Study of the Photovoltaic Energy Production And Storage Scenarios in Poland and Portugal

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

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Abstract

The work concerns study of the photovoltaic energy production from the big-scale photovoltaic farm and study of the incorporation of the battery energy storage into the system. A photovoltaic farm has power of 5MW. It consists of more than 20 000 panels of the power of 240W each, covering around 3 ha of land. The Lithium-Ion battery storage system has capacity of 2MWh. The first aim was to study the power produced in Poland and Portugal from the same installation and creating scenarios when the battery will be charged (the sunniest 2 hours of a day) and discharged (2 hours of the highest electricity price). After comparing them and the circumstances for realising such project, the further analysis in done for Polish conditions only. For the economic assessment, the Variant 1 was concerning the photovoltaic farm with the battery storage system and Variant 2 was the photovoltaic plant alone. As the result, both of the installations had NPV<0 throughout the 25 years of the lifetime of the project, IRR were below the assumed discount rate of 2%, but the SPB for Variant 2 is almost 21 years. Even though the results were not entirely positive, they led to important conclusions about the state of renewables in Poland (and Portugal). The points were made about what needs to be done for these projects to become feasible.

Keywords

Renewable energy sources, photovoltaic energy, battery energy storage systems, profitability assessment, Li-Ion battery.

Resumo

O trabalho diz respeito ao estudo da produção de energia fotovoltaica a partir da exploração fotovoltaica em grande escala e ao estudo da incorporação do armazenamento de energia da bateria no sistema. Uma exploração fotovoltaica tem uma potência de 5MW. É constituída por mais de 20 000 painéis com uma potência de 240W cada, cobrindo cerca de 3 ha de terreno. O sistema de armazenamento de baterias de iões de lítio tem uma capacidade de 2MWh. O primeiro objectivo foi estudar a energia produzida na Polónia e em Portugal a partir da mesma instalação e criar cenários em que a bateria será carregada (as 2 horas mais ensolaradas de um dia) e descarregada (2 horas do preço mais elevado da electricidade). Após a sua comparação e das circunstâncias para a realização de tal projecto, a análise posterior foi feita apenas para as condições polacas. Para a avaliação económica, a Variante 1 dizia respeito à exploração fotovoltaica com o sistema de armazenamento de bateria e a Variante 2 era apenas a instalação fotovoltaica. Como resultado, ambas as instalações tinham NPV<0 durante os 25 anos de vida do projecto, IRR estavam abaixo da taxa de desconto assumida de 2%, mas a SPB para a Variante 2 é de quase 21 anos. Embora os resultados não tenham sido inteiramente positivos, levaram a conclusões importantes sobre o estado das energias renováveis na Polónia (e em Portugal). Foram feitas observações sobre o que é necessário fazer para que estes projectos se tornem viáveis.

Palavras-chave

Fontes de energia renováveis, energia fotovoltaica, sistemas de armazenamento de energia em bateria, avaliação da rentabilidade, bateria de iões de lítio.

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Chapter 1

Introduction

This chapter gives information about the later content of the work. Before getting into the details of the analysis performed and the ideas behind it, the scope and motivation for the work is presented. At the end of this chapter there can found a work structure provided for better navigation of the paper.

Topic introduction

There is no denying that in the modern world one of the most important conveniences is having a continuous access to different forms of energy, among which the most omnipresent is electricity. At the same time the market of electrical energy faces many challenges both on the consumer and supplier side. The electrical energy is considered to be challenging when it comes to the daily and seasonal demand changes, which can affect an everyday life. It is widely-known that in order for the grid to stay stable and safe, while increasing the share of renewable energy sources in the energy mix, the most optimal solution can come from the energy storage systems. Effective storage of especially electrical energy helps in smoothing the transitioning from classical fossil fuels into renewable energy sources energy generation, that under proper management can be very flexible and reliable. Without the energy storage, the grid can soon become unable to meet the peak demands and start to make the supplier simply lose his money by decreasing the efficiencies of classical combustibles-fuelled power plants due to varying load and the lack of energy management while dealing with the unpredictability of the renewable energy sources alone. [1] [2] The conversation of energy storage system is a highly-raised topic, because in theory it can solve many problems that countries and their grids face. Also, all of the European Union countries have the Renewable Energy 2030 Target to meet. In the EU Directive 2018/2001 of the European Parliament and Of The Council On The Promotion Of The Use Of Energy From Renewable Sources [3], one can literally read:

- “Reducing energy consumption,
- Increasing technological improvements,
- The use of energy efficiency technologies,
- Promotion of renewable energy in the electricity sector

are effective tools for reducing greenhouse gas emission and reducing Union’s energy dependence” [3]. These should be the targets that all EU member states follow. The renewable energy source, among which there is a photovoltaic technology, contribute to fulfilling the mentioned points. Investing in greener solutions, makes the whole continent move step-by-step toward the carbon neutral Europe, that is targeted for the year 2050.

Even with the well-done predictions and even with a high level of monitoring and automation of the grid, some issue may still appear. The EU Parliament also mentions the issues connected with energy safety. When it comes to photovoltaic energy, there can be times when electricity surplus is simply wasted, due to the fact that there is, in that moment, no possibility of utilizing it. On the other hand, there can be many times, even sometimes during one day, when the electricity production from PV panels drops drastically, creating a possible shortage. [2] Figure 1 shows the two places of interest for this work – Poland and Portugal and the possible variations of the parameter. What can be concluded here is that as the direct irradiation reaching the Earth’s surface is highly seasonal, proportionally the potential electricity produced with photovoltaic panels will be varying during each month, and also accordingly during each day, creating potential challenges in reaching the energy safety goals.

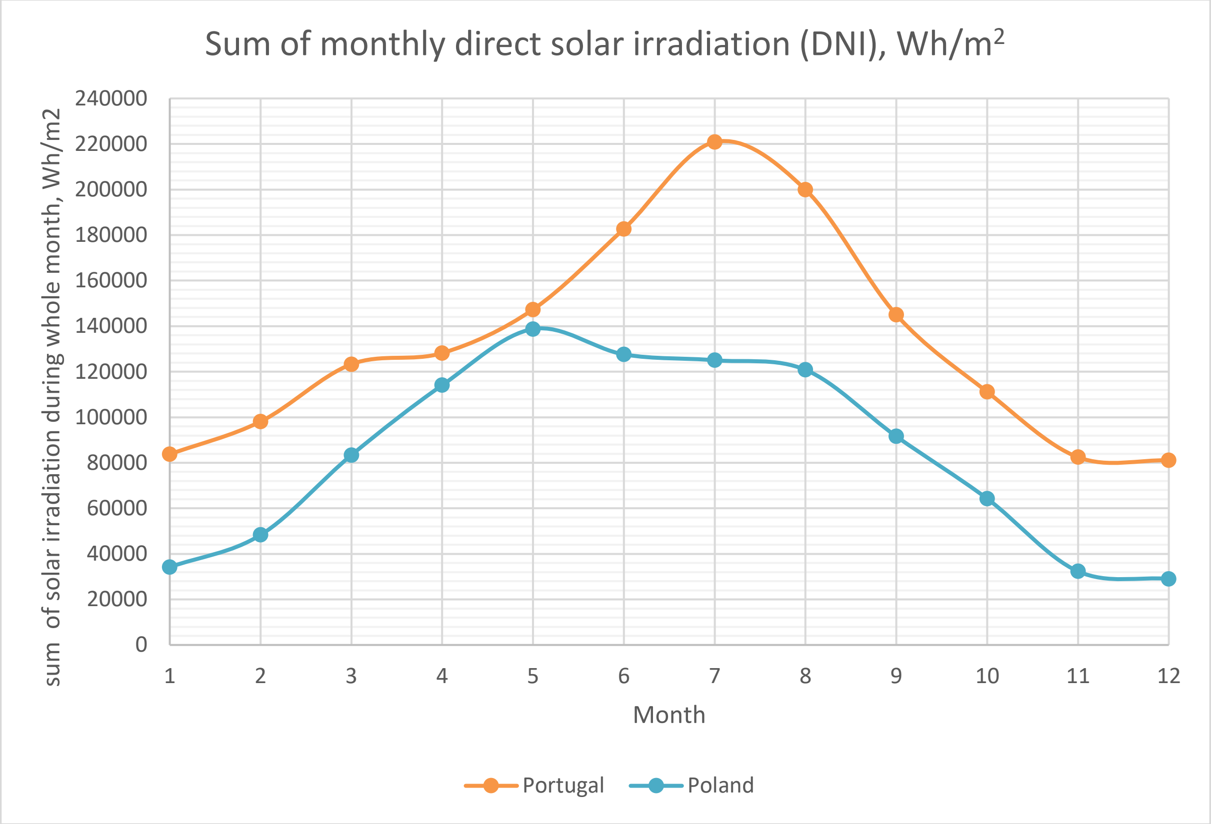

Figure 1 Monthly variations of sums of direct solar irradiation reaching the Earth's surface in Poland and Portugal. *Data adapted from:* [4], [5].

This naturally does not mean that the level of incorporation of the photovoltaic energy in the energy mix should drop, it just means that the national grids must adapt to the new circumstances. One of the best solutions seems to be previously mentioned energy storage, which during the highest production of renewable energy periods would store the excess energy and then release it when most convenient and needed. There are many different kinds of energy storage systems that can help in stabilizing the photovoltaic energy production, among which the electrochemical (or battery) energy storage system seem to have the highest popularity. This is a well-known technology, that can accumulate high ranges of powers and it is relatively not too expensive to realise compared to other kinds of energy accumulators. [6]

This whole issue and its multidimensionality led to formulation of a problem to study in this thesis. The photovoltaic energy will continue to develop and the next step is incorporating battery energy storage to optimize the usage of the produced energy. The journey towards "a greener" planet must be continuously improved and the challenges must be addressed to fuel the energy transition that is inevitable.

Contents

The project concerns designing a system that will consist of the photovoltaic solar power plant of a several-megawatt scale. The same technical solution will be analysed for both Poland and Portugal. The question arises for the motivation for such comparison. Even though both countries are located in Europe and are members of the European Union, there is a number of differences that make them worth comparing when it comes to renewable energy sources and energy storage systems. The locations differ, first of all, by climatic conditions, such as air temperature or direct solar irradiation reaching the Earth surface. The countries are also very different when it comes to structure of energy market – the energy mix and share of renewables, the renewable energy support system and general attitude and pathways that are taken when it comes to development of the green energy solutions. Financial and legal regulations also have a huge impact on the possibility of implementation of any environmentally friendly solution.

The work focuses on the study of the big-scale photovoltaic farm combined with the electrochemical energy storage system. During my Master's level education I had an opportunity to study Energy Engineering and similar subjects in two different locations – Poland and Portugal. Thus, the study includes identical photovoltaic farm model implemented in those two different climatic conditions. To maximize the energy savings, battery energy storage system will be included in the analysis. After that, there will be a country chosen for further development, after decision about which location still has more room for growth and implementation of PV technology. It will have the economic analysis performed to study the profitability of the project in two different, later explained, variants.

Firstly, the review of the Polish and Portuguese energy markets will be performed to give a proper overview of the situation of renewable energy in both countries. Next, the review of existing battery energy storage technologies will be done to evaluate the current development of the most frequently used solutions. The battery energy storage technologies is fast-developing branch that is also being implemented in more and more real life situations. This overview will lead to stating both advantages and disadvantages of most important variants of the battery storage technologies to finally make a choice which is going to be used in the model. Finally, it will be presented how nowadays the battery energy storage is implemented in renewable energy sources solutions, like e.g. photovoltaic farms.

After knowing the current state of described technologies in both locations and choosing the best-fitting system, the technical evaluation will be performed. The exact same model will be analysed for Portugal and Polish conditions. The main focus will be on calculation of the energy that can potentially be produced by the panels and when to charge and discharge the batteries to predict the highest profits. Both the markets overview and technological analysis will lead to the common conclusion about which one of the countries still has more space for renewable energy and storage projects development and which one should be made a priority for this work. After making such choice, the economic assessment will be done for the project. The most important indicators: Net Present Value, Internal Rate of Return and Paybacks will be calculated. To explore more opportunities, the version of the model without the energy storage will also be addressed to debate on its profitability. The sensitivity analysis will be done to draw conclusions about the influence of investment cost and market electricity price on the feasibility assessment of renewable energy project like this.

The performed study will enable drawing the adequate conclusions about the state of the battery storage systems supporting photovoltaic farms. It will be shown whether project like this can be profitable and on which conditions. This could help in understanding the present state of these solutions and enable drawing conclusions that also lead to stating the possible future prospects of photovoltaic energy and battery storage.

The work is especially intriguing for the Poland to compare its possibilities with those in Portugal, where the overall conditions, that are going to be explained later in the paper, for developing such technologies are considered to be "better". It will be studied how, in fact, such projects can look in real life situations and whether Poland should chase European countries with more suitable climatic conditions. What should be done to successfully increase the share of renewables in the energy mix? Can a big-scale solar irradiation-dependent project feasibly run in the moderate climate of Central European country? The answers will be explicitly shown on the realistic example, so that the direct solutions for the problems that Poland needs to face to ensure the energy safety, balance in the energy mix and meet the EU and climate challenges can be properly addressed.

This dissertation is composed of 6 chapters:

- Chapter 1 – Introduction,
- Chapter 2 – Polish and Portuguese energy markets,
- Chapter 3 - Photovoltaic technology and battery energy storage systems,
- Chapter 4 – Methodology,
- Chapter 6 – Results,
- Chapter 6 – Conclusions and future directions.

Chapter 2

Polish and Portuguese energy markets

This chapter provides a closer look into the Polish and Portuguese energy market structures. It focuses on the energy sources for electricity production and share of renewable in the energy mix. It also touches the subject of support systems for renewable energy sources to lay an overview of the current situations in both Poland and Portugal.

Polish energy market

Structure

Poland is one of those countries in the European Union that produces extremely high percentage of electricity originating from the fossil fuels combustion technologies. The International Energy Agency stated that Poland emitted 192 Gt of CO_2 in 2019 from hard coal combustion only [7]. This is amount that should never be reached during the times where much "cleaner", in terms of emission, technologies are widely available. One of the reasons for such approach is the fact that big part of the Polish economy is hard coal exploitation. According to International Energy Agency in 2015, more than 80% of electricity production originated from hard coal [7]. As can be seen on Figure 2 the share of hard coal in electricity generation in Poland peaked in 2005, reaching over 140 TWh, then gradually decreased and continues to do so up to this day. However, it can be stated that this transition is going too slow, as the coal produced more than 120 TWh of electricity in 2019. Coal absolutely dominates the polish energy industry, making it a challenging economy to incorporate renewable energy sources.

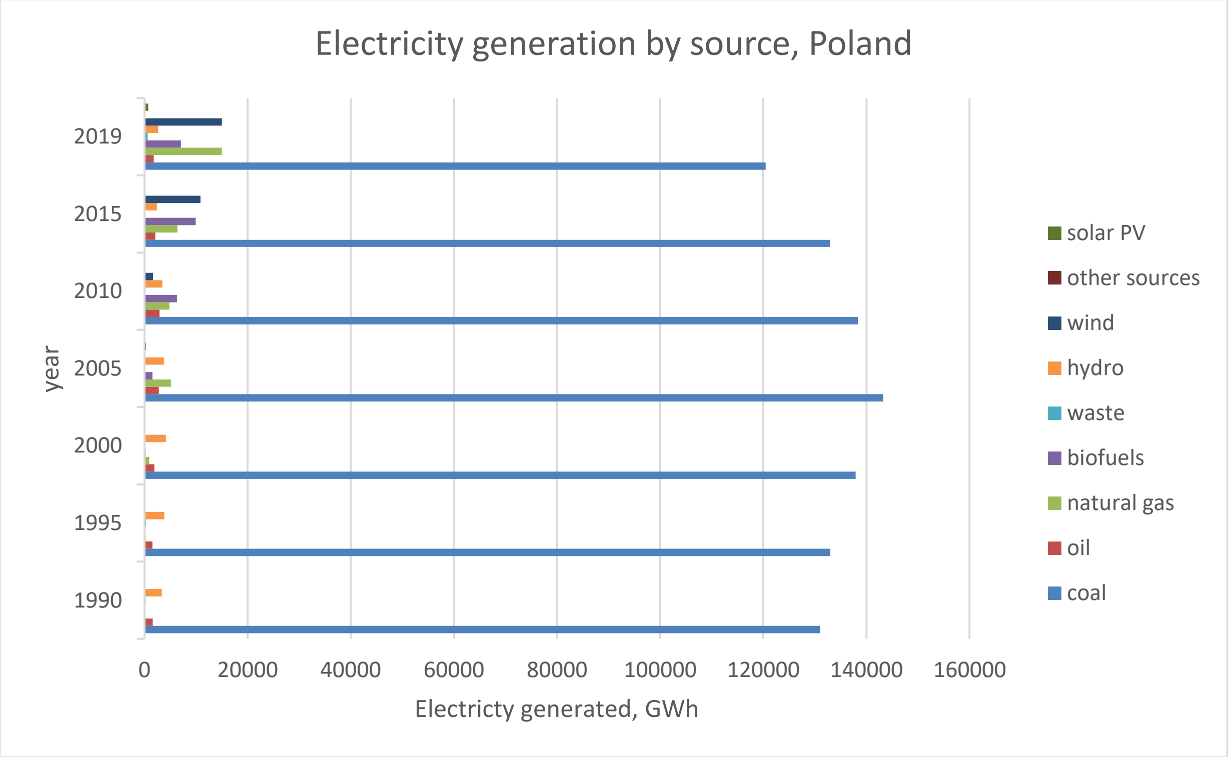

Figure 2 Average electricity generation in GWh by source over the years 1990-2019 in Poland.

Data from: [8]

Table 1 Renewable energy sources for electricity generation in GWh in Poland over the years 1990-2019. *Data from:* [8].

Year	Hydropower	Wind power	Solar PV	Unit
1990	3313	0	0	GWh
1995	3851	1	0	GWh
2000	4116	5	0	GWh
2005	3778	135	0	GWh
2010	3488	1664	0	GWh
2015	2435	10858	57	GWh
2019	2664	15040	712	GWh

When it comes to renewable energy sources only, the Table 1 gives the quantitative data provided by the International Energy Agency's Electricity Information. Nowadays, the renewables are present in Poland mainly in the form of wind power. The first form of renewable energy applied in Poland was the hydropower, which production oscillates around 2500 GWh on average these days. According to the IEA data, the photovoltaic technology started to contribute to the grid electricity generation in Poland between the years 2010-2015 and in 2019 equalled 712 GWh, which is only around 3,9% of the whole renewable energy sources production that year. However, a lot of the industrial-scale photovoltaic farms are currently under construction, so the numbers are expected to grow in the following years.

Renewable energy sources

As mentioned in the previous section, one of the reasons for the small renewables' share in electricity generation in Poland is the present coal resources and its industry. But secondly, obviously the renewable energy sources are highly dependent on the climatic conditions, which in Poland are generally not the most optimal, as it is located in the so-called moderate climate, where irradiation and wind do not reach extreme values. When it comes to PV potential, it is said that solar irradiation in Poland is somewhere around 1000 kWh/m^2 in total a year. Figure 3 shows that the distribution of direct solar irradiation in Poland is rather even. According to the map adapted from The Global Solar Atlas on the Figure 4, if there had to be pointed out the extremes for solar energy production, the relatively least sunny place would be the northern-west and most optimal area for photovoltaic investments would be the southern-east of the country (see the figure below). The difference between the extreme values of the irradiation in Poland is around the 20%.

Figure 3 Long term average of direct solar irradiation (DNI) in Poland in kWh/m^2.

Figure downloaded from: [9].

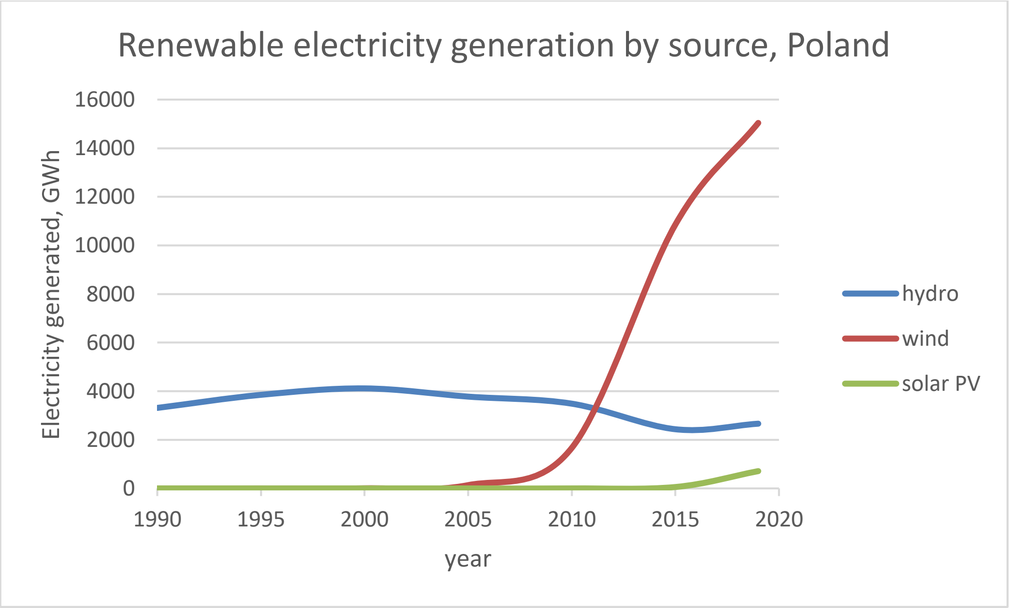

Figure 4 Average electricity generation from renewable energy source in years 1990-2019 in Poland.

Data from: [10]

Figure 3 shows the evolution and development of renewable energy sources for electricity generation. The hydro power is the most stable RES in Poland. The wind energy develops in the most rapid way, with the large growth after the year 2005. It can also be concluded that the photovoltaic technology is starting to develop nowadays, with its start around the year 2015.

In Poland, the share of renewables in the energy mix is constantly increasing and several interesting projects are under construction. For example, one of the biggest electricity distributor in Poland – Tauron Group is about to build up to 100 MW_p of PV power in Poland. One of those is even about to be finished this year and its power is expected to be 6 MW_p. [11] When it comes to interesting battery energy storage systems, the PGE Group, which is also a main electrical energy distributor in Poland, finished building the 4,2 MWh capacity battery energy storage unit in the southern east of Poland as a support for the local grid and as the realisation of their strategy. This increases grid's reliability and safety for the local society and gives a promising path for the next investors. [12]

Auction system

In Poland the energy market regulator is so-called "Urząd Regulacji Energetyki" (Energy Regulatory Office). In reference to the Energy Law Act in Poland, the President of the Energy Regulatory Office has a few general responsibilities:

- To manage the licenses,
- To set the energy tariffs,
- To meet the requirements set by the legislator and international agreements,
- Generally providing the energy safety,
- To promote the sustainability and environmentally-friendly development,
- Caring about the competition and energy economy. [13]

What is maybe the most important in this context, the Office is responsible for the level of the market electricity prices and auction system for renewable energy resources, like the photovoltaics. Around 1000 offers won the latest auction with a guaranteed price of up to around 55 EUR/MWh for 15 years. This price is constantly decreasing, as in 2016 the guaranteed price was around 106 EUR/MWh, which is 48% cheaper, indicating the growth in competition on the RES market in Poland. [14]

Portuguese energy market

Structure

The energy generation structure in Portugal is different than in Poland. Even though both countries are members of the European Union and should try to reach the same energy goals, when it comes to Portuguese energy market structure, it is much more evenly distributed than in Poland and does not depend on one energy source as much as Polish electricity production depends on hard coal. Still, taking into account the whole country of Portugal, a visibly big part of the energy mix in 2019 were fossil fuels (45,1%):

- coal - 10,5%,
- crude oil - 2,2%,
- natural gas - 32,4%. [8]

The hydropower is the biggest part of the renewable energy sources in Portugal – more than 10TWh in 2019. According to REN (Redes Energéticas Nacionais) more than 35% of installed capacity originates in hydropower. Also, other renewable energy sources already started to increase its share and continue to do so. [8] The newest data for Portuguese electricity generation by source is available on the APREN website and was dated for May of 2021. As can be seen on Figure 5 Portugal's dependency on the fossil fuels is still visible.

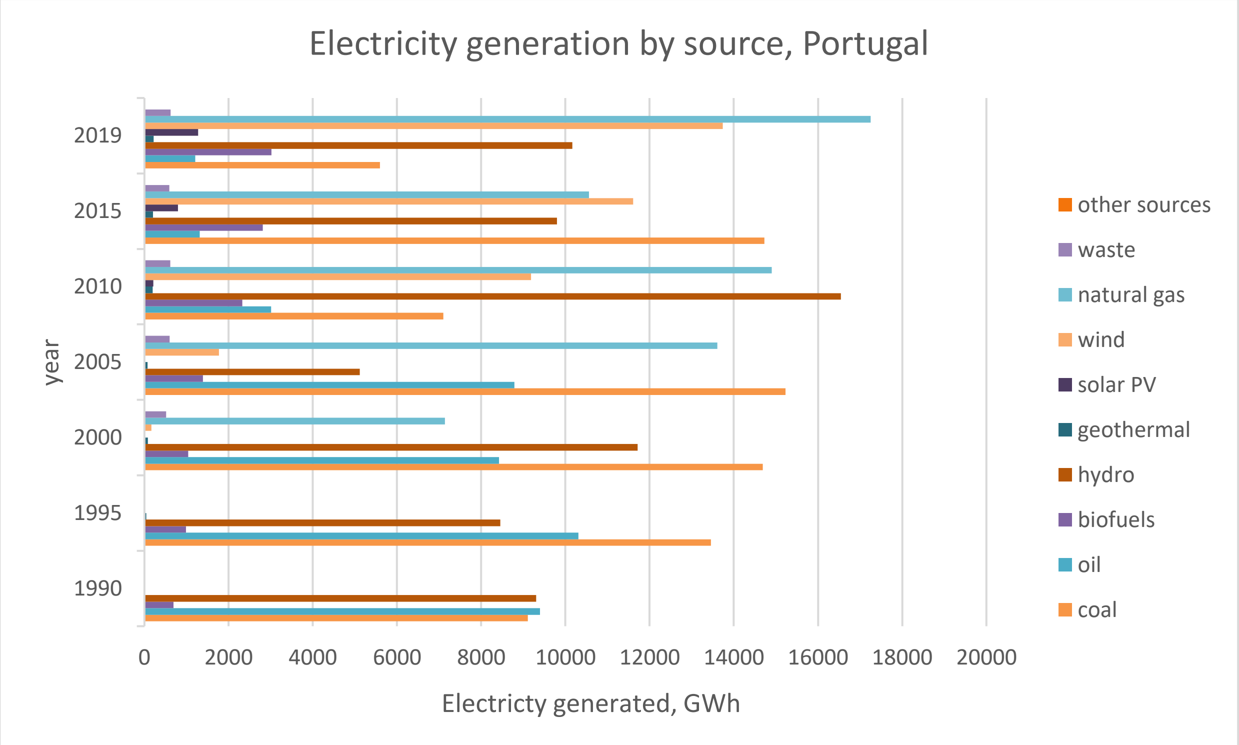

Figure 5 Average electricity generation in GWh by source over the years 1990-2019 in Portugal.

Data adapted from: [8]

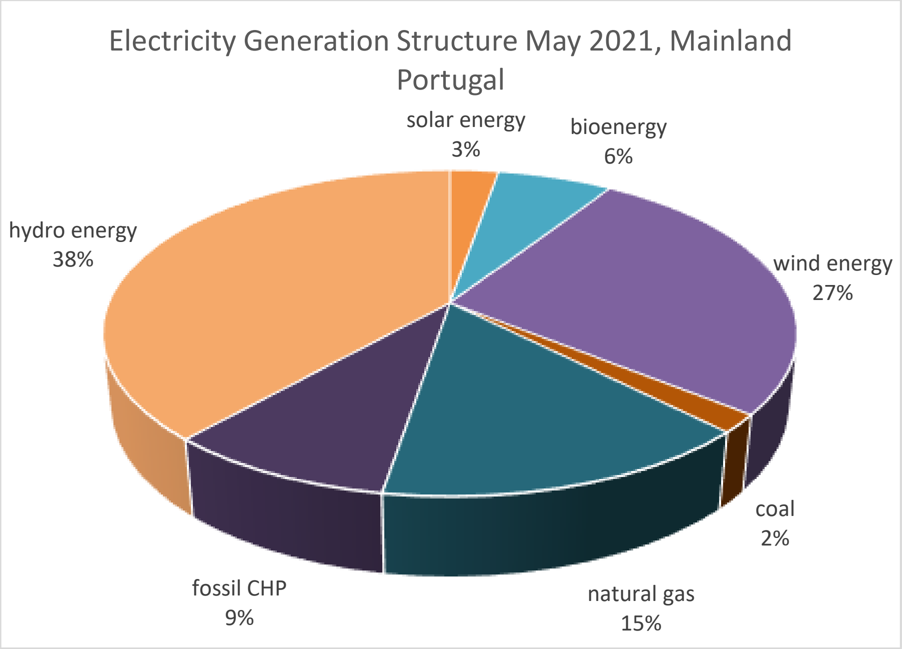

Figure 6 The newest data on electricity generation by source in Mainland Portugal in May 2021.

Data adapted from [15].

Figure 6 shows how the energy mix structure changes in Portugal. Waste and geothermal originating energy are not considered in the Figure 6 probably due to their negligible shares and main appearance in the regions of Azores and Madeira. Due to APREN website, on average, during the first half of the year 2021 in mainland Portugal, more than 71% of the electricity generated was from renewable energy sources. [15] In May 2021 alone, the hydro energy contributed to more than 1/3 of the whole energy structure. On the other hand, the fossil fuels contribute to around 26% of electricity produced in the mainland Portugal. In both Autonomous Regions in Portugal – Azores and Madeira – the share of fossil fuels in the production of energy is highly above 50% of the whole electricity production structure:

- Azores - 59,6%
- Madeira - 72,77%. [15]

The numbers mentioned above contribute to the share of fossil fuels in the energy mix presented on the Figure 5, which considers the whole country of Portugal. In comparison the structure of electricity energy sources of Portuguese mainland and archipelagos is very uneven.

Renewable energy sources

The Table 2 gives the quantitative data provided by the International Energy Agency's Electricity Information. There can be noticed that even though only in the average amount of 216 GWh, geothermal energy is present in Portugal on the Azores islands, in contrast to Poland. In Poland geothermal resources do not naturally reach the desirable temperatures in order to be used as the energy production source. Due to the sufficient climatic conditions and natural habitat predisposition, the renewable energy sources, like hydropower, wind or solar energy have been present in Portugal for at least 30 years. The wind and photovoltaic energy are very fast-developing in Portugal and developed the most in the last 15 years. The share of renewables is expected to grow even more in the following years. In the last 5 years the wind power became a number one in Portugal when it comes to the biggest amount of energy produced from this source – almost 14 TWh in 2019. The direct values can be seen in the table below.

Table 2 Renewable sources for electricity generation in Portugal over the last 30 years. *Data adapted from:* [10]

Year	Geothermal	Hydro power	Solar PV	Wind power	Units
1990	4	9303	1	1	GWh
1995	42	8454	1	16	GWh
2000	80	11715	1	168	GWh
2005	71	5118	3	1773	GWh
2010	197	16547	211	9182	GWh
2015	204	9800	796	11607	GWh
2019	216	10165	1275	13738	GWh

When it comes to natural habitat and climatic conditions for development of the solar-dependent renewables, like photovoltaic farms, Portugal has much higher solar irradiation values. This means that proportionally the power production from photovoltaic solutions will be significantly bigger. The average direct solar irradiation yearly total is above the polish value of 1000 kWh/m^2 and can even reach around 2200 kWh/m^2 in Portugal. According to Figure 7*,* the North and northern-east have the average DNI (Direct Normal Irradiation) lower than in the rest of mainland Portugal. This makes East and South of the country the most suitable for photovoltaic energy installations with the daily totals of direct normal solar irradiation of 6 kWh/m^2. It can also be noticed that both archipelagos located on the open ocean areas, are much less suitable for the solar sourced electricity generation, where the daily totals of irradiation can be 2 or 3 times lower than on the land (see figure below).

Figure 7 Long term average of direct solar irradiation (DNI) in Portugal in kWh/m^2.

Figure downloaded from: [9].

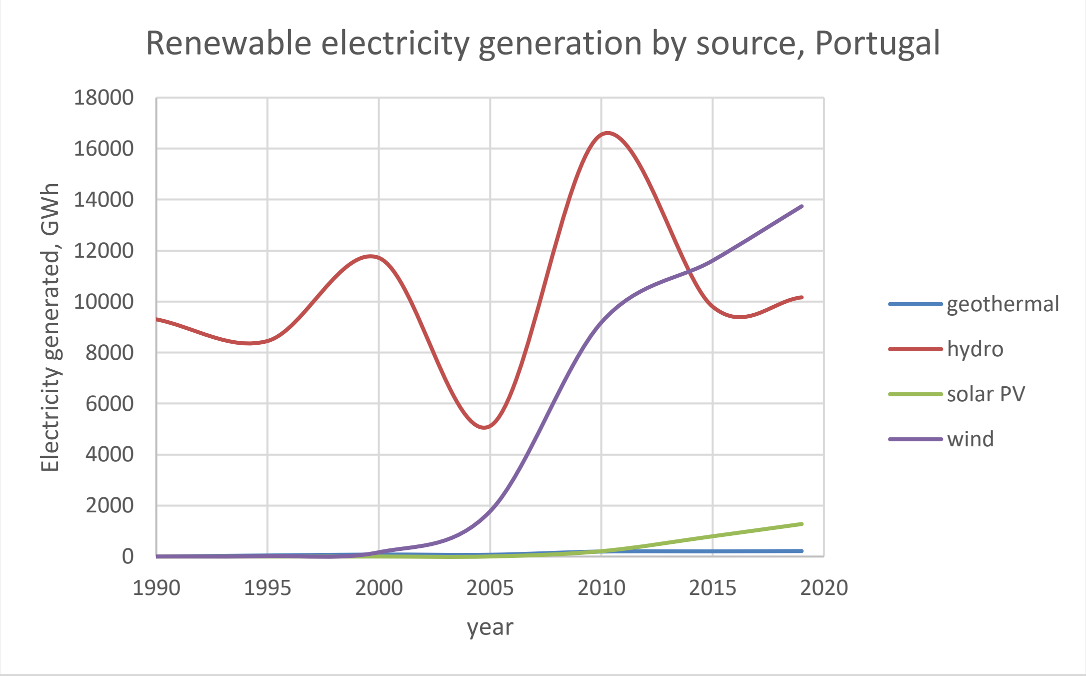

Figure 8 Average electricity generation from renewable energy source in years 1990-2019 in Portugal.
Data from: [10].

Figure 8 shows that only the geothermal energy out of all possible renewables in whole Portugal has been kept stable. The hydropower's electricity production peaked two times - around the year 2000 and 2010, but in the end the production does not differ a lot between the years 1990 – 2019 – it is somewhere between 8 and 10 TWh at start and the end of the investigated time period. The rapid start of electricity production from the wind farms began after the year 2000 and is steeply increasing until this day. The solar PV started to play a visible role after the year 2010, continuing to use more and more solar potential of the country. One of the proofs is PV farm project Amareleja near the town Moura. The installation is able to power 30 000 households with its power being more than 45MW$_p$, making it the one of its kind installation, not really seen in countries like Poland. [16]

Auction system

Portugal has the energy market regulator called Entidade Reguladora dos Serviços Energéticos (ERSE). Function of the Regulatory Office is to control, regulate, supervise, sanction and realise the country and European energy related laws and agreements. The ERSE is obligated to:

- Promote the competition,
- Regulate the energy market in rational and clear way,
- Set the tariffs and prices for electrical energy and natural gas,
- Monitor the markets,
- Help and resolve conflicts,
- Promote access to information. [17]

Overall, The ERSE and Polish Energy Regulator Office have a similar function of taking care of the financial and support aspects of development of the Renewable Energy Sources in the corresponding countries. When it comes to auctions for renewable energy sources, the mechanism in Portugal gives the investor 3 different options:

- CfD: a fixed tariff for 15 years, similar to that in Poland – the share is only 1% of the whole capacity in 2020 auction,
- Flexible option: a solution with fixed payment for 15 years, while also the project is subjected to market prices so the project is then compensated for the hours in which the market price is higher than the fixed tariff – 72% of the capacity,
- Fixed compensation to the system: the installation is paying the system for the interconnection point during all of the years while being subjected to the electricity market prices – 26% of the capacity. [18]

For example, when it comes to the fixed tariff, which is similar to the auction system in Poland, the awarded electricity price in 2020 was 11,14 EUR/MWh [18], while in Poland it was 55 EUR/MWh. This shows the difference in the level of implementation of the similar technologies in two different countries. In Poland, the PV farm is still a rare occurrence and many of the projects are in the planning phase.

Summary

As already mentioned, both countries of interest have a completely different situation in their energy markets. Comparing the energy market structures, the polish one is very focused on the classical fossil fuels power plants, run mainly by the hard coal with a part of the brown coal exploitation as well, with an around 80% share in the energy mix. When the Portugal is treated as a whole, it has a little lower than 50% dependency on the fossil fuels when it comes to electricity production. The generation of electricity from renewable energy sources, due to the climatic conditions like direct normal irradiation, is much different in both countries. In Portugal the yearly totals of irradiation range from around 700 kWh/m^2 in some parts of the islands, reaching up to 2200 kWh/m^2 overall, while in Poland it ranges from around 850 up to 1100 kWh/m^2 in a year. The range is much wider in case of Portugal, especially when islands and mainland are to be compared. In Poland the difference between the average extremes is not that significant and it is harder to choose one most optimal place for the photovoltaic farm.

Table 3 Comparison of the renewable sources for electricity generation in Poland Portugal in the year 2019. *Data adapted from:* [10]

2019					
	Geothermal	Hydro power	Solar PV	Wind Energy	Unit
Poland	-	2664	712	15040	GWh
Portugal	216	10165	1275	13738	

Except from the conditions and markets, what is maybe the most important is how big is the role of renewables in the said countries. The most recent unified data in the Table 3 come from the year 2019 and as it is well known, the green energy sources have a tendency for a very fast development, especially in the case when they are still considered emerging solutions in some areas. With the data that are presented, it can be seen that even though the total area of the Polish country is more than three times larger than Portugal's, the amount of Solar PV farms' generated electricity is more than 44% higher. The wind energy production in on comparable levels. Due to the natural conditions, there are more than 60 hydroelectric power plant in Portugal, while in Poland there is below 20 of them.

There are advantages and disadvantages of choosing to install a solar photovoltaic farm either in Poland or Portugal. What is more, these topics can be very subjective, as some features may seem like both an asset and a possible threat. In Poland the photovoltaic industry is generally a huge opportunity, as the competition is smaller than in Portugal and many constructions are still not finished. Also Poland has a bigger pressure to reduce its dependency on coal. The auctioned electricity prices are 4 times higher for fixed tariffs in Poland. But on the other hand, the auction system is much more flexible and developed in Portugal, where the competition is much higher. The social acceptance can also be a great issue, especially in Poland where not many farms exist and some part of society fears that it destroys their landscapes. What is also a big undeniable advantages is that from the same exact same PV farm in both countries, the production of electricity can be expected to be a lot higher in Portugal. Depending on which of the factors are the most important in a particular situation, it can change the perspective on possible opportunities and threats of a single project.

Chapter 3

Photovoltaic technology and battery storage systems

This chapter is an overview of the photovoltaic energy technologies and also the energy storage systems with a focus on the battery technologies. This will help to later understand the model and solutions chosen for further analysis.

Photovoltaic technology

Among all of the renewable energy sources, the paper will focus on the solar photovoltaic energy production. To better understand the process behind the electricity generation on the PV farm, the photovoltaic effect must be well-understood. The electrical energy in a single photovoltaic cell is generated thanks to the so-called Photovoltaic Effect. In the 19th century, Edmund Becquerel noticed the current produced by a few different materials when they are exposed to the sun. After more than a century, in the 50s, the first photovoltaic module was built, but the real development started when space industry began to perfect these solutions. [19] In the 21st century the photovoltaic technology really took off.

The principle of the photovoltaic effect can be noticed on Figure 9 There can be seen that when a sunlight ray – in form of the set of photons – is absorbed in the area of the junction (called the p-n junction due to the semiconductor types), the valence electrons start to transfer into the excitation state and move away from their original place. This creates a difference in potentials and with the closed circuit and a load, it will make the current flow. The typical photovoltaic cell consists of two semi-conductors where the n-type is negatively charged and p-type is positively charged. They are in contact together, but moving separate ways, creating an electric field. [20]

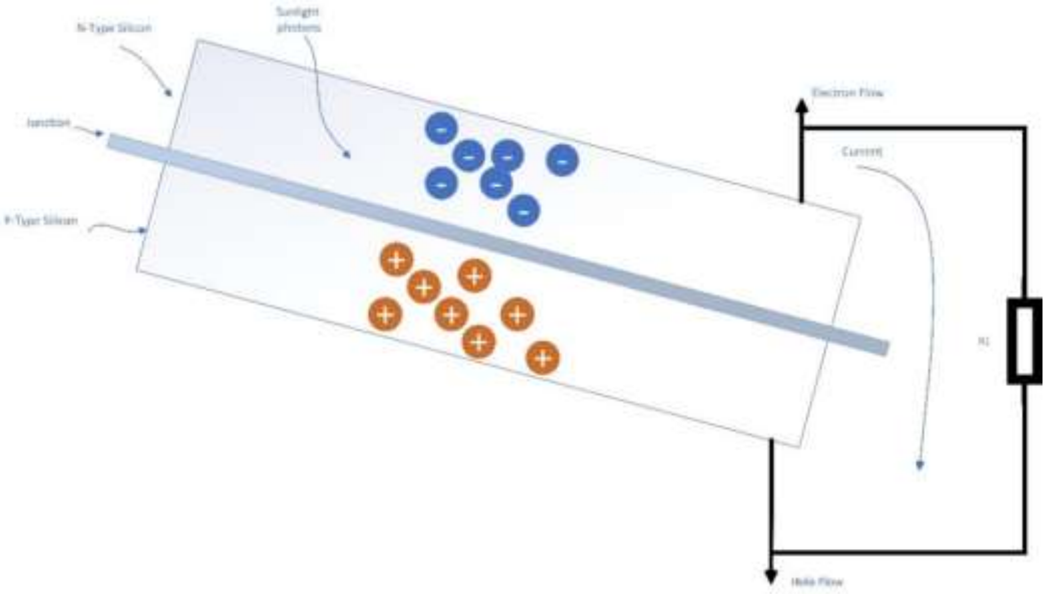

Figure 9 Schematic representation of the photovoltaic effect. *Figure adapted from* [20].

A typical photovoltaic system consists of cells that have around 1 or 2 W of power each, making it not sufficient for any industrial application. That is why they are always bundled in modules and larger systems. The cells are usually made of silicon in one of the forms: monocrystalline, polycrystalline or amorphous. The efficiency of a photovoltaic panel can be around 15-20%, rather rarely reaching values above those. As for the early months of the year 2021, the most efficient panels were offered by:

- LG – 22%,
- REC Solar – 21,7%,
- CSUN – 21,2%,
- Panasonic – 21,2%. [21]

It shows the tendency that soon the efficiencies above the 20% will be a market standard. With that, the lowering of prices of these efficient solutions will be expected. Of course the real efficiency of the panel depends on many things, for example the material from which it has been made (e.g. silicon, telluride, cadmium), also other interesting solutions can improve the efficiency, like for example implementation of a bifacial solar panel. [21] Efficiency of an renewable energy source is also highly dependent on unpredictable and uncontrollable factor, that is the natural or meteorological conditions. In case of the photovoltaic system, it is the irradiation reaching the Earth, meaning how much time the sun is actually shining on the panels, what is the level of cloud cover and how long is the day during each season in the particular place of instalment. To eliminate the possible side effects of these drawbacks the continues improvement should be pushed in this branch of industry. And what the suppliers and distributors can do is to automate and control the grid and maybe when necessary implement a storage unit to ensure further energy safety.

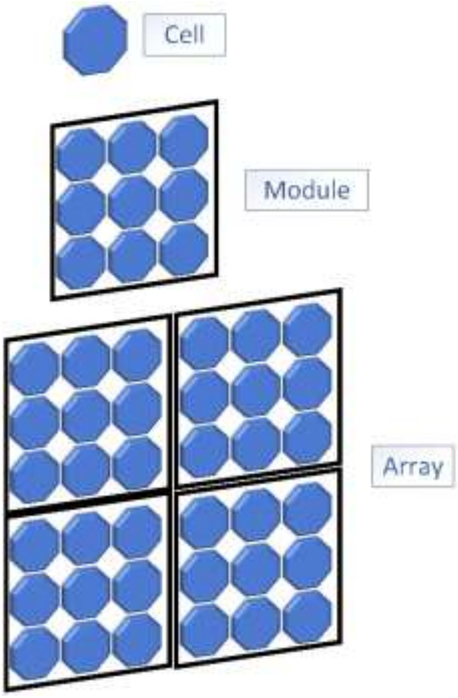

Figure 10 Solar cells are usually combined in modules, which then later create arrays and eventually whole systems – or farms. *Figure adapted from:* [22]

Battery energy storage

The successful energy storage can work as a great support mechanism for stabilization of the grid that has various renewable energy storage incorporated. Energy storage is a very wide, interesting and up-to-date topic, which is playing bigger and bigger role in modern national grids management. The battery energy storage systems can contain several different forms of energy that can be potentially stored, among which we have: electricity, heat or mechanical energy. The energy storage systems differ by the time of storing the energy, the size, the efficiencies and many more other features. One of these criteria is also by the methods and techniques of energy accumulation and amongst these, there are the following most popular ones:

- Mechanical systems:
  - Pumped-storage hydropower plants,
  - Compressed Air Energy Storage,
  - Flywheels,
- Electrical systems:
  - Superconducting magnetics,
  - Capacitors.
- Thermal systems:
  - Using the heat capacity of a substance,
  - Using the latent heat.
- **Electrochemical systems:**
  - **Battery Energy Storage Systems.**

Even if the focus will be on the electricity accumulation alone, there are dozens of options that can be chosen from while deciding on the most optimal energy storage for the particular renewable energy source system. The area of concern for this thesis has been decided to be a BESS or Battery Energy Storage System. This is due to this technology's reliability and a lot of potential for growth and applications in the future. Battery Energy Storage System technology has been proven to work adequately in existing installations where the photovoltaic farms are connected to the batteries, storing the electricity surpluses and on the other hand helping when there is not enough energy to sufficiently supply to the end customers. Example of such successful installation is the EDP's project of two photovoltaic farms connected to BESS in Castanheira do Ribatejo and Azambuja, where according to the article "EDP deploys its largest solar farm with energy storage in the country", each installation has 3,8MW_p, can supply 2000 households and save the planet 31,000 tons of CO_2. [23]

The principle of working of different kinds of batteries is the same, in the sense that thanks to the various reversible electrochemical reactions the chemical energy stored in the substances involved in the process is transformed into the electrical energy. They can, for example, differ by the electrode materials and the electrolyte substances in which they are immersed. The basic construction of a battery is as on the Figure 11 meaning that: two electrodes – one positively charged cathode and one negatively charged anode – are immersed in the fluid called electrolyte. Due to the excess of electrons in the anode, with the load connected, the anions flow will occur in the direction to the cathode, until the point of the equilibrium, which at the same time creates difference in potentials resulting in current flow and electricity production, meaning the discharging of a battery is happening. These electrochemical reactions are reversible in the rechargeable batteries, meaning that with the power supplied, the anions will flow from the negatively charged cathode in the direction of the anode, known as the process of charging of the battery.

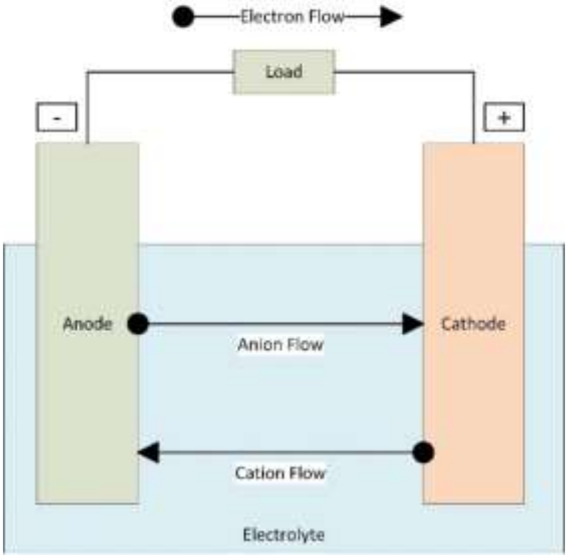

Figure 11 The basic construction of a battery. *Figure adapted from:* [24]

There are many types of batteries that can support the renewable energy sources systems. These are enumerated in the Figure 12 (see the graph below). When it comes to types of batteries, that are the most well-known technologies, there can be distinguished: Li-Ion batteries, that are very popular thanks to automotive industry and applications in the energy sector, lead-acid batteries that were developed as the first type of batteries in the 19th century and also Ni-Cd (nickel-cadmium) type. Among those, Lithium-Ion battery is a technology that has examples of application next to the photovoltaic farms all over the world. The mentioned in the work energy storage units in Poland and Portugal, may increase the odds of the project to turn out to be profitable after performing economic analysis. On the other hand, the conversation about using the second life batteries is getting more and more frequent, but this option is not viable in many cases. The market for second life batteries is unstable and depends on factors that are sometimes very hard to validate. [25]

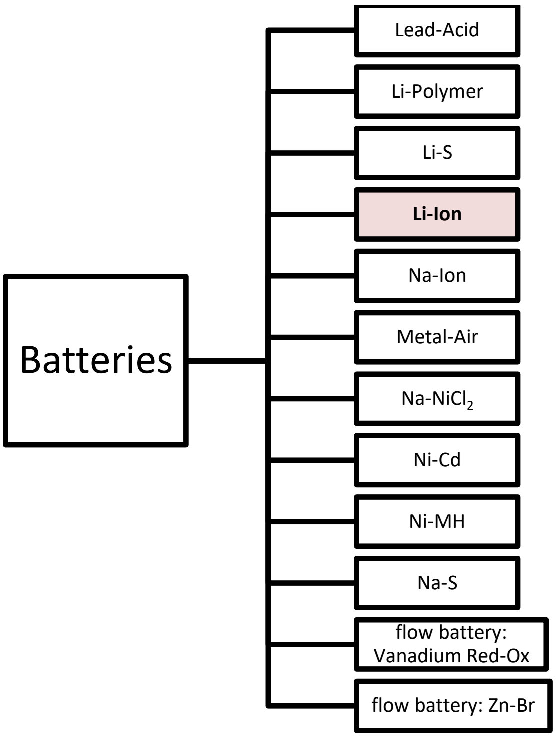

Figure 12 The division of batteries. *Adapted from:* [25]

In the Lithium-Ion battery, the anode is made of a form of a carbon material. The cathode is typically made out of: lithium cobalt oxide, lithium iron phosphate or manganese oxide but also other versions are possible. The electrolyte is a liquid, typically a lithium salt. [6] The Li-Ion batteries are characterised by high efficiency - >90% and under the right circumstances it can reach a few percent more. The huge advantage of the Li-Ion battery is its flexibility – it can be built in different capacities and sizes. The lifetime of up to 2000 cycles is also very useful in the applications. One of the disadvantages is that the battery should not be kept in the high outside temperatures and what is the most important, the Lithium-Ion energy storage is still a very expensive technology to implement. [6] What is good, the valuable materials that form a battery can often be recycled.

Summary

The chapter included the mechanisms and descriptions of the two areas of concern for the model in this paper: photovoltaics and battery storage. The discovery of the photovoltaic effect enabled development of a whole new area of energy engineering, where the “free” sun energy is utilised. Knowing the problems of instability and unpredictability of a photovoltaic sourced energy, implementation of the energy storage, in this case batteries, naturally becomes more and more popular. For such solution to be successfully working, except from panels, inverters, grid connection and battery unit, there has to be decided the how to connect the elements in the system themselves.

To connect photovoltaic farm to the battery energy storage system in an effective way, one can go one of the two routes. The first of them is that the battery energy storage system can be connected in between the photovoltaic system and the inverter. This means that the current stays direct, so thanks to the lack of subsequent conversions, the losses are much less than in the second case. This is the biggest advantage of such solution, but on the other hand such connection means that if the photovoltaic farm experiences a failure, the storage system stops working as well and cannot serve the grid. The second option is much more flexible in that sense. There are two inverters, one connected to the PV farm and one serving the storage unit only. This makes the parts of the system independent on each other. Even though this solution means more losses, this would be a recommended variant to ensure higher safety for the installation and the biggest reliability possible. Once the model is known and its properties are known, the analysis can be performed.

Chapter 4

Methodology

This chapter consists of the development of the theoretical model for analysis. This includes, first of all, description of chosen photovoltaic panels, but also describing the most reasonable battery energy storage option. The methods for calculation of the technical parameters like energy production and charging and discharging scenarios will be presented. When it comes to economic analysis, the location that will be chosen for later development will have calculated parameters like: total income, cash flow and project profitability indicators with later sensitivity analysis for two variables.

The model

The system under consideration consists of the photovoltaic farm supported by the Lithium-Ion battery energy storage system. The total power output of the PV farm is assumed to be 5 MW and it is also assumed that 20% of this energy will be stored. The battery storage has a total capacity of 2 MWh and consists of the whole infrastructure needed for the system to properly work, like inverters or control systems. The presented model is simplified and the values are an estimation, in order to bring the overview of how much energy can be produced from such model with the given data, to later fully investigate the economic aspects.

The photovoltaic panels that could be used are, for example, standard 240W_p power panels with data like shown in the Table 4 below:

Table 4 Specifications of solar PV panels chosen for the analysis. *Data from:* [27].

Company	Jinko Solar
Model	JKM240M-48
Dimensions	1324x992x40mm
Electrical Data at Standard Test Conditions (STC)	
Maximum Power (P_{max})	240W_p
Voltage at Maximum Power (V_{mpp})	26,1V
Current at Maximum Power (I_{mpp})	9,2A
Open Circuit Voltage (V_{oc})	32,1V
Short Circuit Current (I_{sc})	9,72A
Panel Efficiency (η)	18,27%

Figure 13 Representation of the Jinko Solar panel, model JKM240M-48. *Figure taken from:* [27].

When it comes to the Li-Ion battery storage, there are many companies that could provide sufficiently big, comprehensive model. The famously known Tesla power- and giga-packs or even some other companies like Mitsubishi could be used as a real example. Such units are containerised, where each container, in case of e.g. Tesla's, contains ordered battery pods, a converter, air conditioning and a control system with many sensors. [28] Exemplary units are shown on the photography below:

Figure 14 Exemplary representation of the battery storage unit installed. *Figure taken from:* [29].

Energy production

To evaluate the energy production first of all the surface area of a single panel must be calculated by multiplication of the dimensions from the Table 4:

$$S = 1{,}324 * 0{,}992 = 1{,}313\ m^2 \qquad \text{Eq. 1}$$

To evaluate the number of panels that need to be installed, there must be calculated:

$$N = \frac{P_{installed} * 1000000}{P_{max}} = \frac{5MW * 1000000}{240W} = 20833{,}3 \approx 20834 \qquad \text{Eq. 2}$$

Where:

$P_{installed}$ – Planned power of the photovoltaic plant mentioned in the first part of the chapter, MW;

P_{max} – Maximum power of the single panel according to the Table 4, W_p.

Having the surface area of a single panel and knowing number of panels, the total area of all panels is:

$$S_{total} = S * N \approx 27363{,}43\ m^2$$ Eq. 3

Knowing how much space will the panels take, the total energy production can be calculated according to the equation below. The efficiency in the formula is taken from the product specifications in the Table 4. The DNI – Direct Normal Irradiation values are presented in the Table 5 and Table 6.

$$P = S_{total} * \eta * DNI,\ \ Wh$$ Eq. 4

DNI – Direct Normal Irradiation, Wh/m^2.

Table 5 Averages of hourly direct normal irradiation reaching the Earth's surface values in Poland in Wh/m^2. *Data from:* [9].

hour:	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	15	62	26	0	0	0	0	0
6	0	0	0	42	169	184	144	51	0	0	0	0
7	0	0	20	191	267	256	226	206	130	0	0	0
8	0	19	164	284	341	317	308	294	246	141	0	0
9	48	145	248	343	396	366	364	368	307	222	105	38
10	152	206	286	378	428	383	379	399	348	262	152	137
11	171	219	306	393	433	376	365	396	341	268	168	151
12	181	230	311	385	409	352	337	368	331	271	178	172
13	192	243	311	372	381	342	322	363	316	274	179	173
14	180	251	306	349	361	327	316	337	290	242	159	153
15	141	203	269	319	330	306	295	308	263	204	115	104
16	38	166	238	284	309	285	282	283	238	154	22	8
17	0	44	187	260	283	262	262	263	189	35	0	0
18	0	0	44	183	231	226	224	207	54	0	0	0
19	0	0	0	20	123	165	157	54	0	0	0	0
20	0	0	0	0	0	45	26	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0
Sum	1103	1726	2690	3803	4476	4254	4033	3897	3053	2073	1078	936

Table 6 Averages of hourly direct normal irradiation reaching the Earth's surface values in Portugal in Wh/m^2. *Data from:* [9].

hour:	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	36	78	45	0	0	0	0	0
6	0	0	0	117	279	331	342	224	64	0	0	0
7	0	0	193	354	391	438	479	462	361	183	0	0
8	110	286	391	430	450	512	575	567	475	378	281	132
9	351	415	443	462	475	567	650	642	535	440	380	367
10	405	464	476	478	480	600	698	699	575	472	418	428
11	429	493	516	479	491	623	733	723	592	518	429	443
12	431	503	525	465	479	615	740	718	579	472	407	438
13	411	480	480	438	450	592	731	695	546	438	384	416
14	380	444	446	409	438	573	711	665	511	404	363	391
15	185	419	411	382	410	548	672	624	482	281	87	0
16	0	0	96	259	374	500	609	430	113	0	0	0
17	0	0	0	0	0	114	139	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0
Sum	2702	3504	3977	4273	4753	6091	7124	6449	4833	3586	2749	2615

Energy storage

The energy storage system has the capacity of 2MWh. For the purpose of simplification of the model, the assumption is made that the Li-Ion battery energy storage system will be charged and discharged once a day, this is assumed in order to check how well the peak energy production can be shifted and utilised during the part of the day with the highest electricity demand. In the future development of such solution, the battery system could also serve in more periods of time, for example serving the grid itself when it is experiencing its own load variations. In the case of this paper, the battery energy storage system is applied to find out if storing the surplus energy in the most sunny time during the day and selling it when the electricity market price is the highest, will bring a significant profit for the system. The goal is to check how well selling the energy when it is at its peak creates an extra profit and how it changes the economic aspects of the installation. The charging and discharging will last 2 hours each, to average the two sunniest hours of a day during the particular month. The charging during the highest production periods during the day are marked by a colour in Table 7 for Poland and Table 9 for Portugal. These energy production values were calculated according to Eq. 4. The discharge is planned during the hours where according to the tables below the market electricity prices are the highest - Table 8 for Poland and Table 10 for Portugal, sourced from REN [30] (Portugal) and PSE [31] (Poland) websites.

Poland

Table 7 Hourly averages of power produced during average months by the model photovoltaic farm in Polish conditions with marked battery charging hours.

Hour:	January	February	March	April	May	June	July	August	September	October	November	December
-	MWh	MWh	MWh	MWh	MWh	MWh	MWh	MWh	MWh	MWh	MWh	MWh
1	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
3	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
4	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
5	0,00	0,00	0,00	0,00	0,07	0,31	0,13	0,00	0,00	0,00	0,00	0,00
6	0,00	0,00	0,00	0,21	0,84	0,92	0,72	0,25	0,00	0,00	0,00	0,00
7	0,00	0,00	0,10	0,95	1,33	1,28	1,13	1,03	0,65	0,00	0,00	0,00
8	0,00	0,09	0,82	1,42	1,70	1,58	1,54	1,47	1,23	0,70	0,00	0,00
9	0,24	0,72	1,24	1,71	1,98	1,83	1,82	1,84	1,53	1,11	0,52	0,19
10	0,76	1,03	1,43	1,89	2,14	1,91	1,89	1,99	1,74	1,31	0,76	0,68
11	0,85	1,09	1,53	1,96	2,16	1,88	1,82	1,98	1,70	1,34	0,84	0,75
12	0,90	1,15	1,55	1,92	2,04	1,76	1,68	1,84	1,65	1,35	0,89	0,86
13	0,96	1,21	1,55	1,86	1,90	1,71	1,61	1,81	1,58	1,37	0,89	0,86
14	0,90	1,25	1,53	1,74	1,80	1,63	1,58	1,68	1,45	1,21	0,79	0,76
15	0,70	1,01	1,34	1,59	1,65	1,53	1,47	1,54	1,31	1,02	0,57	0,52
16	0,19	0,83	1,19	1,42	1,54	1,42	1,41	1,41	1,19	0,77	0,11	0,04

17	0,00	0,22	0,93	1,30	1,41	1,31	1,31	1,31	0,94	0,17	0,00	0,00
18	0,00	0,00	0,22	0,91	1,15	1,13	1,12	1,03	0,27	0,00	0,00	0,00
19	0,00	0,00	0,00	0,10	0,61	0,82	0,78	0,27	0,00	0,00	0,00	0,00
20	0,00	0,00	0,00	0,00	0,00	0,22	0,13	0,00	0,00	0,00	0,00	0,00
21	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
22	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
23	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
24	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
average	0,23	0,36	0,56	0,79	0,93	0,89	0,84	0,81	0,64	0,43	0,22	0,19

Table 8 Average hourly market electricity prices in Poland with marked battery discharging hours. *Data taken from:* [31].

hour	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
-	**EUR/ MWh**	**EUR/ MWh**	**EUR/ MWh**	**EUR/ MWh**	**EUR/ MWh**	**EUR/ MWh**	**EUR/ MWh**	**EUR/ MWh**	**EUR/ MWh**	**EUR/ MWh**	**EUR/ MWh**	**EUR/ MWh**
1	32,72	29,75	30,49	30,44	34,05	42,57	40,67	40,95	45,34	43,74	43,86	44,82
2	31,84	27,28	29,28	29,06	33,08	42,08	41,58	41,39	44,78	43,01	41,69	41,59
3	29,33	25,86	28,29	28,05	32,32	41,84	40,65	41,17	44,24	42,09	40,63	39,91
4	28,95	25,60	28,16	27,24	31,95	41,61	40,50	41,29	44,19	41,94	40,66	39,38
5	29,94	26,40	28,46	27,42	31,71	41,13	41,24	41,11	44,53	42,67	41,66	40,39
6	32,17	29,21	29,53	27,51	30,94	41,06	42,40	40,82	45,34	43,85	44,41	43,85
7	40,97	39,46	36,17	31,72	36,76	47,13	50,64	46,77	51,85	52,34	51,51	52,51
8	41,82	39,66	36,02	34,03	37,83	48,05	50,11	46,88	55,07	51,88	51,89	56,40
9	44,44	42,74	38,37	36,80	40,09	52,52	55,15	51,33	59,96	57,06	56,89	60,89
10	45,79	44,19	38,79	37,07	40,44	53,33	56,12	53,63	58,20	58,19	58,37	63,46
11	45,42	43,95	37,51	36,22	40,04	53,18	55,07	54,32	55,66	57,14	58,48	63,62
12	46,08	44,24	38,19	36,38	40,06	54,32	55,59	56,13	55,52	57,76	59,66	64,72
13	45,86	44,66	38,49	35,96	40,14	54,52	55,52	56,75	55,50	57,71	59,77	65,37
14	46,03	45,01	38,69	35,52	39,65	53,23	54,91	56,26	54,52	57,13	60,34	65,34
15	44,96	43,66	36,92	33,45	38,22	51,18	53,52	53,58	52,71	55,71	59,49	64,58
16	44,99	42,56	35,54	32,38	37,57	49,08	53,93	52,68	52,98	56,13	60,29	65,41
17	48,03	43,89	35,31	32,11	37,18	47,92	55,20	51,30	53,82	57,40	64,95	69,47
18	49,01	48,09	37,32	32,27	36,82	46,74	56,71	50,69	55,84	58,82	67,16	68,65
19	48,00	47,72	42,47	33,74	37,29	46,84	60,39	50,64	59,20	62,42	62,07	65,51
20	46,71	46,75	42,81	37,89	38,86	47,54	61,75	53,14	67,88	64,06	58,84	63,16
21	43,34	43,27	39,22	41,02	40,33	47,41	55,35	54,01	64,79	57,44	54,41	58,14
22	38,09	36,31	34,76	36,21	39,29	46,89	47,35	49,46	54,29	49,02	48,83	51,30
23	39,46	37,17	36,18	36,21	39,41	48,47	48,35	50,25	53,08	50,09	50,77	50,81
24	33,69	31,49	32,73	31,20	34,54	44,24	44,03	46,10	48,06	45,53	45,81	45,88
average	40,74	38,70	35,40	33,33	37,02	47,62	50,70	49,19	53,22	52,63	53,43	56,05

Portugal

Table 9 Hourly averages of power produced during average months by the model photovoltaic farm in Portuguese conditions with marked battery charging hours.

Hour:	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
-	**MWh**	**MWh**	**MWh**	**MWh**	**MWh**	**MWh**	**MWh**	**MWh**	**MWh**	**MWh**	**MWh**	**MWh**
1	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
3	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
4	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
5	0,00	0,00	0,00	0,00	0,18	0,39	0,22	0,00	0,00	0,00	0,00	0,00
6	0,00	0,00	0,00	0,58	1,39	1,65	1,71	1,12	0,32	0,00	0,00	0,00
7	0,00	0,00	0,96	1,77	1,95	2,19	2,39	2,31	1,80	0,91	0,00	0,00
8	0,55	1,43	1,95	2,15	2,25	2,56	2,87	2,83	2,37	1,89	1,40	0,66
9	1,75	2,07	2,21	2,31	2,37	2,83	3,25	3,21	2,67	2,20	1,90	1,83
10	2,02	2,32	2,38	2,39	2,40	3,00	3,49	3,49	2,87	2,36	2,09	2,14
11	2,14	2,46	2,58	2,39	2,45	3,11	3,66	3,61	2,96	2,59	2,14	2,21
12	2,15	2,51	2,62	2,32	2,39	3,07	3,70	3,59	2,89	2,36	2,03	2,19
13	2,05	2,40	2,40	2,19	2,25	2,96	3,65	3,47	2,73	2,19	1,92	2,08
14	1,90	2,22	2,23	2,04	2,19	2,86	3,55	3,32	2,55	2,02	1,81	1,95
15	0,92	2,09	2,05	1,91	2,05	2,74	3,36	3,12	2,41	1,40	0,43	0,00
16	0,00	0,00	0,48	1,29	1,87	2,50	3,04	2,15	0,56	0,00	0,00	0,00
17	0,00	0,00	0,00	0,00	0,00	0,57	0,69	0,00	0,00	0,00	0,00	0,00
18	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
19	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
20	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
21	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
22	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
23	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
24	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
average	0,6	0,7	0,83	0,89	0,99	1,269	1,484	1,3	1,0067	0,747	0,573	0,54

Table 10 Average hourly market electricity prices in Portugal with marked battery discharging hours. *Data taken from:* [30].

hour	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
-	**EUR/ MWh**	**EUR/ MWh**	**EUR/ MWh**	**EUR/ MWh**	**EUR/ MWh**	**EUR/ MWh**	**EUR/ MWh**	**EUR/ MWh**	**EUR/ MWh**	**EUR/ MWh**	**EUR/ MWh**	**EUR/ MWh**
1	38,76	34,76	27,34	18,68	22,61	32,30	35,39	36,09	40,13	34,41	38,41	38,88
2	35,82	32,79	25,59	17,11	21,55	30,29	31,91	33,28	37,26	31,42	36,33	34,72
3	33,49	31,00	24,69	15,91	20,45	28,90	30,06	31,79	35,56	30,21	34,81	32,89
4	32,08	30,16	23,68	14,68	19,65	28,37	29,27	30,70	33,99	28,95	33,61	30,52
5	31,65	29,88	23,39	14,35	19,39	28,00	29,20	30,43	33,46	29,17	33,12	30,48
6	32,93	31,10	23,79	14,95	19,91	29,07	29,87	31,72	35,04	30,61	33,98	31,65
7	35,41	33,43	25,59	16,60	20,24	30,41	31,95	34,19	41,44	34,12	37,35	35,96
8	40,62	36,72	27,51	17,41	20,76	32,12	34,37	35,99	43,72	38,95	41,01	41,82
9	42,19	38,19	28,62	17,83	21,10	32,94	35,88	36,69	44,59	40,63	42,63	43,89
10	43,68	38,67	29,29	18,56	21,82	32,63	36,00	37,83	44,68	41,17	43,39	46,70
11	44,12	37,76	28,94	18,22	21,49	32,05	35,80	37,22	43,04	39,24	42,81	47,18
12	43,20	36,99	28,57	18,51	21,69	31,79	36,04	36,53	42,27	36,75	42,76	45,66
13	42,58	35,97	28,32	18,49	21,65	31,61	36,81	37,44	42,82	35,91	42,46	44,34
14	41,72	35,43	28,17	18,61	23,48	31,47	37,11	36,80	42,72	34,70	42,44	43,74
15	40,35	34,30	27,04	17,85	21,27	30,05	36,35	35,80	41,33	32,58	41,92	42,17
16	39,86	33,88	26,01	15,96	19,70	27,94	34,67	34,33	40,22	31,75	41,49	41,19
17	40,83	34,60	25,97	14,82	18,94	27,29	33,97	33,69	40,14	32,15	42,50	42,71
18	43,80	35,94	26,94	14,89	19,05	28,41	34,54	34,71	41,35	34,69	45,13	46,90
19	46,10	38,52	28,75	17,00	20,41	29,94	35,70	36,21	43,20	37,88	49,56	51,52
20	47,84	42,42	33,54	18,82	22,25	31,26	37,42	38,27	46,19	42,82	49,66	52,26
21	48,07	43,04	35,37	20,77	23,61	32,76	37,97	40,65	50,54	46,57	48,42	51,73
22	46,75	41,85	33,51	23,44	25,73	34,25	38,80	41,91	49,76	43,52	45,65	49,27
23	43,77	38,64	31,38	21,67	25,62	34,87	39,45	41,05	45,27	39,80	42,85	46,78
24	40,23	35,83	29,43	19,63	23,48	31,97	35,94	37,81	41,16	36,81	39,99	42,37
average	40,66	35,91	27,98	17,70	21,49	30,86	34,77	35,88	41,66	36,03	41,35	42,30

Economic assessment

After calculating the potential electrical energy produced and taking into account the average electricity selling market prices, the country chosen for further development of the project is Poland. The reason for this is the fact that in Poland the photovoltaic energy is less developed and implemented on a smaller scale. The transition to become independent on fossil fuels must happen fast and intensive and such big-scale projects could help in shaping the energy engineering future. To check the actual advantages from implementation of battery storage and giving the climatic conditions, it is interesting to see whether photovoltaic installation with Li-Ion battery storage system can bring financial profits (Variant 1) and if not, whether the photovoltaic installation alone can be profitable. So it has been decided to check the profitability of a photovoltaic farm standalone as a Variant 2 as well.

Cash flow

Income

To calculate the total annual income, one must realise that in the case of this project there are three parts (or two in case of the PV farm alone) of this total income and they include:

- Income 1: from selling the discharged energy which was stored thanks to the battery system. The assumption is that the stored amount equals to 20% of the daily electricity production, but not more than 2MWh a day,
- Income 2: from the won auction bet. This is the main source of income, from the guaranteed won tariff for the first 15 years of operation. The amount of electricity sold to the grid this way is assumed to be 95% of the remaining energy that was not stored. The share is not 100% for the security reasons.
- Income 3: from the assumed remaining 5% of produced electricity that will be sold to the grid with the average market electricity price.

Knowing the electricity production and all of the market electricity prices from previous paragraphs, all three separate parts of the total income can be calculated as follows:

$$Income_1 = (0{,}5 * P_{stored} * P_{N1}) + (0{,}5 * P_{stored} * P_{N2}), \qquad EUR \qquad \text{Eq. 5}$$

$$Income_2 = [0{,}95 * (P_{month} - P_{stored})] * P_{N,auction}, \qquad EUR \qquad \text{Eq. 6}$$

$$Income_3 = (P_{month} - P_{aution} - P_{stored}) * P_{N,market}, \qquad EUR \qquad \text{Eq. 7}$$

$$Income_{month} = Income_1 + Income_2 + Income_3, \qquad EUR \qquad \text{Eq. 8}$$

Where:

$Income_1$ - Income from selling the stored energy, EUR;

P_{stored} – the amount of stored energy, MWh;

P_{N1} – electricity market price during the hour 1 of discharging EUR/MWh;

P_{N2} – electricity market price during the hour 2 of discharging EUR/MWh;

$Income_2$ – Income from the auctioned electrical energy, EUR;

P_{month} - total monthly energy production, MWh;

$P_{N,auction}$ – guaranteed electricity price from the won auction, EUR;

$Income_3$ – Income from the remaining energy sold to the grid, EUR;

$P_{auction}$ – the amount of energy sold for the auction price, MWh;

$P_{N,market}$ – average market electricity selling price, EUR;

$Income_{month}$ - total monthly income from the installation, EUR.

After calculating the total monthly income, the values are added up to calculated the yearly income, which results will be presented in the next chapter. The photovoltaic farm is assumed to have a lifetime of 25 years, so the procedure is repeated for each year. The income decreases every year due to the assumption that the efficiency of power production decreases 0,5% each year. Also, as mentioned, the winning auction agreement lasts only 15 years, so after this period, besides the stored energy, the whole electricity production is sold to the grid having the price of an average selling market electricity price.

Costs

For the costs, the following sources are considered as part of the initial investment cost: photovoltaic farm cost, the cost of purchasing the land and battery storage unit cost. The following values were taken into the account:

- Photovoltaic installation cost:

$$I_{PV} = 2\ 000\ 000 \frac{PLN}{MW} * 5\ MW * 0{,}22 \frac{EUR}{PLN} = \ 2\ 272\ 727{,}27\ EUR \qquad \text{Eq. 9}$$

Where the cost of 2 MLN PLN/MW is an average general price for installation of 1MW in total adapted as an average from polish articles explaining the industry and market of photovoltaic farms in Poland, like the example of Helios Strategia article *source:* [32]. The quantity $0{,}22\frac{EUR}{PLN}$ is the general currency conversion factor when switching from polish currency (PLN) into EUR.

- Land cost:

$$S_L = \frac{S_{total} + (0,2 * S_{total})}{10000} = 3,28\ ha \qquad \text{Eq. 10}$$

$$I_L = 3,28\ ha * 7869,32 \frac{EUR}{ha} = 25\ 839,89\ EUR \qquad \text{Eq. 11}$$

S_L – total land area, ha;

I_L – total land cost, EUR.

The total area is calculated as the sum of total area of the panels and the 20% excess reserved for the rest of infrastructure needed for the system to work, including the battery storage unit. The total land cost is multiplication of the land surface area and the average cost of land in Poland. The price of the land is an average value from the OnGeo.pl website, that does reports connected with lands and infrastructure in Poland *source:* [33]. In Poland the best type of land for photovoltaics is the class V or VI – meaning the worst category of soil quality, not really suitable for crops, rather suitable to utilise in another way.

- Battery storage system cost *(source:* [34]*)*:

$$I_B = 492\ 820,00\ EUR \qquad \text{Eq. 12}$$

The total investment cost is calculated as the sum of all the initial costs (Eq. 9, Eq. 11, Eq. 12) and is considered only in the so-called “year 0” of the investment. In the case of study of the Variant 2 where only the PV farm is considered, the battery system cost is not included:

$$I = I_{PV} + I_L + I_B = 2\ 791\ 387,16\ EUR \qquad \text{Eq. 13}$$

- Labour costs:

As for the other costs that happen annually, the labour costs must be considered. The photovoltaic farm system, once built, generally does not require any person supervising it, so the only thing is one part-time worker to supervise the farm and sometimes do simple maintenance work, like cutting grass or washing the panels with water.

$$C_{labor} = n_e * n_s * \left(C_e * (1 + i)\right) * 12 months, \qquad EUR \qquad \text{Eq. 14}$$

n_e – number of employees (equal to 1);

n_s – number of shifts (equal to 0,5);

C_e – costs of monthly payment (initially the minimum wage for 2021 in Poland: 747,39EUR);

i – inflation (2%).

- Operational and maintenance costs:

$$C_{om} = 0{,}005 * I * (1 + i), \qquad EUR \tag{Eq. 15}$$

The operational and maintenance cost are assumed to be 0,5% of the investment cost a year, in case e.g. any panel experiences a malfunction.

- Bank loan:

$$C_{bank} = \left(\frac{I}{10}\right) + \left[0{,}023 * (I - \frac{I}{10})\right], \qquad EUR \tag{Eq. 16}$$

To afford the construction of a big-scale photovoltaic farm and storage unit like in the case of this model, there was decided to go for a bank loan. The bank loan consists of the total of 10 fixed rate payments occurring annually. The interest rate is assumed to be 2,3%.

- Income tax:

In Poland income tax equals to 19% of the profit that the project brought during the particular year.

Cash flow

Cash flow is a notion that studies the difference between the income and the costs. Generally, the formula for the cash flow in the studied cases is as follows:

$$CF_n = Income - Costs \tag{Eq. 17}$$

$$Costs = I + C_{labor} + C_{om} + C_{bank} + C_{tax} - C_b \tag{Eq. 18}$$

The formula for the costs shown above is a general one, because during some years of the ongoing project, its components can differ. For instance, the costs of a bank loan are included only for the first 10 years, as this is the assumed duration of the bank loan. The costs connected with the income tax are calculated only for the years where the initial cashflow is positive – there is profit generated. C_b is a cost associated with a renovation of the batteries that is assumed to happen every 7 years in Variant 1 only and is equal to 10% of the battery energy storage system cost, so it will be included 3 times during the investigated period of lifetime of the system. The investment cost is different in the Variant 2 of the project, as the cost of battery system is then not included.

Once the cash flow for each year of the project lifetime is calculated, the profitability indicators can be determined. The profitability indicators are a direct way of checking whether the project is feasible and has a potential of being a successful investment.

Profitability indicators and sensitivity analysis

Net Present Value

$$NPV_n = \sum_{n=0}^{N} \frac{CF_n}{(1+a)^n} \qquad \text{Eq. 19}$$

Where:

a – discount rate (assumed to equal 2%);

n – the consecutive year for which the values are calculated [n∈(0;25)].

Internal Rate of Return

$$\sum_{n=0}^{N} \frac{CF_n}{(1+IRR)^n} = 0 \qquad \text{Eq. 20}$$

Internal rate of return is a value that can be obtained iteratively. In this case, the IRR is explicitly calculated from a built-in function in MS Excel software.

The simplest indications of the feasibility of a project are as follows:

- IRR>a and NPV>0 – the project is feasible and the investment was able to return the initial costs and make a profit,
- IRR<a and NPV<0 – the project is not feasible and the minimum amount of capital to return costs of investments was not reached.
- NPV=0 project is uncertain, meaning that the investment was returned, but the profit is not really there.

Discounted and Simple Payback

Discounted Payback (DPB) and Simple Payback (SPB) inform about the exact period in the lifetime of the investment when the project becomes profitable. Simple Payback informs about the breakeven point of the project, which is when the cash flow becomes stops being a negative value, so the investment is returned. Discounted Payback is longer than SPB, because it informs when the cash flow reaches 0, but the values considered are discounted - taking into account the loss in the value of the money itself (see Eq. 21 and Eq. 22).

DPB

$$\sum_{n=0}^{DPB} \frac{CF_n}{(1+a)^n} = 0 \qquad \text{Eq. 21}$$

SPB

$$\sum_{n=0}^{SPB} CF_n = 0 \qquad \text{Eq. 22}$$

Sensitivity analysis

The purpose of the sensitivity analysis is to study the influence of chosen key parameters on the overall results. In this case it has been decided to study the influence of two parameters on the Net Present Value:

- Investment cost (EUR),
- Market electricity price (EUR/MWh).

The deviation from the original values is assumed to be 20% on each side. Investment cost is a parameter that originates in different assumptions, meaning that many factors could change it. This makes the parameter worth the sensitivity study, as each of the components of the installation can change its price in the future or simply if a slightly different solution was to be chosen. The market electricity price is a parameter that changes very often and the trend is that in the future it could go up. On the other hand, the policy connected with renewable energy sources in Poland could be adjusted in either way, so deviations of the electricity price in both directions are worth the study to find out its influence on the NPV. The studied values and ranges were chosen as presented in the Table 11 below:

Table 11 The selected parameters and their values for the sensitivity analysis of the NPV.

	Unit	**-20%**	**0**	**20%**
Investment cost	MLN EUR	2,23	2,79	3,34
Market electricity price	EUR/MWh	44,47	55,59	66,71

The methodology of calculations shown in the Chapter 4 enables a better understanding of the results shown in the next sections. The goal is to study the viability and feasibility of the Variant 1 and Variant 2 of the model and the results of each step's calculations will lead to drawing the proper conclusions.

Chapter 5

Results

After explaining the methodology behind the performed analysis, the appropriate comments of the results will be done. This chapter includes the presentation of the results in forms of tables and graphs and also the description of the results obtained.

Introduction

The methodology, assumptions and equations shown in the previous chapter had a purpose of explaining what is hidden behind the results that will be presented in this chapter. To study whether the model in Variant 1 and Variant 2 could be successfully realised thanks to the methods of the profitability indicators checking, the technological parameters must be calculated first. The chapter is divided into parts:

- **Energy production** – where firstly the two most important parameters for this paragraph are shown: the set of data for irradiation and market prices. Later, according to the presented method of calculations, the energy production is shown in the tables, as the hourly averages during the average month from which there can be read when the electricity production has its peaks. Finally there is presented the sum of how much electricity can be produced during a month and what is the average monthly price of electricity,
- **Energy storage** – this paragraph serves a purpose of determining the charging and discharging scenarios in Variant 1 of the system, which depends on the electricity produced, which is highly seasonal and the market prices, that can vary especially when comparing the morning and evening hours. By the visualization on the monthly graphs, the hours chosen for the mentioned scenarios are directly noticeable,
- **Economic assessment –** the main goal of the paper is to see whether at least one of two variants of the adapted model is profitable. Firstly, the exemplary yearly income table is presented, meaning the amount of electricity stored, utilised in an auction system and remaining sold to the grid and how much income each of those sources produce. To summarise this, the table with annual incomes throughout the lifetime of the project is presented. Later the results of the variable costs will be discussed – labour costs, operational and maintenance costs and the bank loan. When the results for income and costs are known, the cash flow results can be shown in form of a table and graphs showing which parts of the income and costs influence the cash flow the most and the least for both variants. For profitability analysis, the graph showing the NPV during the lifetime of the project will be shown to visualise the financial state of the project through the years of operation, done for two variants. Later, the IRR, SPB and DPB results will be presented in a table to check whether any variant of the model is feasible. The sensitivity analysis is presented on the adequate graphs.

Energy production

Direct solar irradiation and market electricity prices

The Figure 15 and Figure 16 are presented below. Their purpose is to notice how the electricity prices and amount of irradiation change during the months, or seasons in Poland and Portugal. It can be concluded that the monthly direct normal irradiation is the smallest in the winter season, where the days are the shortest. The maximal DNI (Direct Normal Irradiation) in Poland is noticeable in May and reaches almost 150 kWh/m^2 in total. The values above 100kWh/m^2 are present during 5 months in Poland, that is when production of the electricity from the PV farm will be the highest. The market electricity prices on the Figure 15 show that the electricity is the most expensive in the second half of the year, with the highest value of almost 60 EUR/MWh in December. All of the average electricity prices are in the range 40-60 EUR/MWh.

On the Figure 16 there can be seen that in Portugal the DNI is visibly higher than in Poland, reaching the values over 100 kWh/m^2 during 8 months, with the peak of value around 220 kWh/m^2 in average July. For 5 months during a year the irradiation in Portugal has bigger average values than the highest ranking month in Poland. The market electricity prices are generally lower in Portugal than in Poland. For the end customers it is a great option, but when the supplier wants to sell the produced electricity, this could mean a smaller profit from her project. The highest prices are in the winter season and the cheapest electricity is in the month of April with only around 20 EUR/MWh.

From both graphs presented below (Figure 15 and Figure 16) there can be concluded that the basic parameters before modelling a PV farm in both locations have certain similarities in trends. When it comes to the trends in the irradiation, the values reach the extremes in the similar periods of the year in the summer. At the same time this means that the electricity production from the same 5 MW installation in Poland and Portugal, will be proportionally always higher in Portugal. The market electricity prices, although with a different values, experience the similar patterns during an average year. What can also be concluded is that in case of both the countries, after the market price reaches its lowest value in April, after that the electricity prices rise along with the irradiation in the following months. For the investor, the higher the prices the bigger the storage income and the higher the values of Direct Normal Irradiation, the bigger the auction income. The drop of irradiation in winter can lead to considerably lower income, that can affect the project feasibility which will be later discussed. All of the described dependencies can be seen on the figures below.

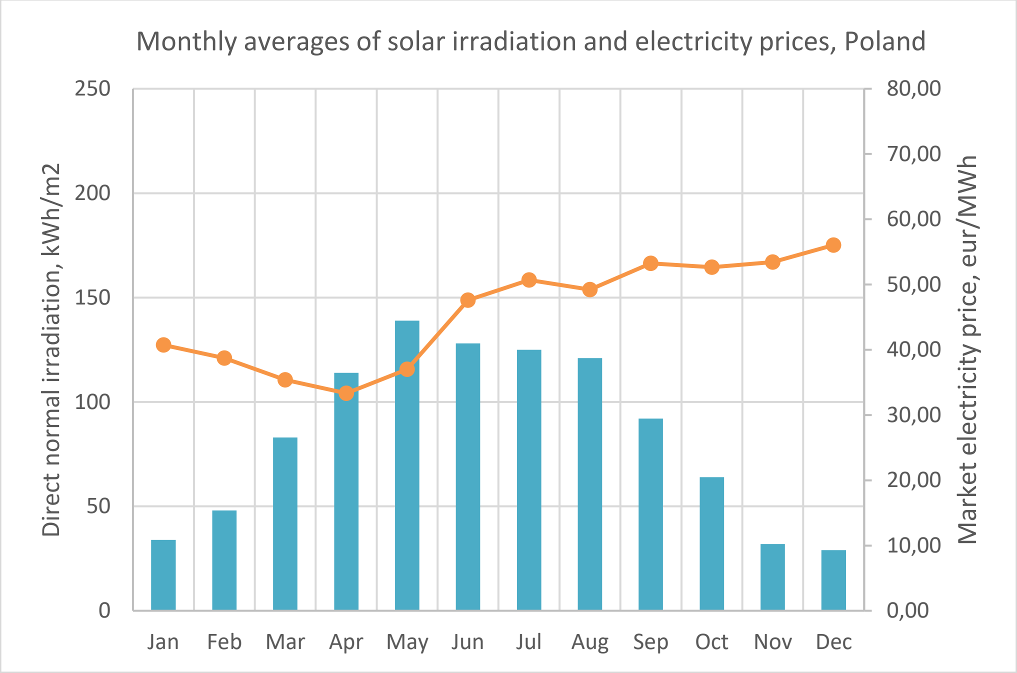

Figure 15 Comparison of monthly average direct normal solar irradiation (kWh/m^2) and average monthly market electricity prices (EUR/MWh) in Poland

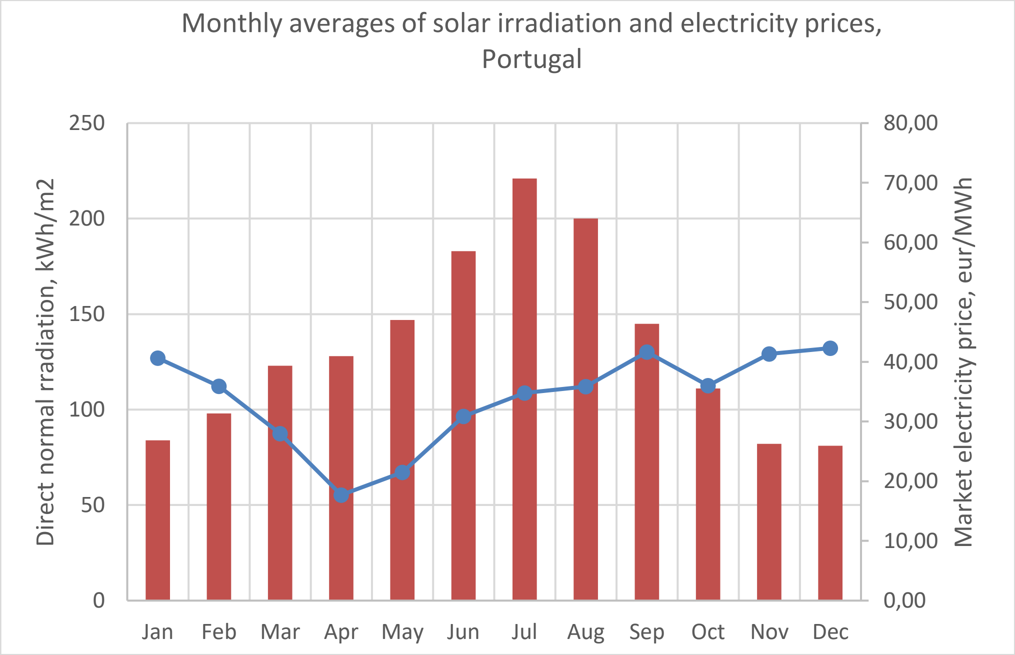

Figure 16 Comparison of monthly average direct normal solar irradiation (kWh/m^2) and average monthly market electricity prices (EUR/MWh) in Portugal

Energy production results

The Table 12 and also Table 13 are presented as the set of data below. This is the summary of how much electrical energy can be produced by the pre-described model during the every average month in both locations. It can noticed than in Poland at least 8 hours a day are without the sunlight, so without the energy production. On the other hand, during the coldest months, the sun shines for only 8 hours. The hourly production is the highest in the summer months, but never instantly reaching much more than 2MWh. In Portugal the highest extremes of the electricity production are higher, reaching almost 4 MWh in several points, especially during the month of July. The fact that during the summer season, the farm produces energy for 13 hours at most, which is 3 hours less than in Poland, can lead to the conclusion that the distribution of the energy production is more even in Poland. From the most basic point of view, the most important conclusion is that of course more energy will be produced from the same PV installation in Portugal than in Poland. The unevenness and randomness of the electricity production that can be concluded from Table 12 and Table 13 from photovoltaic energy lead to the proposition of incorporation of the battery storage system into the model.

Table 12 Hourly averages of the energy production for every month from whole photovoltaic farm in an average year in Poland

	Energy production, MWh											
hour:	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
1	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
2	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
3	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
4	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
5	0,000	0,000	0,000	0,000	0,075	0,310	0,130	0,000	0,000	0,000	0,000	0,000
6	0,000	0,000	0,000	0,210	0,845	0,920	0,720	0,255	0,000	0,000	0,000	0,000
7	0,000	0,000	0,100	0,955	1,335	1,280	1,130	1,030	0,650	0,000	0,000	0,000
8	0,000	0,095	0,820	1,420	1,705	1,585	1,540	1,470	1,230	0,705	0,000	0,000

9	0,240	0,725	1,240	1,715	1,980	1,830	1,820	1,840	1,535	1,110	0,525	0,190
10	0,760	1,030	1,430	1,890	2,140	1,915	1,895	1,995	1,740	1,310	0,760	0,685
11	0,855	1,095	1,530	1,965	2,165	1,880	1,825	1,980	1,705	1,340	0,840	0,755
12	0,905	1,150	1,555	1,925	2,045	1,760	1,685	1,840	1,655	1,355	0,890	0,860
13	0,960	1,215	1,555	1,860	1,905	1,710	1,610	1,815	1,580	1,370	0,895	0,865
14	0,900	1,255	1,530	1,745	1,805	1,635	1,580	1,685	1,450	1,210	0,795	0,765
15	0,705	1,015	1,345	1,595	1,650	1,530	1,475	1,540	1,315	1,020	0,575	0,520
16	0,190	0,830	1,190	1,420	1,545	1,425	1,410	1,415	1,190	0,770	0,110	0,040
17	0,000	0,220	0,935	1,300	1,415	1,310	1,310	1,315	0,945	0,175	0,000	0,000
18	0,000	0,000	0,220	0,915	1,155	1,130	1,120	1,035	0,270	0,000	0,000	0,000
19	0,000	0,000	0,000	0,100	0,615	0,825	0,785	0,270	0,000	0,000	0,000	0,000
20	0,000	0,000	0,000	0,000	0,000	0,225	0,130	0,000	0,000	0,000	0,000	0,000
21	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
22	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
23	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
24	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000

Table 13 Hourly averages of the energy production for every month from whole photovoltaic farm in an average year in Portugal

	Energy production, MWh											
hour:	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**Septermber**	**October**	**November**	**December**
1	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
2	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
3	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
4	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
5	0,000	0,000	0,000	0,000	0,180	0,390	0,225	0,000	0,000	0,000	0,000	0,000
6	0,000	0,000	0,000	0,585	1,395	1,655	1,710	1,120	0,320	0,000	0,000	0,000
7	0,000	0,000	0,965	1,770	1,955	2,190	2,395	2,310	1,805	0,915	0,000	0,000
8	0,550	1,430	1,955	2,150	2,250	2,560	2,875	2,835	2,375	1,890	1,405	0,660
9	1,755	2,075	2,215	2,310	2,375	2,835	3,250	3,210	2,675	2,200	1,900	1,835
10	2,025	2,320	2,380	2,390	2,400	3,000	3,490	3,495	2,875	2,360	2,090	2,140
11	2,145	2,465	2,580	2,395	2,455	3,115	3,665	3,615	2,960	2,590	2,145	2,215
12	2,155	2,515	2,625	2,325	2,395	3,075	3,699	3,590	2,895	2,360	2,035	2,190
13	2,055	2,400	2,400	2,190	2,250	2,960	3,655	3,475	2,730	2,190	1,920	2,080
14	1,900	2,220	2,230	2,045	2,190	2,865	3,555	3,325	2,555	2,020	1,815	1,955
15	0,925	2,095	2,055	1,910	2,050	2,740	3,360	3,120	2,410	1,405	0,435	0,000
16	0,000	0,000	0,480	1,295	1,870	2,500	3,045	2,150	0,565	0,000	0,000	0,000
17	0,000	0,000	0,000	0,000	0,000	0,570	0,695	0,000	0,000	0,000	0,000	0,000
18	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
19	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
20	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
21	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
22	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
23	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
24	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000

The next section of the subchapter concerns the data that summarise the energy production both in Poland and Portugal. In the Table 14 and Table 15 the hourly data has been summed up to see how big of potential there is for the daily production during different months. The monthly energy production was then presented as the daily production multiplied by number of days in a month. The market electricity prices were also averaged for the purpose of the subsequent results creation. The monthly energy production calculations are highly depended on the season of the year. This makes the production highly unstable and unpredictable. This is one of the biggest concerns when discussing the profitability of a renewable energy project, that so much depends on the highly-arbitrary data. Even the data taken from the most reliable source, it is still some average and can be untrue for the following years. Besides the meteorological data, the climate changes also play a big role here, as, for example, 20 years from now the Earth can be a lot hotter in terms of temperature and irradiation. The biggest possible monthly production is in Poland in May and in Portugal in July. This summarised value is more than 37% bigger for Portuguese conditions. In the cases of some months, the production in Poland can be 2 or 3 times lower than during the same months in Portugal (see for example November or December). In conclusion, this makes implementation of photovoltaic farm in Poland even more challenging and much needed, as the dependency on coal must be lower and here it can be concluded that electricity production in the highest point in Poland is the same as early spring in hotter countries like Portugal.

Table 14 Monthly energy production results in Poland

	Unit	January	February	March	April	May	June	July	August	September	October	November	December
Daily energy production	MWh	5,51	8,63	13,45	19,01	22,38	21,27	20,16	19,48	15,26	10,36	5,39	4,68
Number of days in a month	-	31	28	31	30	31	30	31	31	30	31	30	31
Monthly energy production	MWh	170,94	241,61	416,89	570,37	**693,69**	638,01	625,03	603,95	457,89	321,27	161,68	145,06
Average daily market electricity price	EUR/MWh	40,74	38,70	35,40	33,33	34,54	47,62	50,70	49,19	53,22	52,63	53,43	56,05

Table 15 Monthly energy production results in Portugal

	Unit	January	February	March	April	May	June	July	August	September	October	November	December
Daily energy production	MWh	13,51	17,52	19,88	21,36	23,76	30,45	35,62	32,24	24,16	17,93	13,74	13,07
Number of days in a month	-	31,00	28,00	31,00	30,00	31,00	30,00	31,00	31,00	30,00	31,00	30,00	31,00
Monthly energy production	MWh	418,75	490,49	616,35	640,86	736,61	913,53	**1104,07**	999,46	724,85	555,75	412,29	405,27
Average daily market electricity price	EUR/MWh	40,66	35,91	27,98	17,70	21,49	30,86	34,77	35,88	41,66	36,03	41,35	42,30

Energy storage

To evaluate the scenarios for charging and discharging, the energy storage unit according to the previously mentioned methodology and assumptions, the graphs for each month in the average year in Poland and Portugal are created. They represent the market electricity price and electrical power production. On this basis and according to the methodology assumed, the predictions when the battery energy storage system will operate are going to be determined.

What can be seen on the figures below, is that when it comes to the prices of the electricity in Poland, they are the highest almost always in the evening, between the 19-21h. The only exception is actually June and the winter months like November and December. These prices are typically between 40-70 EUR/MWh. When it comes to electricity production, during the whole year, every day there are a few hours with no production, that is where the other energy sources need to compensate in a grid, or in the future development of the project, a storage could also help. The power production is balanced in Poland, in winter the shapes of the graphs look similar and in the summer season they are similar between each other as well, usually oscillating between 1-2 MWh.

Comparing the Portuguese graphs to the Polish ones, the curves representing the electricity prices look a lot like the Polish ones, with the exception that the prices themselves are typically much lower than in Poland during the same seasons. The highest extremes are always in the evening hours, but the general averages of these prices can drop to even below 20 EUR/MWh and never reach much more than 50 EUR/Wh. This could result in an insufficient profit from the implementation of batteries. The power production in the summer reaches unbelievably higher values than typically during the same season in Poland. In month like June, July and August a production equalling or higher 3 MWh is occurring on average during a sunny day.

In conclusion to the graphs below (Figures 18 – 41) the market electricity prices are generally higher in Poland than in Portugal at all times. On the other hand, the electricity production is on average bigger in Portugal. One of these parameters is influencing the other one. Due to the higher production from renewable energy sources, the market electricity price in Portugal can be successfully lower than in the case of the second location. In Poland due to the milder climate, the production of electricity from the same photovoltaic farm is usually smaller, but at the same time it is more uniformly distributed, which can ensure a little more energy safety for this location, due to the more continuous production. The graphs one by one can be seen below with the later detailed discussion of the presented results.

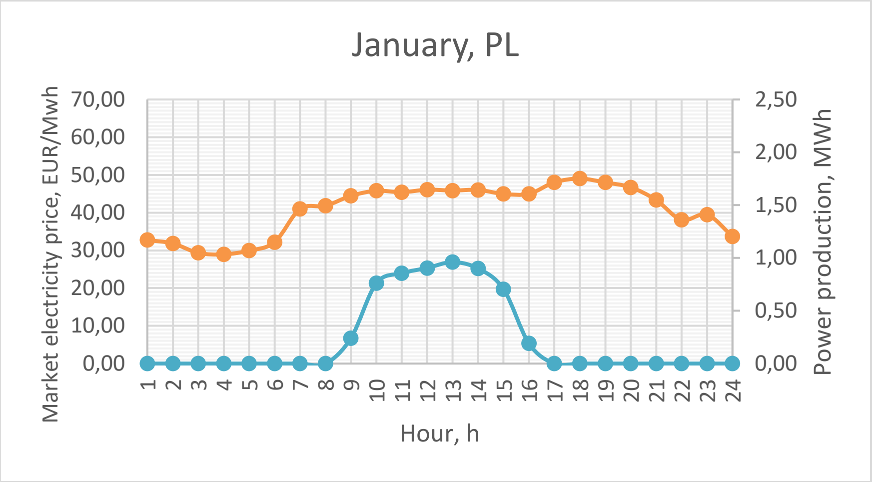

Figure 17 The representation of the average power production and market electricity prices in January in Poland

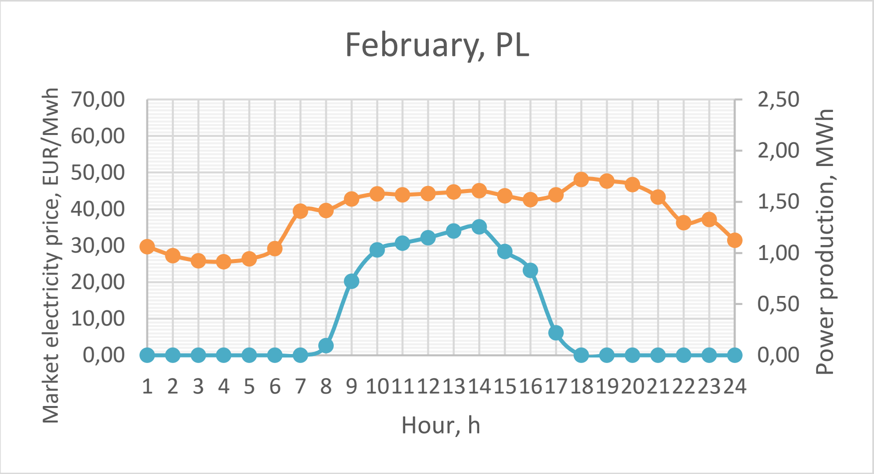

Figure 18 The representation of the average power production and market electricity prices in February in Poland

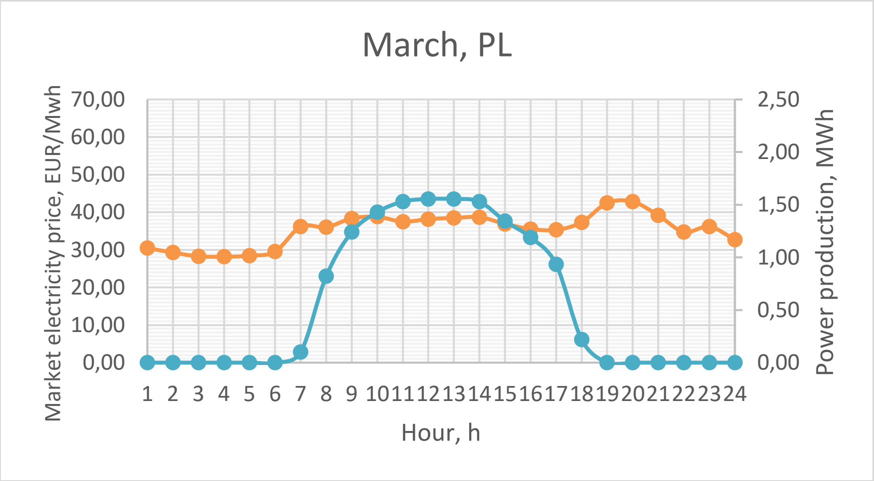

Figure 19 The representation of the average power production and market electricity prices in March in Poland

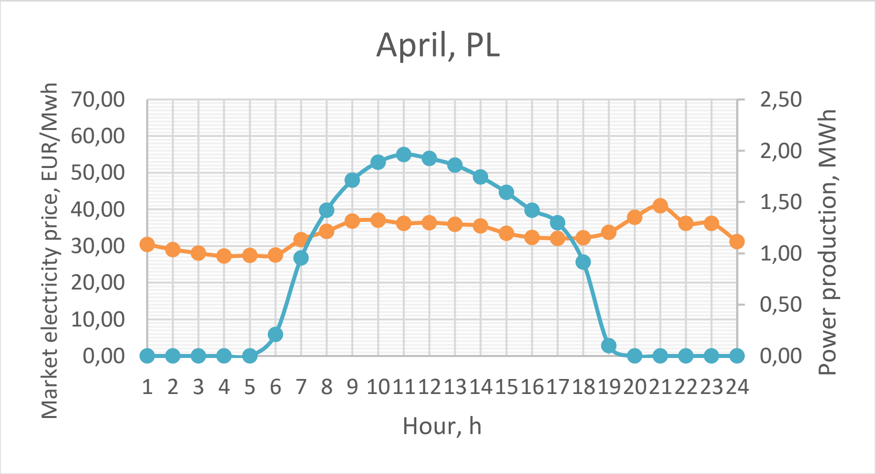

Figure 20 The representation of the average power production and market electricity prices in April in Poland

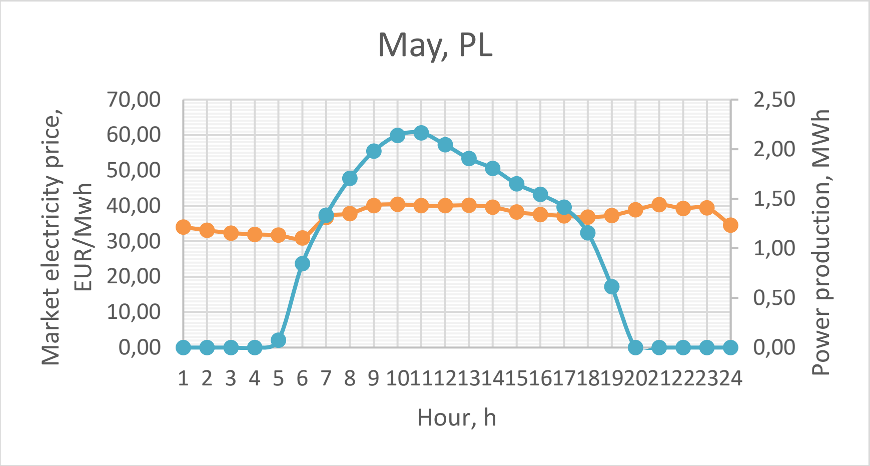

Figure 21 The representation of the average power production and market electricity prices in May in Poland

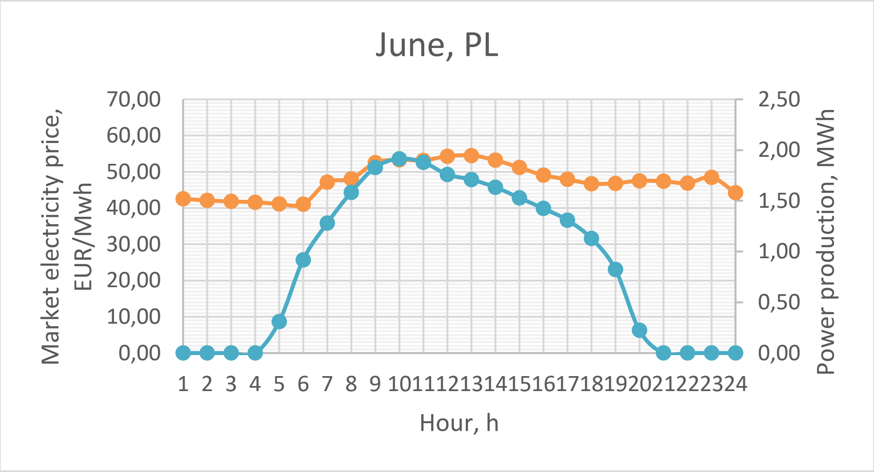

Figure 22 The representation of the average power production and market electricity prices in June in Poland

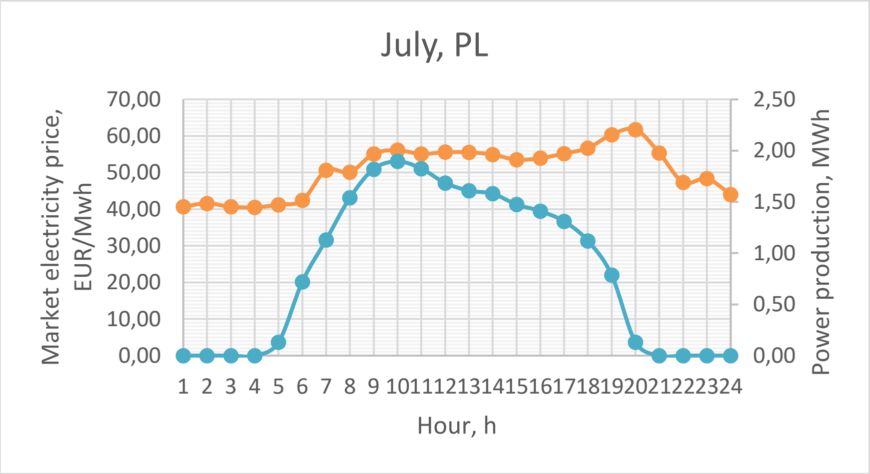

Figure 23 The representation of the average power production and market electricity prices in July in Poland

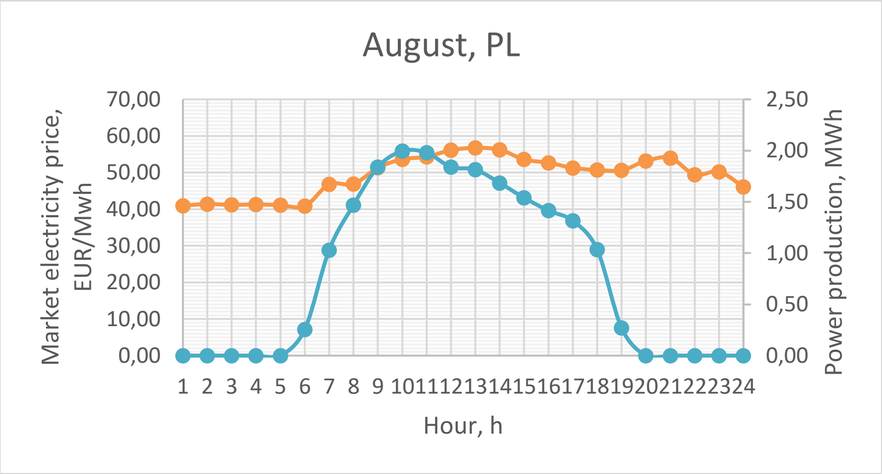

Figure 24 The representation of the average power production and market electricity prices in August in Poland

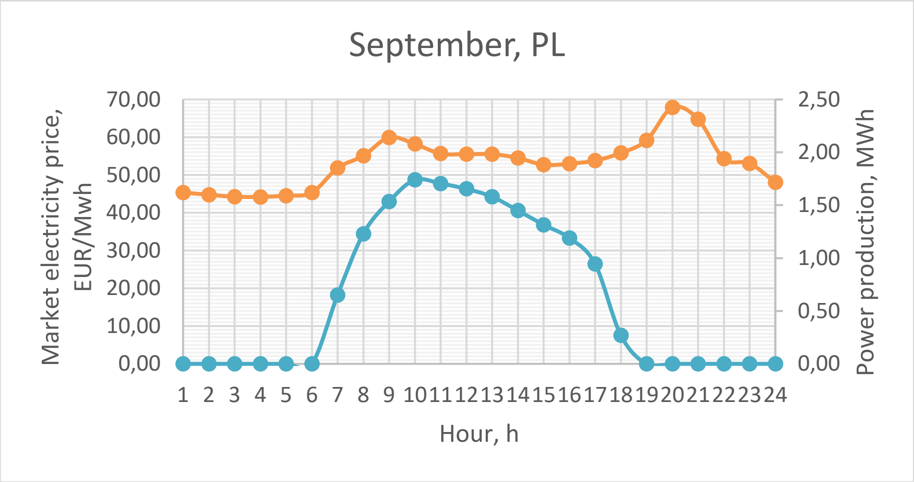

Figure 25 The representation of the average power production and market electricity prices in September in Poland

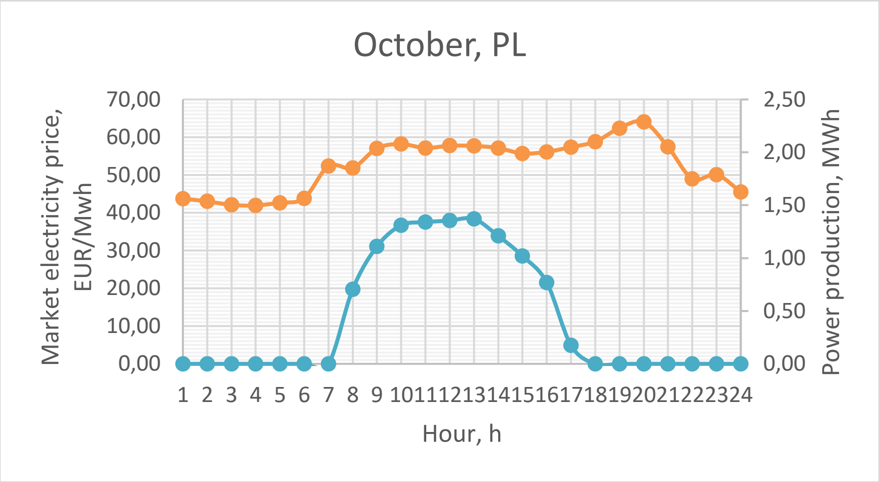

Figure 26 The representation of the average power production and market electricity prices in October in Poland

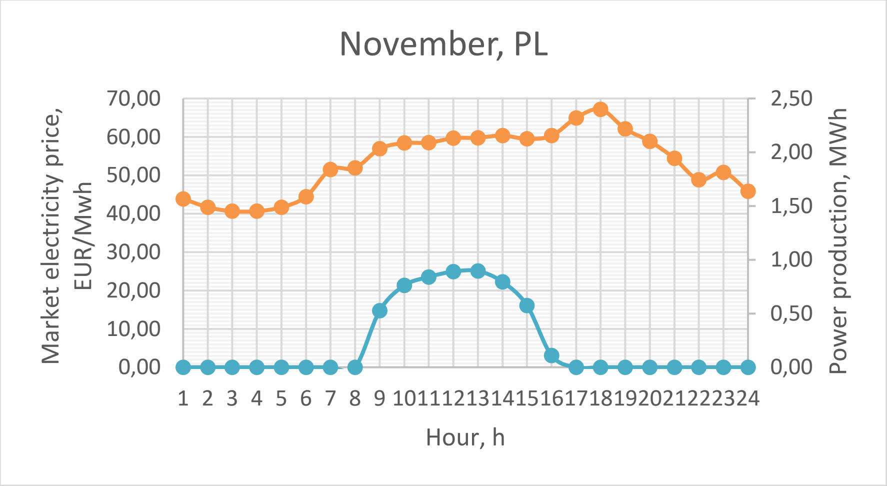

Figure 27 The representation of the average power production and market electricity prices in November in Poland

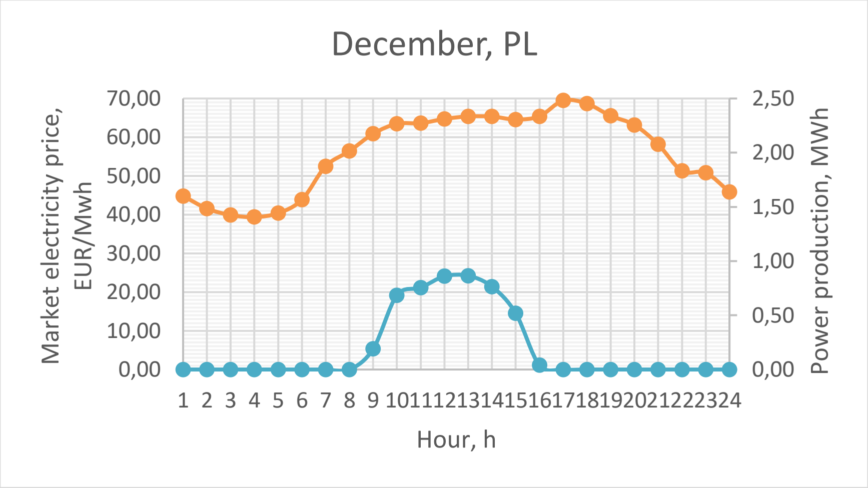

Figure 28 The representation of the average power production and market electricity prices in December in Poland

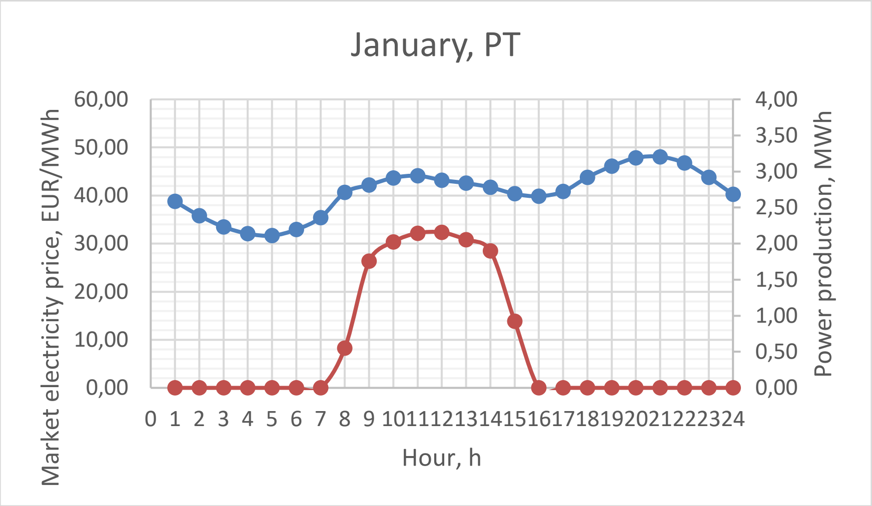

Figure 29 The representation of the average power production and market electricity prices in January in Portugal

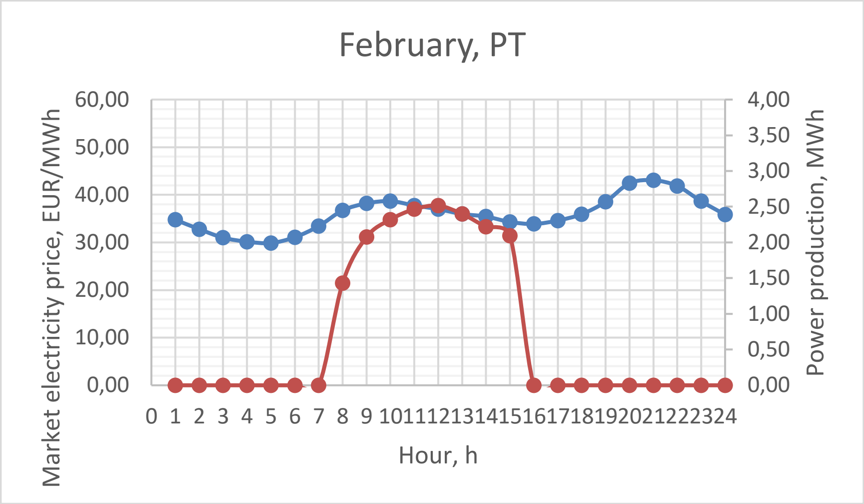

Figure 30 The representation of the average power production and market electricity prices in February in Portugal

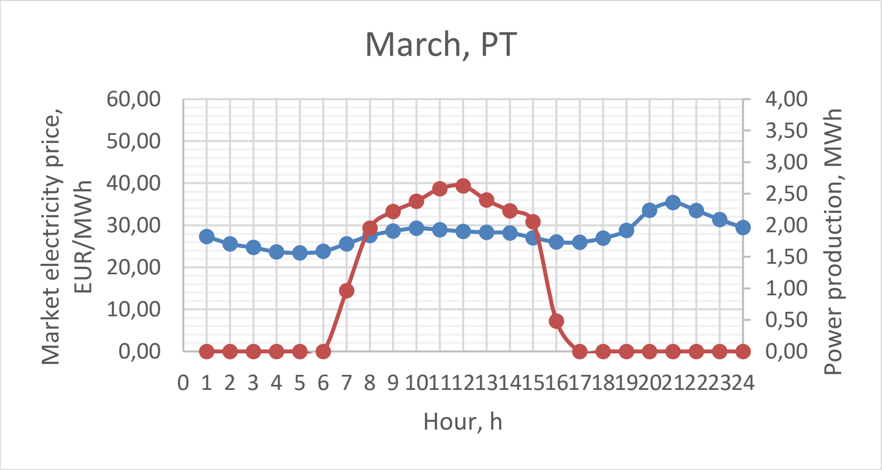

Figure 31 The representation of the average power production and market electricity prices in March in Portugal

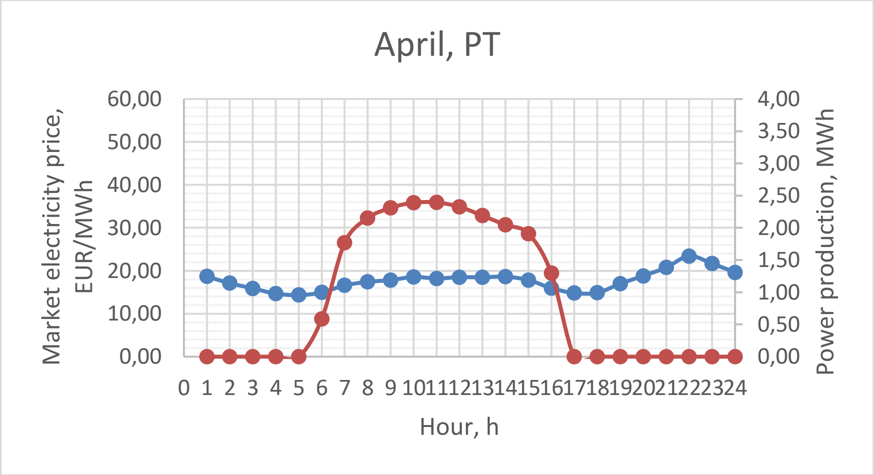

Figure 32 The representation of the average power production and market electricity prices in April in Portugal

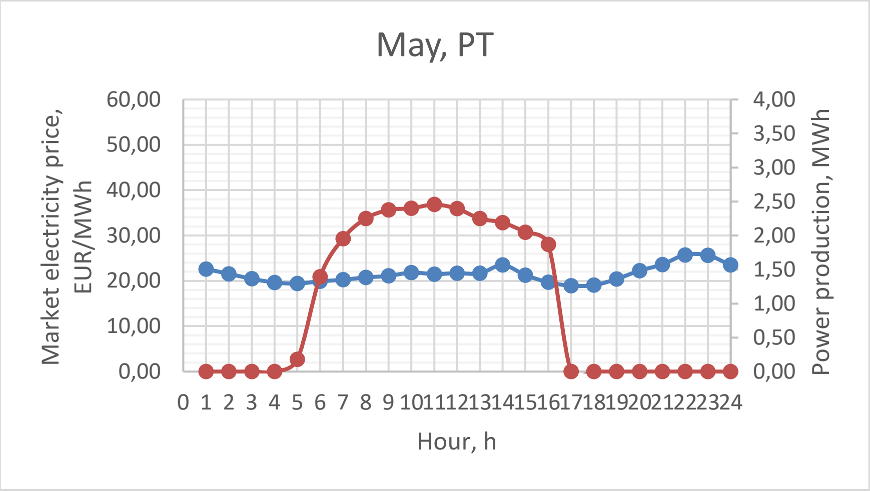

Figure 33 The representation of the average power production and market electricity prices in May in Portugal

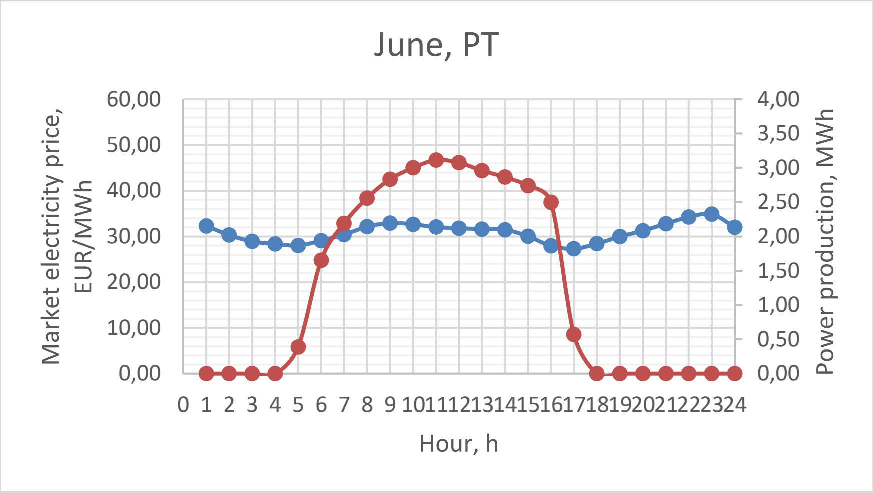

Figure 34 The representation of the average power production and market electricity prices in June in Portugal

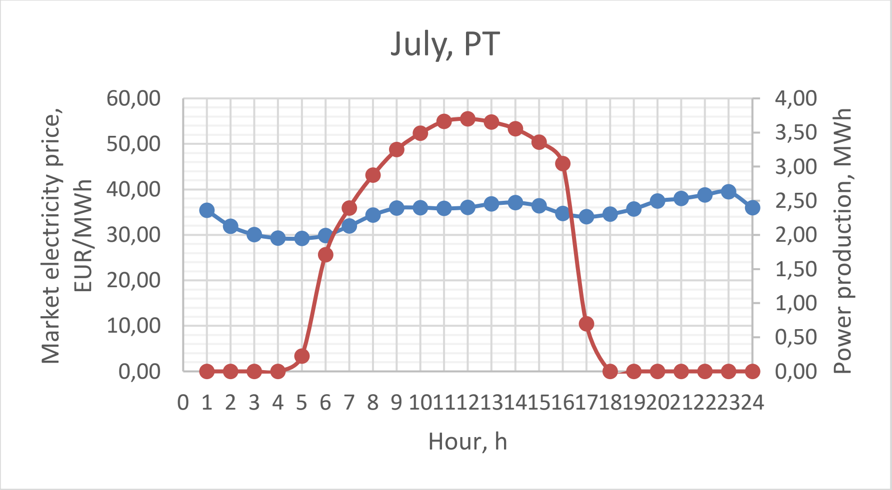

Figure 35 The representation of the average power production and market electricity prices in July in Portugal

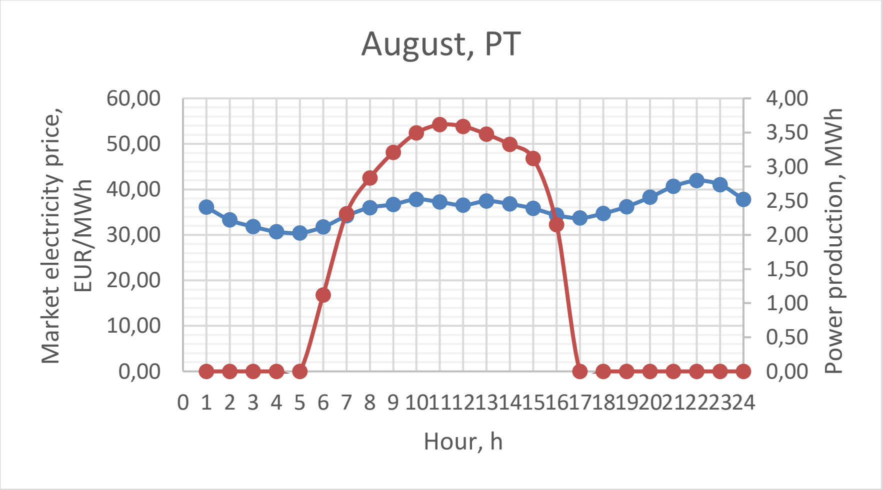

Figure 36 The representation of the average power production and market electricity prices in August in Portugal

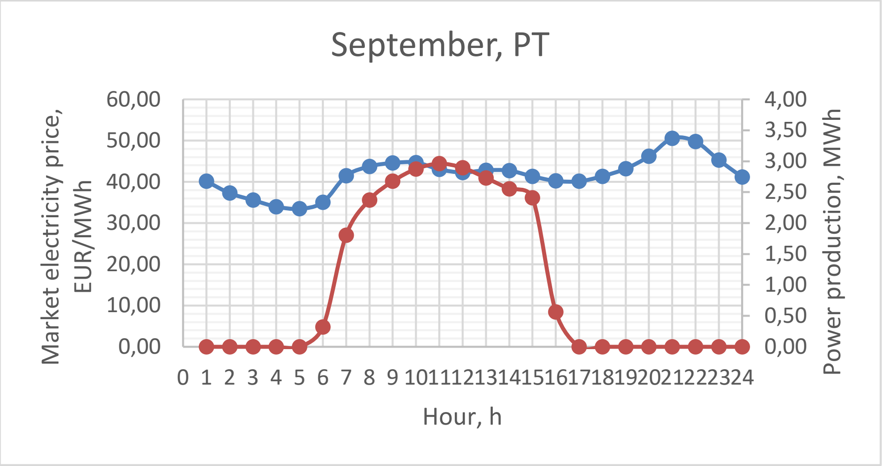

Figure 37 The representation of the average power production and market electricity prices in September in Portugal

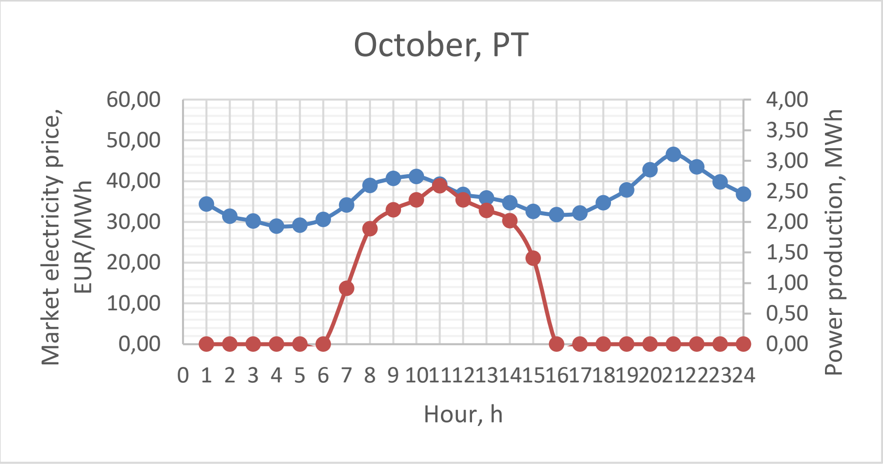

Figure 38 The representation of the average power production and market electricity prices in October in Portugal

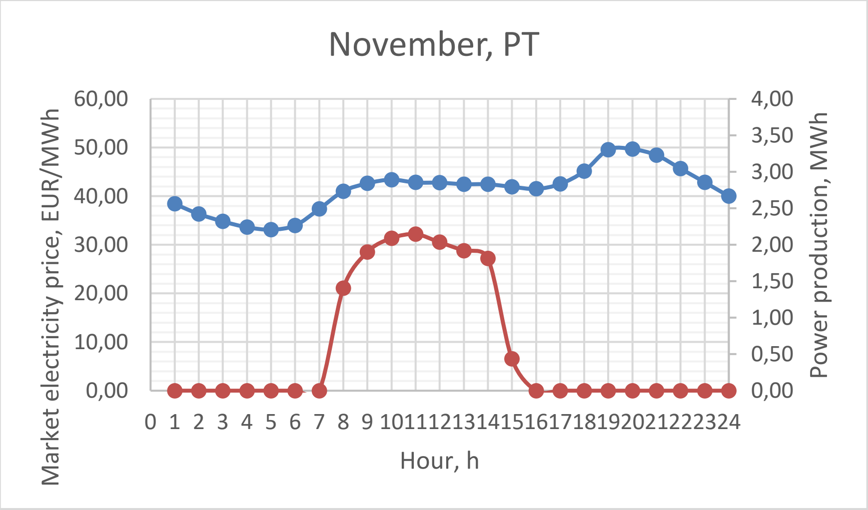

Figure 39 The representation of the average power production and market electricity prices in November in Portugal

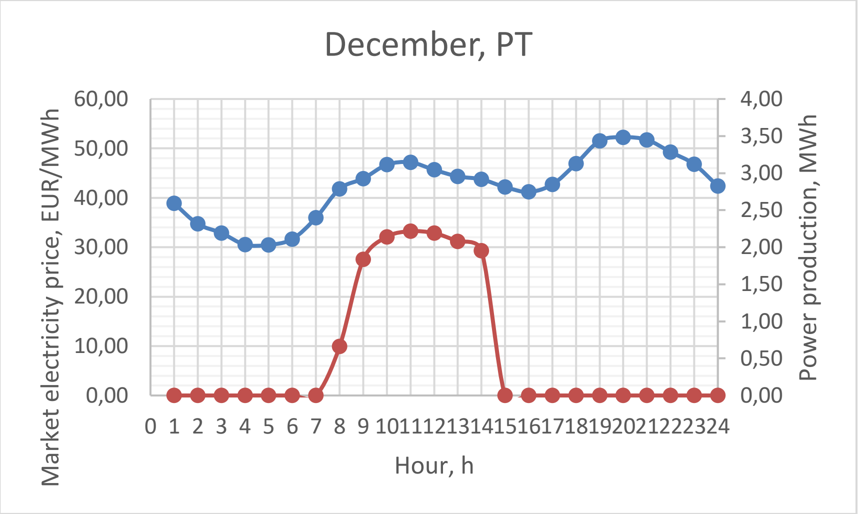

Figure 40 The representation of the average power production and market electricity prices in December in Portugal

In the average January in Poland (Figure 17) and in Portugal (Figure 29) the average electricity prices have the similar range 30-50 EUR/MWh. At the same time, to electricity production reaches 1 MWh in Poland and 2 times more in Portugal at their highest points around midday. Average February is similar to January in Poland, only with the slight increase in power production up to 1,2-1,3 MWh in the peak (Figure 18). During February in Portugal, the electricity prices start becoming lower and this process lasts through March, April and May (Figure 30, Figure 31, Figure 32, Figure 33) and in May it reaches below 30 EUR/MWh at all times, which leads to lower profits from a unit of electricity produced. March, April and May in Poland (Figure 19, Figure 20, Figure 21) have an average price below 50 EUR/MWh, but on the other hand the production rises and reaches more than 2 MWh in May (Poland). In can be concluded that both investigated values are co-dependent and in the end, the final incomes can oscillate in narrow ranges, as always the higher production of electricity, the lower the price of it while selling. Summer months in Poland (Figure 22, Figure 23, Figure 24,Figure 25) produce the most energy before midday, reaching around 2 MWh at the sunniest hours. The same months in Portugal (Figure 34, Figure 35, Figure 36, Figure 37), especially July and August, can produce almost 4 MWh in a peak hour and during these the electricity market price is 30-40 EUR/MWh, which averaged and combined means the most profit during these months. In autumn and winter both countries experience a growth in electricity prices and we also use electricity much more. In Poland (Figure 26, Figure 27, Figure 28) the sun shines for only 8 hours a day, leading to small energy production, in winter below 1 MWh at all times. For comparison, in Portugal (Figure 38, Figure 39, Figure 40), the production at a peak I around 2 MWh, but the sun shines for only several hours as well. In conclusion, the graphs on the Figure 18 - 41 were developed to verify at which two hours a day during a month the electricity production in MWh will be typically the highest, to store the surplus of the energy (with the assumptions explained in the Chapter 4). At the same time, the curves for the market electricity prices in EUR/MWh enabled identification of the two hours during the typical day when they reach they highest values, to discharge the battery energy storage system with maximal profit. The so-called charging and discharging scenarios are presented in Table 16 and Table 17 Hours predicted for charging and discharging the battery storage for Portugal. The charging and discharging hours differ between the each month’s averages, but the general tendency says quite the same. Charging of the battery is always done around midday – not later than after 1 pm. The peaks of the electricity market prices, are almost always in the evening, so naturally this when the discharging daily session takes place, typically after 8 pm.

Table 16 Hours predicted for charging and discharging the battery storage for Poland

	Charging and discharging scenarios											
	January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
Charging	12,13h	13,14h	12,13h	11,12h	10,11h	10,11h	10,11h	10,11h	10,11h	12,13h	12,13h	12,13h
Discharging	17,18h	18,19h	19,20h	20,21h	20,21h	12,13h	19,20h	13,14h	20,21h	19,20h	17,18h	17,18h

Table 17 Hours predicted for charging and discharging the battery storage for Portugal

	Charging and discharging scenarios											
	January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
Charging	11,12h	11,12h	11,12h	10,11h	10,11h	11,12h	11,12h	11,12h	10,11h	10,11h	10,11h	11,12h
Discharging	20,21h	20,21h	20,21h	22,23h	22,23h	22,23h	22,23h	22,23h	21,22h	21,22h	19,20h	20,21h

Economic assessment

As mentioned in the previous sections, the economic assessment is the main tool in this model and its two variants to check how successful the project really is. In this case, firstly the cash flow and its components are presented. Later, the profitability analysis results in form of the NPV, IRR, SPB and DPB are shown with the sensitivity analysis as the last part. The detailed discussion will appear in the next dedicated sections.

Cash flow

Income

According to the described methodology, the income in this model comprises of two or three parts, depending whether this is the variant with or without the battery energy storage system. In the Table 18 and Table 19 there are shown the results for the first year of the installation's operation, similarly the calculations were done for the following years with the summed up values in Table 20 and Table 21. The first two tables show the amount of energy sold in the auction system, sold to the grid and in the case of the Variant 1 also through the stored energy in each month of the first year of the operation.

In the Table 18 it can be seen that except for the winter months, the potential for the storage is bigger than the assumed limitation, so a bigger or the second unit could be applied in the future or the battery storage system could serve other purposes as well. According to the table, the biggest share of the total income comes from the auctioned electricity selling, which is not surprising giving the assumptions for this model. The tariff from the won auction is guaranteed and stays the same during the whole period of 15 years, so it is the most steady part of the income. The same calculations were performed for each year of the lifetime of the system for both Variant 1 and Variant 2.

The Table 20 and Table 21 show total income during each year of the installations' operation. All of the yearly incomes are between 250 000 – 300 000 EUR. The incomes decrease in time, as the efficiency of the whole system drops according to the model's assumptions. In the Variant 1, the battery energy storage system rings around 30 000 EUR of profit a year. The most important conclusion that may be drawn here, which is surprising, is that the total yearly income is higher in the case of the Variant 2 – the photovoltaic plant working without the battery storage. The conclusion here can be that this happens due to the fact, that the auction guaranteed price is often higher than the highest daily market electricity price. This creates a problem, because if the battery storage is an extra cost and does not bring the extra income, the profitability of such installation is very doubtful. The precise data are shown in the tables below.

Table 18 The step-by-step income results for exemplary year 1 of the investment in Poland – Variant 1

	Unit	January	February	March	April	May	June	July	August	September	October	November	December
Amount of stored energy	MWh	34,19	48,32	62,00	60,00	62,00	60,00	62,00	62,00	60,00	62,00	32,34	29,01
Amount of energy sold through auction system	MWh	129,92	183,62	337,15	484,85	600,10	549,11	534,88	514,86	377,99	246,31	122,88	110,25
Amount of energy sold to the grid	MWh	6,84	9,66	17,74	25,52	31,58	28,90	28,15	27,10	19,89	12,96	6,47	5,80
Income from selling stored energy	EUR	1658,93	2314,72	2643,48	2367,40	2454,71	3265,16	3786,25	3503,13	3980,13	3920,57	2135,87	2003,50
Income from selling through an auction system	EUR	7684,98	10861,87	19943,55	28680,84	35498,15	32481,98	31639,98	30455,53	22359,66	14569,99	7268,51	6521,44
Income from selling the remaining energy to the grid	EUR	380,12	537,25	986,46	1418,63	1755,83	1606,64	1564,99	1506,41	1105,96	720,67	359,52	322,57

Table 19 The step-by-step income results for exemplary year 1 of the investment in Poland – Variant 2

	Unit	January	February	March	April	May	June	July	August	September	October	November	December
Amount of energy sold through auction system	MWh	162,39	229,53	396,05	541,85	659,00	606,11	593,78	573,76	434,99	305,21	153,59	137,81
Amount of energy sold to the grid	MWh	8,55	12,08	20,84	28,52	34,68	31,90	31,25	30,20	22,89	16,06	8,08	7,25
Income from selling through an auction system	EUR	9606,23	13577,33	23427,70	32052,60	38982,30	35853,73	35124,13	33939,68	25731,42	18054,13	9085,64	8151,79
Income from selling the remaining energy to the grid	EUR	475,15	671,57	1158,79	1585,40	1928,16	1773,41	1737,33	1678,74	1272,74	893,00	449,40	403,21

Table 20 Total income during the year in Poland - Variant 1

Year	Income 1, EUR (selling stored energy)	Income 2, EUR (RES auction)	Income 3, EUR (selling to the grid)	Total income, EUR
1	34 033,86	247 966,48	12 265,04	294 265,38
2	33 993,29	246 588,97	12 196,90	292 779,17
3	33 952,93	245 218,35	12 129,11	291 300,38
4	33 912,77	243 854,57	12 061,65	289 829,00
5	33 872,81	242 497,62	11 994,54	288 364,97
6	33 833,05	241 147,45	11 927,75	286 908,25
7	33 793,49	239 804,04	11 861,30	285 458,83
8	33 754,12	238 467,34	11 795,19	284 016,65
9	33 697,80	237 152,57	11 730,16	282 580,52
10	33 639,31	235 846,55	11 665,56	281 151,41
11	33 581,11	234 547,06	11 601,28	279 729,45
12	33 523,21	233 254,06	11 537,33	278 314,60
13	33 465,59	231 967,53	11 473,69	276 906,82
14	33 408,27	230 687,44	11 410,37	275 506,08
15	33 351,23	229 413,74	11 347,37	274 112,34
16	33 294,47	0,00	225 693,78	258 988,25
17	33 238,00	0,00	224 446,35	257 684,35
18	33 181,81	0,00	223 205,15	256 386,96
19	33 125,90	0,00	221 970,16	255 096,06
20	33 070,28	0,00	220 741,34	253 811,61
21	33 014,93	0,00	219 518,66	252 533,59
22	32 959,85	0,00	218 302,10	251 261,96
23	32 905,05	0,00	217 091,63	249 996,68
24	32 850,53	0,00	215 887,20	248 737,73
25	32 796,28	0,00	214 688,80	247 485,08

Table 21 Total income during the year in Poland - Variant 2

Year	Income 2, EUR (RES auction)	Income 3, EUR (selling to the grid)	Total income, EUR
1	283 586,68	14 026,90	297 613,59
2	282 168,75	13 956,77	296 125,52
3	280 757,91	13 886,98	294 644,89
4	279 354,12	13 817,55	293 171,67
5	277 957,35	13 748,46	291 705,81
6	276 567,56	13 679,72	290 247,28
7	275 184,72	13 611,32	288 796,04
8	273 808,80	13 543,26	287 352,06
9	272 439,75	13 475,55	285 915,30
10	271 077,56	13 408,17	284 485,73
11	269 722,17	13 341,13	283 063,30
12	268 373,56	13 274,42	281 647,98

13	267 031,69	13 208,05	280 239,74
14	265 696,53	13 142,01	278 838,54
15	264 368,05	13 076,30	277 444,35
16	0,00	260 218,40	260 218,40
17	0,00	258 917,30	258 917,30
18	0,00	257 622,72	257 622,72
19	0,00	256 334,60	256 334,60
20	0,00	255 052,93	255 052,93
21	0,00	253 777,67	253 777,67
22	0,00	252 508,78	252 508,78
23	0,00	251 246,23	251 246,23
24	0,00	249 990,00	249 990,00
25	0,00	248 740,05	248 740,05

Variable costs

The initial investment costs calculations and results were already presented in the previous chapter. The variable costs (Table 22 and Table 23) are labour costs, operational and maintenance costs and bank loan. Under the set assumptions, the labour costs is calculated and the values are between more than 4000 up to more than 7000 EUR a year, this is a relatively small contribution in the yearly cash flow. Operational and maintenance costs are several thousand EUR a year and do not differ much between both Variants. The bank loan is definitely the biggest variable cost contributing to the cash flow. The bank loan starts at the payment of almost 350 000 EUR in the first year in the Variant 1 and almost 300 000 EUR in the Variant 2 and it decreases gradually for the next 10 years of the loan duration. The conclusion here is that if there would be possible to get the a government funding or a different kind of support financing, it would decrease the investment cost and a bank loan, giving a better opportunity for the investments to become profitable sooner.

Table 22 The yearly variable costs – Variant 1

Year	**Labor costs, EUR/year**	**Operational and maintenance costs, EUR/year**	**Bank loan**	
			Capital, EUR/year	**Interest, EUR/year**
0	0,00	0,00	0,00	0,00
1	4 484,34	13 956,94	279 138,72	57 781,71
2	4 574,03	14 236,07	279 138,72	51 361,52
3	4 665,51	14 520,80	279 138,72	44 941,33
4	4 758,82	14 811,21	279 138,72	38 521,14
5	4 853,99	15 107,44	279 138,72	32 100,95
6	4 951,07	15 409,58	279 138,72	25 680,76
7	5 050,10	15 717,78	279 138,72	19 260,57
8	5 151,10	16 032,13	279 138,72	12 840,38
9	5 254,12	16 352,77	279 138,72	6 420,19
10	5 359,20	16 679,83	279 138,72	0,00

11	5 466,39	17 013,43	0,00	0,00
12	5 575,71	17 353,70	0,00	0,00
13	5 687,23	17 700,77	0,00	0,00
14	5 800,97	18 054,78	0,00	0,00
15	5 916,99	18 415,88	0,00	0,00
16	6 035,33	18 784,20	0,00	0,00
17	6 156,04	19 159,88	0,00	0,00
18	6 279,16	19 543,08	0,00	0,00
19	6 404,74	19 933,94	0,00	0,00
20	6 532,84	20 332,62	0,00	0,00
21	6 663,49	20 739,27	0,00	0,00
22	6 796,76	21 154,06	0,00	0,00
23	6 932,70	21 577,14	0,00	0,00
24	7 071,35	22 008,68	0,00	0,00
25	7 212,78	22 448,86	0,00	0,00

Table 23 The yearly variable costs – Variant 2

Year	**Labor costs, EUR/year**	**Operational and maintenance costs, EUR/year**	**Bank loan**	
			Capital EUR/year	**Interest, EUR/year**
0	0,00	0,00	0,00	0,00
1	4 484,34	11 482,07	229 641,38	47 535,77
2	4 574,03	11 711,71	229 641,38	42 254,01
3	4 665,51	11 945,94	229 641,38	36 972,26
4	4 758,82	12 184,86	229 641,38	31 690,51
5	4 853,99	12 428,56	229 641,38	26 408,76
6	4 951,07	12 677,13	229 641,38	21 127,01
7	5 050,10	12 930,67	229 641,38	15 845,26
8	5 151,10	13 189,29	229 641,38	10 563,50
9	5 254,12	13 453,07	229 641,38	5 281,75
10	5 359,20	13 722,14	229 641,38	0,00
11	5 466,39	13 996,58	0,00	0,00
12	5 575,71	14 276,51	0,00	0,00
13	5 687,23	14 562,04	0,00	0,00
14	5 800,97	14 853,28	0,00	0,00
15	5 916,99	15 150,35	0,00	0,00
16	6 035,33	15 453,35	0,00	0,00
17	6 156,04	15 762,42	0,00	0,00
18	6 279,16	16 077,67	0,00	0,00
19	6 404,74	16 399,22	0,00	0,00
20	6 532,84	16 727,21	0,00	0,00
21	6 663,49	17 061,75	0,00	0,00
22	6 796,76	17 402,99	0,00	0,00
23	6 932,70	17 751,05	0,00	0,00
24	7 071,35	18 106,07	0,00	0,00
25	7 212,78	18 468,19	0,00	0,00

Cash flow

This paragraph represents cash flow data in the form of the summary table with comparison of the yearly values throughout the lifetime of the modelled projects. Except from it, the graphs below - Figure 41 and Figure 42 - represent the average relations between all kinds of the incomes and the costs of the installations, showing all the flows in a year. It visualises well which kinds of notions contributes on which scale to the final results (the visualization is done in the first year of operation, where there is not profit generated, so the tax is not present). It also shows how big of a cost is the bank loan compared to the rest of them. The labour and operational costs are only a small percentage. The cash flow in the variant with the battery storage stays negative for the longer period of time, while in the standard option of photovoltaic farm without the BESS, the cash flow is almost immediately, after the first year of operations, positive. In the final year, the values of the cash flow are somewhat similar with a difference of around 10 000 EUR in favour of the Variant 2 (see Table 24). In conclusion, a single bank loan payment for the installation is higher that the overall income during that year.

Table 24 Year by year cash flow values for Variant 1 and 2

Year	Cash flow, Variant 1, EUR	Cash flow, Variant 2, EUR
0	-2 791 387,16	-2 296 413,84
1	-61 096,33	3620,72
2	-56 531,18	6434,95
3	-51 965,97	9250,03
4	-47 400,89	12 065,83
5	-42 836,13	14 882,22
6	-38 271,88	17 699,05
7	-82 990,33	20 516,19
8	-29 145,68	23 333,50
9	-24 585,28	26 150,83
10	-20 026,33	28 968,03
11	208 372,21	213 516,27
12	206 862,00	212 054,56
13	205 350,24	210 592,28
14	163 918,34	209 129,27
15	202 321,37	207 665,38
16	189 676,67	193 371,07
17	188 218,43	193 318,28
18	186 757,42	191 941,57
19	185 293,47	190 563,54
20	183 826,39	189 184,04
21	142 437,55	187 802,90
22	180 882,02	186 419,96
23	179 404,34	185 035,05
24	177 922,74	183 648,02
25	176 436,99	182 258,68

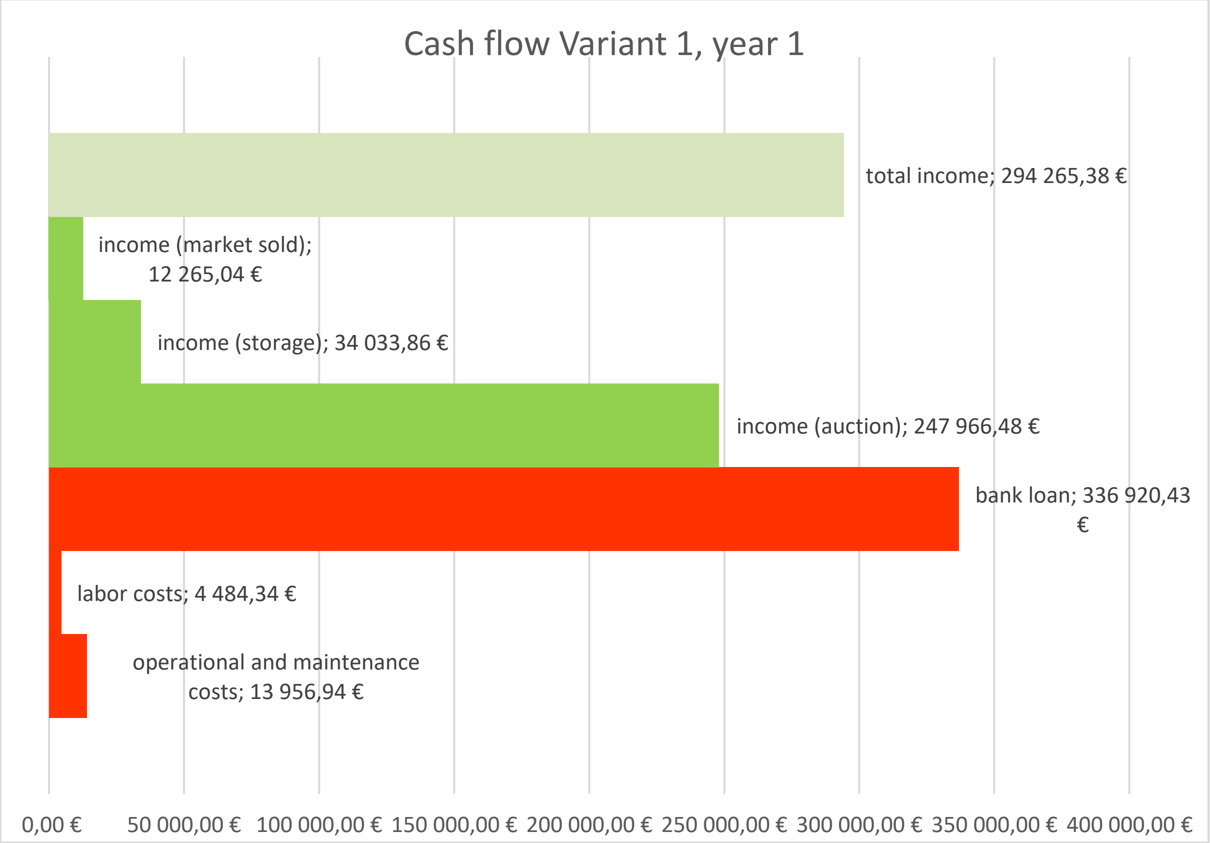

Figure 41 Cash flow representation for Poland in the year 1 of the investment for Variant 1

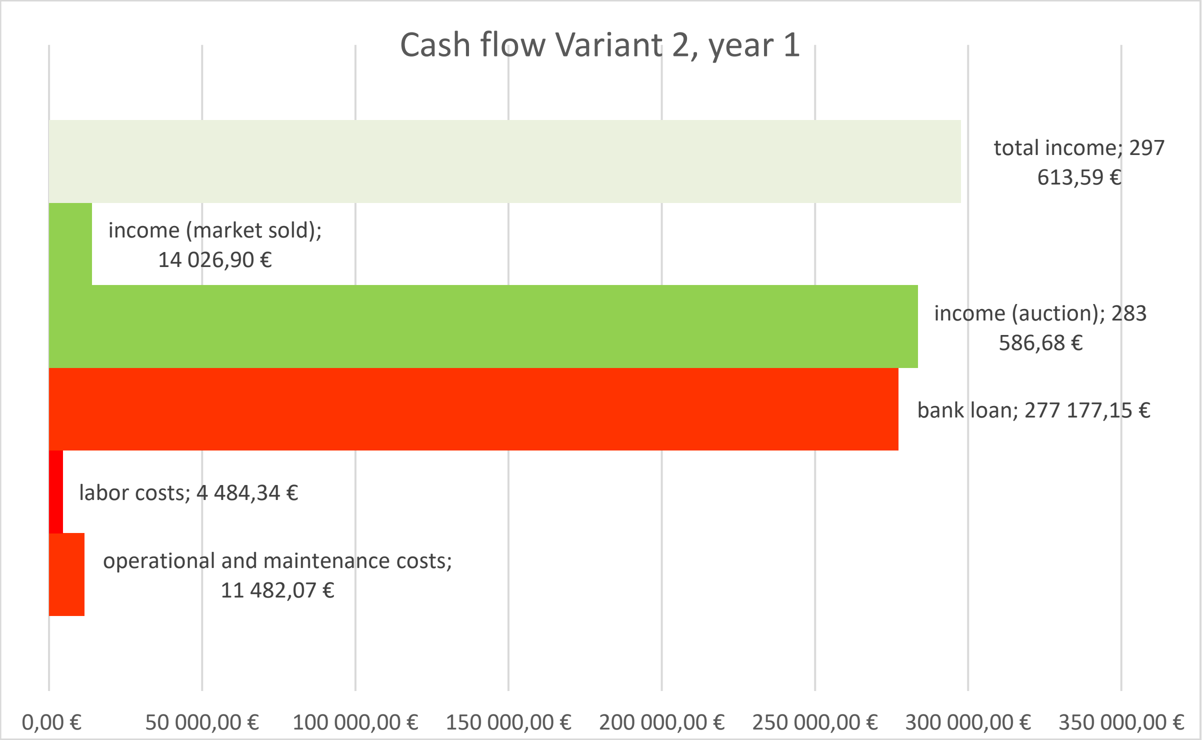

Figure 42 Cash flow representation for Poland in the year 1 of the investment for Variant 2

NPV

The Figure 43 and Figure 44 show the change of the Net Present Value parameter through the years of the project realisation. The Table 25 NPV results for Variant 1 and 2 represent specific values of the NPV parameter throughout the projects' lifetime. As can be seen, the feasibility criteria is not met (NPV<0) in both cases of the photovoltaic farm solutions. This is due to extremely high initial cost with mediocre incomes both in Variant 1 and Variant 2. This again raises the question of how much the government or big investors could help, for the projects realised in conditions like those in Poland. For the shape of the first 10 years of the graph, there are responsible huge bank loan yearly payments. After giving back all the borrowed money, the installation's feasibility (in the form of NPV indicator) rises rapidly. The NPV for the installation of only a photovoltaic farm (where the initial investment cost is obviously lower), at the end of the assumed lifetime, is on the edge of becoming feasible, which again raises the questions for the future funds for such projects. Also the tax of 19% plays a he role in the NPV not being able to reach the 0 value. In conclusion, the Variant 2 - without the battery system – even though it cannot be described as "profitable" is surely closer to the making profit, with a possibility of reaching it under a few adjustments. The Variant 1 does not have a chance for NPV>0 unless the funding for the projects comes from the outside.

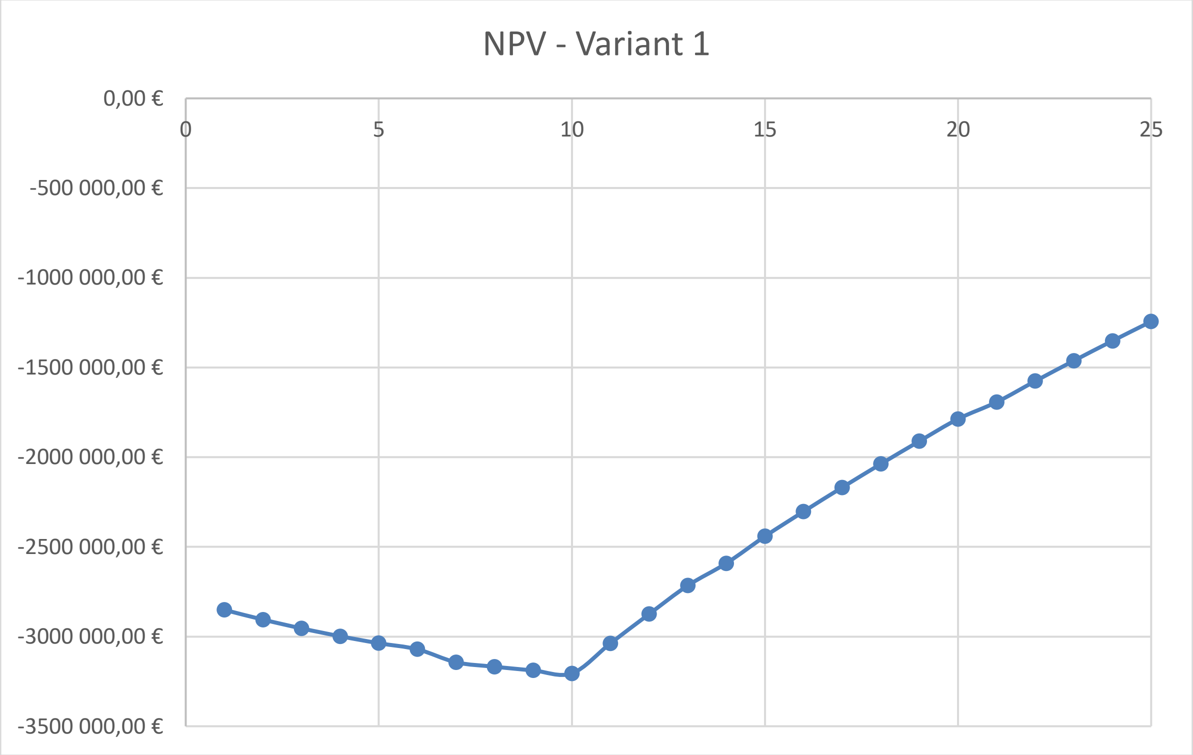

Figure 43 Year-by-year Net Present Value representation for Variant 1

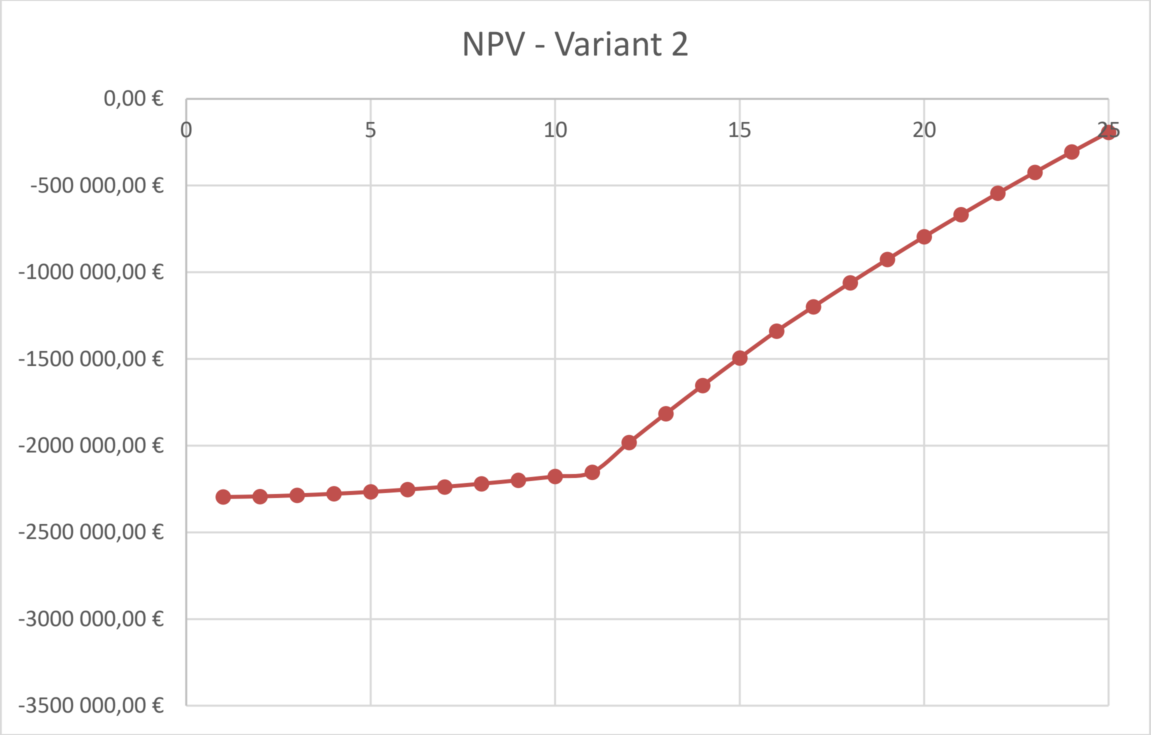

Figure 44 Year-by-year Net Present Value representation for Variant 2

Table 25 NPV results for Variant 1 and 2

Year	NPV Variant 1	NPV Variant 2
0	-€ 2 791 387,16	-€ 2 296 413,84
1	-€ 2 848 880,61	-€ 2 292 864,11
2	-€ 2 900 871,96	-€ 2 286 679,04
3	-€ 2 947 554,75	-€ 2 277 962,53
4	-€ 2 989 117,22	-€ 2 266 815,56
5	-€ 3 025 742,46	-€ 2 253 336,28
6	-€ 3 057 608,50	-€ 2 237 620,02
7	-€ 3 127 791,38	-€ 2 219 759,44
8	-€ 3 150 653,52	-€ 2 199 844,53
9	-€ 3 169 262,33	-€ 2 177 962,68
10	-€ 3 183 776,93	-€ 2 154 198,80
11	-€ 3 016 190,87	-€ 1 982 475,56
12	-€ 2 851 262,17	-€ 1 815 271,98
13	-€ 2 690 745,85	-€ 1 652 477,30
14	-€ 2 564 786,70	-€ 1 493 983,45
15	-€ 2 412 772,69	-€ 1 339 685,01
16	-€ 2 241 722,38	-€ 1 198 824,67
17	-€ 2 075 245,59	-€ 1 060 763,99
18	-€ 1 913 229,80	-€ 926 374,30
19	-€ 1 755 565,23	-€ 795 565,62
20	-€ 1 602 144,82	-€ 668 250,19

21	-€ 1 479 201,35	-€ 544 342,38
22	-€ 1 333 958,53	-€ 423 758,67
23	-€ 1 192 654,22	-€ 306 417,60
24	-€ 1 055 191,49	-€ 192 239,68
25	-€ 921 475,80	-€ 81 147,39

Table 26 The profitability indicators’ values for Variant 1

Indicator	Unit	Value
IRR	%	-0,90%
DPB	year	0,00
SPB	year	0,00

Table 27 The profitability indicators’ values for Variant 2

Indicator	Unit	Value
IRR	%	1,78%
DPB	year	0,00
SPB	year	20,65

According to the Table 25 NPV results for Variant 1 and 2, Table 26 and Table 27 The profitability indicators’ values for Variant 2 tTable 25 NPV results for Variant 1 and 2he conclusions are as follows. The Net Present Values for both project stay negative through the assumed lifetime of the project. In the Variant 1, the IRR<a (a=2%), which confirms the unfeasibility of the project, so that is why the payback values are 0. This means that the Variant 1 of the project is not economically justified. In the Variant 2 of the investment, the IRR<a slightly, but that unfortunately is also meaning that the project is unfeasible. What is interesting in the Variant 2, is that the Simple Payback has a value of a bit less than 21 years, meaning that the break-even point is reached and the initial investment is returned.

Sensitivity analysis

The sensitivity analysis is the tool for checking how much does the chosen key parameter change the overall outcome of the project. In the case of this sensitivity analysis - Figure 45 and Figure 46 – the shown below graphs represent how much the change in the investment cost and electricity market price would influence the NPV of the project in both variants.

In the case of the Figure 45, the decrease of the investment cost by 20% still would not cause the NPV to reach 0 or above. The market electricity prices does not change the outcome in this case significantly. In conclusion, the Variant 1 would have to have more funding than 20% to become somewhat feasible.

For the Variant 2 of the work, presented on the Figure 46, even a few percentage decrease of the investment cost makes the project profitable, meaning that a few adjustments, maybe cheaper solutions here and there could justify the project realisation. The similar situation is connected with sensitivity analysis of the market electricity price for the Variant 2. The rise of the price by 5% makes the project's NPV>0. The fact that electricity price are expected to grow in the following years, could also contribute to the better financial situations of renewable energy sources projects.

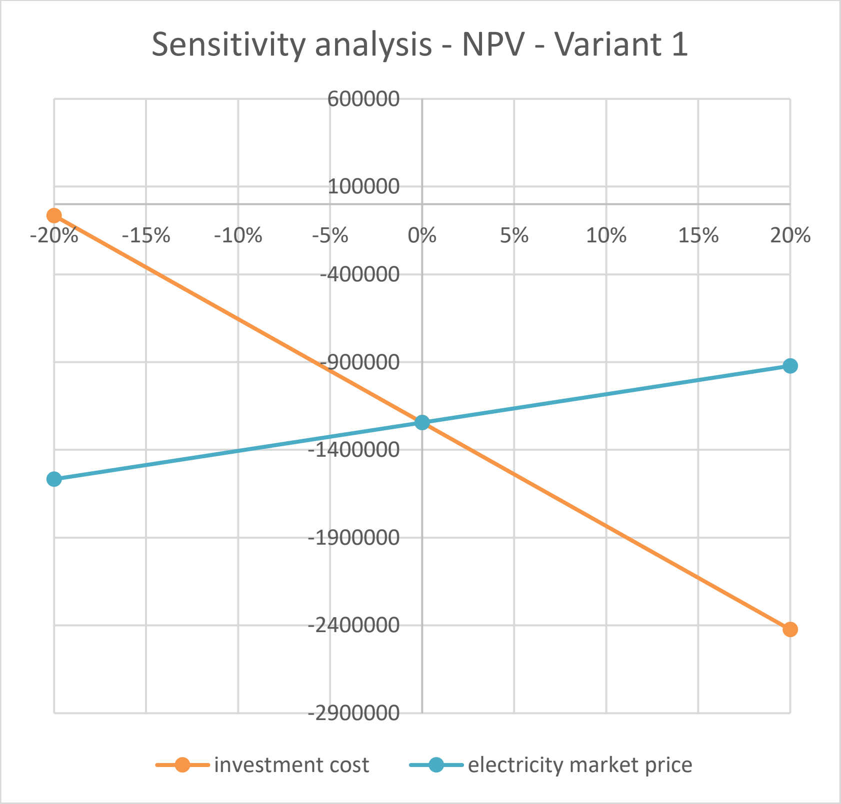

Figure 45 Representation of the influence of the change in investment cost and electricity market price on the NPV of Variant 1

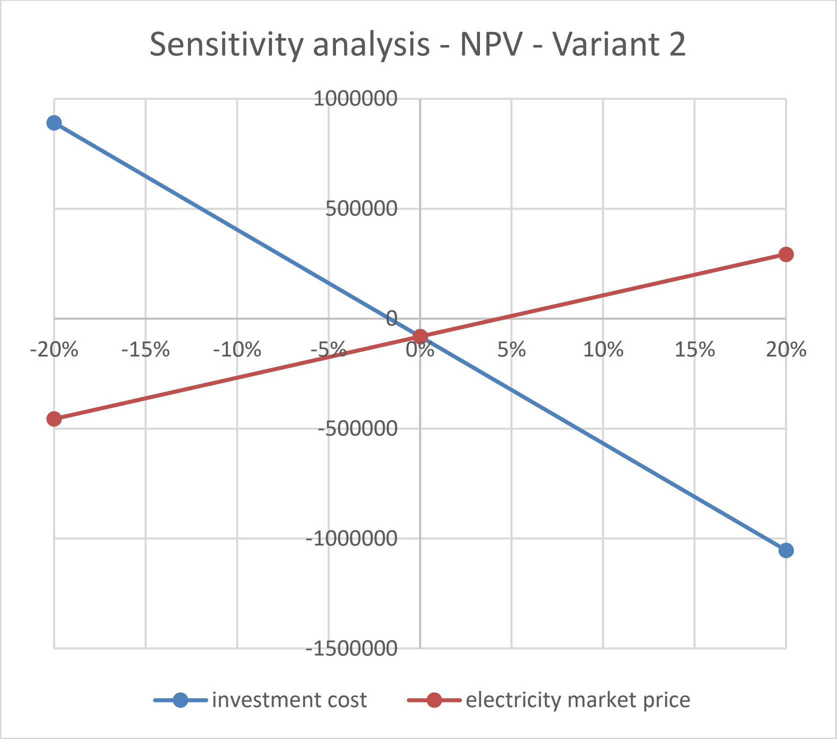

Figure 46 Representation of the influence of the change in investment cost and electricity market price on the NPV of Variant 2

Chapter 6

Conclusions and future directions

This section summarizes the work done during the project. It touches on all of the ideas mentioned, sums up a model, calculation and the results. This is all done to draw conclusions and point the directions for the development of the similar projects.

Conclusions

The Renewable Energy Sources Market is fast-developing one which on one hand can mean many amazing opportunities, that solve many serious global problems. On the other hand however, such direction for development creates many new challenges that need our constant, iterative adjustments. The advantages of course are much bigger than the disadvantages so any green initiatives that could potentially help our planet to fight the generations of pollution and climate changes should be, by all means, supported. In the realm of Energy Engineering, the continuous support invented for helping the humanity should be always applauded. The solutions that were tackled in this paper, generally play a huge role in the energy policies in most parts of the European Union and other developed counties. This is particularly why the big-scale installations like photovoltaic farms and battery energy storage systems that support the national grids and increase the energy safety are so interesting to check for profitability and possible kinds of solutions.

The work considered a development of the model of the photovoltaic farm connected to the battery energy storage system. Firstly, the study of the climatic conditions and the market structures were investigated. Then later auction systems were explained and the photovoltaic energy and energy storage were revised. The methodology of the calculations of the energy production, energy storage scenarios and the economic assessment were presented. After that the results were explained so that also the conclusions could be drawn.

The results of the analysis show a perspective on the energy production in two different countries – Poland and Portugal and also the economic aspects of actually constructing such photovoltaic farm with and without the battery energy storage system for the chosen location. A 5 MW PV farm can change a lot the local communities' energy mix structure. With more and more of such solutions connected to the adequately modernised grids, the whole energetic system could become more reliable and up-to-date.

The actual analysis and results presented show that the challenges of building and running such an investment are multi-dimensional and often difficult. For example, in the 2021 polish economy, the 5MW PV farm with brand new Li-Ion battery storage system installed has no change of feasibility on its own. Even the 5 MW PV farm alone during its lifetime of operation is on the verge of becoming slightly feasible, but this happens much past the 20 years of operation, which was explained in the previous chapter. This of course does not mean that these solutions are not appropriate, it just brings us to the very important conclusion: environmentally-friendly renewable energy solution should receive a constant support from the government and other organisations to continue the energy transition in countries where it is much needed. Poland is one of the countries where the meteorological conditions may not be optimal for either the wind or solar energy, but that should never stop the transition that has to be made for the pollution decrease in soil, air and water.

The sensitivity analysis gives a great hope for the future and can give a clue how the projects like this could become feasible in Poland. If the photovoltaic panels and their installation could become, for example, 20% cheaper in the future or if the government would be willing to pay some of the investment cost, such project would have a huge potential of being successful and actually feasible. If this is kind of not the option, the big hope for such project can be changing electricity selling prices. When they rise, especially during the period of the lifetime of the project when the auction tariff has already finished, it can bring a significant extra income while evaluating such project. Also, the taxes play a huge contributor to such projects. Giving away 19% of the profit you have made, drastically changes the final outcome of the project.

In the nearest future, European Union countries need to aim at the targets set by the EU Parliament. The recommendation for the country in situation like this described in Poland should support development of the big-scale photovoltaic farms like the one developed in this work. When it comes to the battery energy storage systems, in the very near future they will become necessary when increasing the share of renewables in the traditionally-built national grids. They will help in stabilising the grid and protecting the end-customers from the renewable energy sources threats connected with disturbing the constant supply of electricity.

In conclusion, although the results may not seem as optimistic as one could have hoped, the upcoming perspectives for development of photovoltaic energy and battery energy storage units have a huge potential. It should never be wasted. It is a relatively simple and known path leading directly to the better and cleaner world for ourselves and the next generations.

Future directions

The work in this paper is complete in the sense that the calculations were finished and on their basis the proper conclusions were drawn. This does not mean that the research should stop at this point. There are many future directions and prospects that could be followed to improve a model like this. As for the revision, the model consisted of the photovoltaic farm of the set power of 5 MW built from 240 W power photovoltaic panels, on more than 3 ha of land. Next, to check how well the Li-Ion battery energy storage system could generate the extra profit thanks to storing the energy in their peak production points, a 2MWh capacity storage was proposed. Giving the assumptions made, the charging of the system lasted for two hours when the electricity production was the highest and the two hours of discharging were when the market electricity prices were the highest to maximize the profit in the chosen circumstances. Knowing these results, thanks to the comparison of the energy markets, auction systems, the stage of development of the renewable technologies in Poland and Portugal, for further analysis it was chosen to go with application of the model in Poland. There are reasons for that, meaning mainly that in Poland the share of renewables in the energy mix is much smaller than in Portugal and promoting such solutions connected with photovoltaic energy is much anticipated. Doing the economic assessment of the project in Poland gave the clue on what could be pointed out as the future directions when expanding this work.

The most important conclusion of the assessment was that a big-scale photovoltaic farm modelled with the given assumptions is not economically feasible: both in the case of the addition of the battery energy storage system and without it. In the future choices for the development of the projects, some new routes could be taken. For example, there could be found new ways to decrease the initial investment cost: try to get a government of European Union funding. In case of the photovoltaic farm alone, this is the direction that could directly turn the project into the feasible one. Also, maybe panels of the higher power could be checked, to utilise less land, which can mean savings as well. As the project would develop, the new ways of incorporating more working hours of the battery energy storage system should be considered. In the future the battery storage system could serve as the gird balancing device. In countries like Poland, the grid is often overloaded and implementing storage, could be a way to balance the loads, without big losses.

Another interesting direction for future development of similar models, would be checking different option of the battery energy storage systems. Another type of electrodes/electrolytes combination could be checked. Also, a merging technology in energy storage is using second-life used car batteries instead of recycling the noble parts of them after they have to be replaced in the electric car. For now, the profitability of this solution is very doubtful, but in the future it is definitely worth checking.

For the sake of the improvement of the feasibility of the model, in the sensitivity analysis other factors' influence could be verified. As an example – maybe a difference in location could be checked – in different parts of Poland, the irradiation differs: it gets the highest values in the southern-east of the country, which would increase the power production. Also, if the investment like this was to happen a few years from now, the prices of the equipment would probably be lower.

To sum up, this kind of model has a huge potential to be further studied from many aspects. Some of them can directly bring profits to the project of the photovoltaic farm with and without the battery storage. Nevertheless changing any of the aspects to increase the profitability or designing a system similar to the one like in this paper, the renewable energy sources should be constantly supported and invested in to improve the environment and our lives.

References

[1] „U.S. Department of Energy SmartGrid.gov,” [Online]. Available: https://www.smartgrid.gov/the_smart_grid/smart_grid.html.

[2] „Electrical Energy Storage,” *The International Electrotechnical Commission.*

[3] „DIRECTIVE (EU) 2018/2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the promotion of the use of energy from renewable sources,” *Official Journal of the European Union,* 2018.

[4] GSA, „Global Solar Atlas Report Poland,” Blizanowek, 2020.

[5] GSA, „Global Solar Atlas Report Portugal,” Vide, 2020.

[6] O. Grygar, „Accumulation of electricity,” Prague, 2014.

[7] „IEA CO2 Emissions from Fuel Combustion,” [Online]. Available: https://www.iea.org/subscribe-to-data-services/co2-emissions-statistics.

[8] „IEA Electricity Information,” 2020. [Online]. Available: https://www.iea.org/subscribe-to-data-services/electricity-statistics.

[9] „Global Solar Atlas,” [Online]. Available: https://globalsolaratlas.info/map?c=11.609193,8.4375,3.

[10] „IEA Renewables Information,” 2020. [Online]. Available: https://www.iea.org/subscribe-to-data-services/renewables-statistics.

[11] „Zielony Zwrot Taurona,” [Online]. Available: https://www.tauron.pl/tauron/o-tauronie/tauron-dla-otoczenia/zielony-zwrot.

[12] PGE i Group, „PGE uruchomiła pierwszy w Polsce magazyn energii elektrycznej,” [Online]. Available: https://www.gkpge.pl/relacje-inwestorskie/magazyny-energii.

[13] „Energy Regulatory Office,” Poland, [Online]. Available: https://www.ure.gov.pl/en/about-us/presidents-duties/22,Presidents-duties.html.

[14] Urząd Regulacji Energetyki, „Informacja Prezesa Urzędu Regulacji Energetyki Nr 38/2021,” Warszawa, 2021.

[15] „Electricity Generation by Energy Sources in Mainland Portugal,” May 2021. [Online]. Available: https://www.apren.pt/en/renewable-energies/production.

[16] „AMARELEJA PHOTOVOLTAIC PLANT,” [Online]. Available: https://www.acciona.com/projects/amareleja-photovoltaic-plant/?_adin=02021864894.

[17] „Entidade Reguladora dos Serviços Energéticos,” Wikipedia, [Online]. Available: https://pt.wikipedia.org/wiki/Entidade_Reguladora_dos_Servi%C3%A7os_Energ%C3%A9ticos.

[18] AFRY Management Consulting, „Portuguese Auction 2020 Review”.

[19] „How do Photovoltaics Work?,” [Online]. Available: https://science.nasa.gov/science-news/science-at-nasa/2002/solarcells.

[20] O. C. O. Alireza Khaligh, „Enegy Sources,” w *Power Electronics Handbook*, 2018.

[21] V. Aggarwal, „Most efficient solar panels: solar panel cell efficiency explained,” energysage, Feb 2021. [Online]. Available: https://news.energysage.com/what-are-the-most-efficient-solar-panels-on-the-market/.

[22] Office of Energy Efficiency & Renewable Energy, „PV Cells 101: A Primer on the Solar Photovoltaic Cell,” 2019. [Online]. Available: https://www.energy.gov/eere/solar/articles/pv-cells-101-primer-solar-photovoltaic-cell.

[23] EDP, „EDP deploys its largest solar farm with energy storage in the country,” [Online]. Available: https://www.edp.com/en/news/2019/04/09/edp-deploys-its-largest-solar-farm-energy-storage-country.

[24] M. M. Biswas, M. S. Azim, T. K. Saha, U. Zobayer i M. Urmi, „Towards Implementation of Smart Grid: An Updated Review on Electrical Energy Storage Systems,” *Smart Grid and Renewable Energy,* tom 4, pp. 122-132, 2013.

[25] Circular Energy Storage Research and Consulting, „Prices for used batteries are higher than for new batteries – this is why,” [Online]. Available: https://circularenergystorage.com/articles/2021/1/15/prices-for-used-batteries-are-higher-than-for-new-batteries-this-is-why.

[26] J. Paska i M. Kłos, „Magazynowanie energii elektrycznej - technologie, zastosowania, koszty,” Politechnika Warszawska.

[27] „ENF Solar Panel Directory,” [Online]. Available: https://www.enfsolar.com/pv/panel-datasheet/crystalline/29331.

[28] „Tesla Powerpack,” [Online]. Available: https://www.tesla.com/pl_PL/powerpack.

[29] „IEA Energy Storage,” [Online]. Available: https://www.iea.org/reports/energy-storage.

[30] REN, „Precos Mercado Spot Portugal,” [Online]. Available: https://www.mercado.ren.pt/PT/ELECTR/INFOMERCADO/INFOP/MERCOMEL/Paginas/Precos.aspx.

[31] PSE, „Rynkowa cena energii elektrycznej (RCE),” [Online]. Available: https://www.pse.pl/dane-systemowe/funkcjonowanie-rb/raporty-dobowe-z-funkcjonowania-rb/podstawowe-wskazniki-cenowe-i-kosztowe/rynkowa-cena-energii-elektrycznej-rce.

[32] „Ile kosztuje farma fotowoltaiczna?,” [Online]. Available: https://heliosstrategia.pl/faq/koszt-budowy-farmy-fotowoltaicznej/.

[33] „Ceny gruntów rolnych w 2020 roku,” [Online]. Available: https://blog.ongeo.pl/ceny-gruntow-rolnych-w-roku.

[34] „Bateryjny magazyn energii. Ile kosztuje i co składa się na jego cenę?,” [Online]. Available: https://www.gramwzielone.pl/magazynowanie-energii/33914/bateryjny-magazyn-energii-ile-

kosztuje-i-co-sklada-sie-na-jego-cene.

[35] URE, „Raport Krajowy Prezesa Urzędu Regulacji Energetyki,” 2020.