Radiation (kWh/m²)
		0%	10%	20%	30%	40%	50%	0%	10%	20%	30%	40%	50%	
Fixed	34	7,93191	7,13872	6,34553	5,55234	4,75915	3,96596	2,37%	2,19%	2,07%	2,13%	2,08%	2,28%	1031,7900
Tracker	34	7,93222	7,139	6,34577	5,55255	4,75933	3,96611	2,37%	2,19%	2,07%	2,13%	2,09%	2,29%	1031,8304
Tracker	0	7,65932	6,89339	6,12746	5,36152	4,59559	3,82966	2,39%	2,17%	2,12%	2,15%	2,14%	2,39%	995,9720
	5	7,86008	7,07407	6,28806	5,50205	4,71605	3,93004	2,37%	2,19%	2,08%	2,14%	2,10%	2,31%	1022,3380
	10	8,00754	7,20678	6,40603	5,60528	4,80452	4,00377	2,36%	2,20%	2,06%	2,13%	2,07%	2,26%	1041,7511
	15	8,09891	7,28902	6,47913	5,66924	4,85935	4,04946	2,36%	2,22%	2,05%	2,13%	2,05%	2,22%	1053,8002
	20	8,13378	7,3204	6,50702	5,69364	4,88027	4,06689	2,36%	2,22%	2,04%	2,14%	2,04%	2,21%	1058,4020
	25	8,1129	7,30161	6,49032	5,67903	4,86774	4,05645	2,36%	2,22%	2,04%	2,13%	2,05%	2,22%	1055,6467
	30	8,03487	7,23138	6,4279	5,62441	4,82092	4,01743	2,36%	2,21%	2,06%	2,13%	2,06%	2,25%	1045,3535
	35	7,90098	7,11088	6,32078	5,53069	4,74059	3,95049	2,37%	2,19%	2,08%	2,13%	2,09%	2,30%	1027,7191
	40	7,71062	6,93956	6,1685	5,39743	4,62637	3,85531	2,38%	2,17%	2,11%	2,14%	2,13%	2,37%	1002,7026
	45	7,4671	6,72039	5,97368	5,22697	4,48026	3,73355	2,37%	2,15%	2,16%	2,15%	2,18%	2,46%	970,793
	50	7,16827	6,45144	5,73462	5,01779	4,30096	3,58414	2,28%	2,15%	2,24%	2,15%	2,24%	2,48%	931,7712
	55	6,8205	6,13845	5,4564	4,77435	4,0923	3,41025	2,19%	2,16%	2,20%	2,16%	2,32%	2,48%	886,5370
	60	6,42213	5,77991	5,1377	4,49549	3,85328	3,21106	2,13%	2,21%	2,14%	2,18%	2,40%	2,48%	834,9429
	65	5,97678	5,3791	4,78143	4,18375	3,58607	2,98839	2,10%	2,10%	2,08%	2,19%	2,39%	2,44%	777,5261
	70	5,4882	4,93938	4,39056	3,84174	3,29292	2,7441	1,99%	1,94%	2,01%	2,21%	2,28%	2,38%	714,8285
	75	4,95801	4,46221	3,9664	3,4706	2,9748	2,479	1,73%	1,78%	1,94%	2,06%	2,11%	2,26%	647,1100
	80	4,39106	3,95196	3,51285	3,07374	2,63464	2,19553	1,45%	1,60%	1,72%	1,75%	1,86%	2,07%	575,0350
	85	3,79057	3,41151	3,03246	2,6534	2,27434	1,89529	1,13%	1,18%	1,22%	1,31%	1,47%	1,73%	499,0401
	90	3,15784	2,84205	2,52627	2,21049	1,8947	1,57892	0,33%	0,39%	0,48%	0,63%	2,48%	1,16%	419,3143

Figure A.2: Modeling Results and Relative Errors

Appendix B

Systematic Literature Review Results

Table B.1: List of Articles Constituting the Final Portfolio

Theme	Authors	Title	Year	Journal/Proceedings	IF	Nº citations	InOrdinatio
Soiling	Adinoyi, M.J. and Said, S.A.M.	Effect of dust accumulation on the power outputs of solar photovoltaic modules	2013	RENEWABLE ENERGY	5,439	180	220
	Darwish, Z.A., Kazem, H.A., Sopian, K., Al-Goul, M.A. and Alawadhi, H.	Effect of dust pollutant type on photovoltaic performance	2015	RENEWABLE & SUSTAINABLE ENERGY REVIEWS	10,556	94	154
	Appels, R., Lefevre, B., Herteleer, B., Goverde, H., Beerten, A., Paesen, R., Medts, K.D., Driesen, J. and Poortmans, J.	Effect of soiling on photovoltaic modules	2013	Solar Energy	4,674	108	148
	Said, S.A.M., Hassan, G., Walwil, H.M. and Al-Aqeeli, N.	The effect of environmental factors and dust accumulation on photovoltaic modules and dust-accumulation mitigation strategies	2018	RENEWABLE & SUSTAINABLE ENERGY REVIEWS	10,556	35	125
	Hammad, B., Al-Abed, M., Al-Ghandoor, A., Al-Sardeah, A. and Al-Bashir, A.	Modeling and analysis of dust and temperature effects on photovoltaic systems' performance and optimal cleaning frequency: Jordan case study	2018	RENEWABLE & SUSTAINABLE ENERGY REVIEWS	10,556	19	109
Tilted Angle	Hafez, A.Z., Soliman, A., El-Metwally, K.A. and Ismail, I.M.	Tilt and azimuth angles in solar energy applications – A review	2017	Renewable and Sustainable Energy Reviews	12,210	43	123
	Al-Sayyab, A.K.S., Al Tmari, Z.Y. and Taher, M.K.	Theoretical and experimental investigation of photovoltaic cell performance, with optimum tilted angle: Basra city case study	2019	CASE STUDIES IN THERMAL ENGINEERING	3,790	0	100
	Ali Morad, A.M., Al-Sayyab, A.K.S. and Abdulwahid, M.A.	Optimisation of tilted angles of a photovoltaic cell to determine the maximum generated electric power: A case study of some Iraqi cities	2018	Case Studies in Thermal Engineering	3,790	1	91