Optimal design and economic analysis of a grid-connected PV systems operating under Net Metering or Feed-In-Tariff support mechanisms – case study of a warehouse in Poland.

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ABSTRACT

The thesis focuses on cost effective design of the grid-connected rooftop photovoltaic (PV) system. The work is based on the case study of a warehouse located in Poland. The work aims to find the optimal system configuration, indicated by the highest Net Present Value (NPV) of an investment, for the scenario of Net-Metering (NM) and Feed-In-Tariff (FIT) support mechanisms. PVsyst software was used to simulate performance of various system sizes, tilts of the modules, as well as types and capacities of PV panels and inverters. Financial analysis was performed for each variant, by treating PV generation data in economic evaluation model. Since the benefits of a PV system derive from minimization of electricity imports from the grid, it was necessary to determine the building's electricity demand, using the bottom-up method. Preliminary analysis, based on generic components, allowed to estimate the optimal size of the system. Detailed simulations of the selected modules and inverters were later conducted in the specified ranges. Results of the simulation showed that the support mechanism has a substantial impact on the optimal size of the installation. For the analysed case, the system capacity optimized for NM was nearly twice bigger, than for FIT one. Comparing installations with the same nominal powers, the NM support system proves to be more beneficial than FIT, as it generates significantly larger NPVs. The sensitivity analysis showed that the three parameters most affecting the NPV of the systems studied were: electricity prices, the building's electricity demand and capital expenditures.

Keywords: Economic assessment, Electricity demand estimation, Feed-In-Tariff, Net-Metering, Net Present Value PV design optimization

1. Introduction

Human society faces major challenges to keep up with the growing need for energy, and it finally became obvious to the world's governors that necessity for the major transitions in the global energy sector is undeniable. According the World Energy Outlook 2018, published by the International Energy Agency (IEA), and the model of New Policies Scenario, it is predicted that the energy demand will increase by at least 25% in the next 20 years, requesting more than 2 trillion $ each year to finance the necessary investments in the new energy supply [1]. At the forefront of this transition are renewable energy technologies, which are by far the fastest growing energy sector [2]. One of the energy sources that seems particularly appealing is solar energy. On average, solar power reaching the earth's surface is of about 90 000 TW. It has been estimated that around 1000 TW is technically recoverable out of it. In comparison, current global power consumption is roughly 18 TW and in 2050 it is predicted to reach about 30 TW [3]. This makes solar a virtually limitless energy resource, which offers reliable energy production with low embodied carbon emissions.

Construction of grid-tie solar PV system may seem like a simple job. The system is composed of a number of photovoltaic modules, that are connected to an inverter, which is later linked to a building's electrical grid through a switchgear and energy meter. Regardless of this apparent straightforwardness, designing a PV generation system that is efficient, reliable, safe in operation, compliant with the regulations, and very importantly, economically optimized is a complex, time consuming, and not always well executed task [4]. It requires employing a number of interrelated models describing solar geometry, assessing available solar radiation from the historic meteorological data, computing electrical properties of a solar cell and an inverter, and comparing PV production with the building's electricity demand.

In the last years, investments in a rooftop PV systems, which are meant to reduce building's electricity imports from the grid, are booming. Such systems generate their value from a displacement of electrical energy or sales of a surplus generated electricity. Thus, to assess the financial attractiveness of the PV installation, it is necessary to estimate current and future electricity demand of the examined building. Given that the building is already in operation, and has a building management system or is equipped with the smart metering devices, the task of finding the electrical load should in principle be simple, as the electricity consumption data can be accessed easily. Several methods addressing modelling and predicting the electricity load profiles in such cases can be found in the literature. Barak and Sadegh [5] treat all analyzed buildings as a black-box, and based on their present energy consumption profiles they forecast the future demand by applying artificial intelligence algorithms. Gruber et al. [6] describes how a residential energy consumption can be predicted by combining data recorded by smart-metering devices with a statistical forecasting methods. Even though very precise, the above mentioned sophisticated methods require access to the electricity consumption data, which is very often scarce or not available at all. In case of its absence, present energy bills can be used to assess the energy needs and produce an estimate of daily electricity consumption. However, if the building has not yet been constructed, which was a case of this work, the task of estimating the electricity demand becomes more challenging. This is due to the incomplete and imperfect information regarding the electrical equipment that is the be used in the building, as well as the unknown work and behavior patterns of the building users. To answer this problem, the literature points out that the most common method of estimating the load profiles, when the consumption data is not accessible, is the bottom-up approach. The study of Chuan et al. [7] describes this method, in which facility's load is estimated based on a detailed list of electrical appliances, their electrical requirements and the consumption patterns. Analysis done by Swan and Ugursal [8] indicate that in order to achieve a good accuracy of the model, an investigation of a behavioural patterns regarding the use of electrical devices is highly recommended. Such analysis can be done through personal interviews of specific questionnaire. Both Sepher et al. [9] and Paatero [10] compared the measured energy profiles with the ones estimated with the bottom-up method, and suggested that this approach proves to be the best choice when load profiles need to be modelled from scratch.

Since the photovoltaic system considered in this work is to be located in Poland, the impact of snow cover on the operation of photovoltaic modules has been reviewed. Heidari et al. [11] analyzed how a snowfalls can influence the system's performance, and highlights the importance of taking into account seasonality of the weather, and in particular the effect of snowfall, when modelling the systems operating in cold climates. The study showed that the snow cover may significantly limit the solar radiation reaching the surface of the PV cells, which in turn results in dampening the electricity generation. On the other hand, Andenæs et al. [12] analyzed that due to the high reflectance of the snow, the reflected component of irradiance may increase, improving the performance of the photovoltaic system. Even a thin layer of snow pack will result in increasing the albedo - being the ratio of the amount of reflected irradiation to the amount of incidence irradiation – to the values between 0.7 and 0.9, in contrast to the standard 0.2 for the cases of no snow. In case the snow cover is present only on the ground, and the PV panels are clear, the electricity generation is expected to be slightly bigger. The situation however changes dramatically when also the PV cells are cover in snow. According to the research done by Perovich [13] even the relatively slight snow cover will reduce the electricity generation form PV panels to nearly nothing. The study claims that the first 2 cm of snow sheet are the most impactful on soiling loss, as they may reduce the light transmittance by as much as 90%. A snow cover of 10 cm will block around 95% of visible light and 99% of infrared one, halting the PV electricity generation completely. Paper produced by Andrews et al. [14] argues that snow covers are also very problematic due to the potential shading of PV cells, which depending on the circumstances may be uniform or partial. The uniform shading caused also for instance by cloud coverage, will just slightly reduced the performance of the PV system, however partial shading is much more critical to the operation of the PV system, as it triggers complex fluctuations in the balance of electric currents inside the conductive elements of the cells.

The leading issues faced by those who consider purchasing a PV system, is its economic viability. Over the last years number studies have been conducted to assess the financial attractiveness of equipping buildings with this technology. Orioli et al. [15] and Bernal et al. [16] studied the economic and environmental benefits of a grid-tied PV system using several financial indicators. Both suggested that the economic convenience of the PV system is best estimated by the means of a Net Present Value and a Discounted Payback Period. Their works analysed also the influences of different economic parameters, such as energy sale price, costs of initial investment and maintenance, as well as inflation on the profitability of the investment. Audenaert et al. [17] uses the cash flow projection method to evaluate the economic feasibility of investing in PV systems by companies, which are subjected to much higher corporate energy tariffs.

One of the factors that influence the economic viability of the investment are the regulations supporting development of the PV distributed generation systems. Dusonchet et al. [18],[19] presented an overview of main support policies in the European countries. The findings highlighted that the support models have a strong impact on profitability of the investments, however their efficiencies depends greatly on the details of each country's national law. Depending on the country, different regulations are in force. García-Álvarez et al. [20] analyzed the energy policies promoting distributed PV in EU and indicated that Feed In Tariffs, which is the most predominant support mechanism in EU, under which 70% of the self-consumption PV systems operate, has a positive, but not significant impact on the development of this technology in the EU region. Poullikkas [21] made an comparative economic evaluation of the Net Metering (NM) and Feed-In-Tariff (FIT) support mechanism, and researched how the profitability of the system changes, depending on the installed capacity. The study points out that due to the grid storage option of NM, the optimal size of the installation will be bigger than for FIT. The comparison revealed that the NM support model is financially more appealing, than FIT for the PV owners. When analyzing installations of the same capacity, study of Christoforidis et al. [22] shows that PV systems working under NM achieve lower LCOE. Moreover, they are likely to generate higher savings, which leads to a quicker pay-off, than the systems operating under FIT mechanism. The study concludes that the type of support mechanism has a significant impact on profitability of the system.

A notable volume of literature focuses on the optimization of production, system sizing and operating conditions of the PV systems. Mehleri et al. [23] describes the optimal tilt angle and orientation of the fixed-tilted PV modules at the any given location. The approach taken in this study maximizes the amount of global solar irradiance reaching the PV cells. The same topic has been also studied by Rowlands et al. [24], though the approach was different. Optimal tilt angles were found in respect to the highest global solar irradiance and later in respect to the maximum revenue generated by the solar system. It has been noticed that those angle are not the same, implying that the highest output performance doesn't always go together with the highest economic benefit. While designing the system it is crucial to know which one is prioritized.

Another difficulty is connected with an optimal sizing of the system. Mondol et al. [25] studied the optimal array and inverter sizes for the grid-connected systems. As a leading criterion the highest system output and system outputs per specific system cost were optimized. The study found that the optimal PV/inverter power ratio ranges from 1.1 to 1.3. Notton et al. [26] also researched the optimum PV/inverter sizing ratios, though maximizing the annual system's efficiency. Results were in line with those of Mondol et al.. Gong et al. [27] describe the optimization method of a large scale rooftop PV installation in which the nominal power of system is based on maximal utilization of PV produced energy and minimal electricity imports from the grid. The model proposed by Ren et al. [28] optimizes the capacity of the PV system operating under FIT with regard to the minimal annual cost of energy. The method accounts for the investment and maintenance costs, cost of electricity purchased from the grid and revenues for the energy injected to the grid. Finally, the model developed by Kornelakis et al. [29] used particle swarm optimization algorithm to define the optimal size of the grid-tied PV installation in respect to the highest NPV of such system. The proposed methodology computes also the discounted payback time and the internal rate of return as additional economic parameters.

As presented, the existing literature reports several studies on the topics on the estimation of building's electricity demand, design, operating conditions and optimization of PV system, as well as their regulatory support mechanisms and economic assessments of such investments.

This paper pursues an approach that, in author's opinion, has not been reported yet. It follows an integrated economic assessment of the PV system solutions currently offered in the market, adapted to the specifics of the Polish regulations. By simulating various grid connected PV generation system capacities, tilts of the panels as well as the types and sizes of PV panels and inverters, it aims to find the optimal system configuration, indicated by the highest NPV of an investment. It also investigates how the optimal configuration changes, depending on the direction in which Polish regulations regarding support mechanism of micro-PV systems will change.

The two possible regulatory outcomes will either be the adoption of a new NM support mechanism or the continuation of the current FIT support model. With the first one, NM, owners of micro-installations will be permitted to virtually store the surplus of produced energy and collect it later at the reduced amount. For the installations with the capacity up to 10 kWp, for each 1 kWh injected into the grid, the prosumer will receive 0.8 kWh. In case of the micro-installations between 10 and 50 kWp the ratio is 1 to 0.7. The injected surplus energy can be recovered from the grid within 365 days from the moment of injection and the recovery will be done in a First In-First Out basis [30]. In case of FIT, the PV owner are only allowed to sell the surplus electricity "at a price equal to 100% of the average electricity sales price on the competitive market in the previous quarter announced by the President of Energy Regulatory Office". [31]

The paper is organized as follows. Section 2 presents the methodology of economic assessment and building's electricity estimation. Section 3 provides information on the case study and describes the preliminary study. Section 4 presents results of the detailed simulations and of the sensitivity analysis. Last but not least, Section 5 summarizes the paper and contains the conclusions.

2. Methodology

2.1. Economic assessment

Solar projects can be optimized with regard to several different production indicators, such as amount of energy available from the rooftop PV system, self-consumption ratio, overall system efficiency, etc.. Yet, from the investor's point of view, most important is the economical attractiveness of the proposed project. For this reason, the economic assessment of all simulated PV system was made to evaluate its feasibility, and profitability.

Financial indicators used in this study include: Net Present Value (NPV), Internal Rate of Return (IRR), Discounted Payback Period (DPP) and Levelized Cost of Electricity (LCOE). To take into account the concept of time value of money – meaning that the money available at present moment is worth more than the same amount in the future, owing to its possible earning capacity – a discount rate will be applied to all the cash flows. This will enable to evaluate the present value of the project investment based on the forecasted future cash flows.

NPV is a difference between a discounted present values of cash inflows and cash outflows calculated over the project's lifetime. During the project, the goal would be to find a system for which the NPV will be highest, as it translates to the highest monetary benefit for the investor. The NPV measures profitability in an absolute manner and as a general rule, only the project with positive NPV should be undertaken [32].

To gain a better understanding of the profitability of the project, an IRR will also be calculated for each case. IRR is a discount rate that would make NPV equal to zero, and is a projection of the rate of growth the project will generate [33]. IRR takes into account the time value of money, and the higher the value of it is, the more desirable the case is. It is important to use IRR in conjunction with NPV, as alone the results may be misleading. For example an investment can have a low IRR and high NPV, which means that although the rate of return is slower, the added monetary value at the end of the project's lifetime will be bigger [32].

There are long debates in the literature of finance about which of the indicators, NPV or IRR, is superior for decision making properties, however most of the literature concludes the supremacy of the NPV [34]. Firstly, because the NPV undertakes that cash inflows are to be reinvested at the assumed rate of return, while the IRR assumes that inflows of cash are to be reinvested at the computed IRR. Reinvestment at the required rate of return turns to be more realistic and provides reliable results, when comparing mutually exclusive projects. Secondly, if projects are mutually exclusive and different in size, which is a case of this paper, then NPV is superior, as it selects the option that maximizes the value of the project [35], [36].

DPP is the measure that indicated how long it would take to recover the initial capital expenditure from the present value of the anticipated future cash flows. The shorter the recovery time, the more feasible and attractive the project is. Only projects whose DPP is lower than their lifetime should be accepted.

The last parameter to be calculated is the LCOE, which can be defined as discounted lifetime cost of an investment and system operation, divided by produced electricity. LCOE is usually expressed in €/MWh and is used to compare with each other the simulated system variants [37].

2.2 Description of the economic assessment model

To start with, it is essential to list all the components that build up the investment cost. Next, gross investment cost per installed Wp of the PV system is calculated, as it is the key information needed when applying for the governmental subsidies [38]. It is defined as:

$$c_{gross} = c_{PV} + c_{inv} + c_{inst} + c_{mount} + c_{BOS} + c_{trans} \quad (1)$$

All of the costs are given per installed Wp of the system, expressed in €/Wp. c_{gross} stands for the gross cost of the system, c_{pv} for cost of the PV panels, c_{inv} for the inverter cost, c_{inst} for the installation service, c_{mount} for the structure mounting, c_{BOS} for the cost of the balance of the system and c_{trans} for the transportation.

The amount of the subsidy for the PV system in Poland may cover up to 15% of the total investment, with the provision that subsidies will be granted only up to the gross investment cost per Wp equal to 1.4 €/Wp [31]. The amount is calculated as (PV_{cap} is the PV system capacity, given in Wp):

$$Subsidy = \begin{cases} 15\% \times c_{gross} \times PV_{cap} & if \quad c_{gross} \leq 1.4\,€/Wp \\ 15\% \times 1.4 \times PV_{cap} & if \quad c_{gross} > 1.4\,€/Wp \end{cases} \quad (2)$$

After knowing the amount of subsidy that the system is entitled for, the capital expenditures (CAPEX) are calculated according to the formula (C_{inv} is the nominal cost of the inverter, given in €):

$$CAPEX = PV_{cap} \times (c_{PV} + c_{inst} + c_{mount} + c_{BOS} + c_{trans}) + C_{inv} - Subsidy \quad (3)$$

Annual operating expenditures (OPEX), that include the costs of regular operation and maintenance (O&M) of the equipment, can be approximately accounted for 1% of the CAPEX [39]. However, as the expected lifetime of a string inverter is of 10-15 years [40], the cost of the OPEX will vary depending on the year. For this study, the worst case was assumed, requiring the replacement on the every 10th year. The cost of operating expenditures in the nth year – $OPEX_n$ – is given as:

$$OPEX_n = \begin{cases} 1\%\ CAPEX & years\ 1st\ to\ 25th\ excluding\ 10th\ and\ 20th \\ 1\%\ CAPEX + C_{inv} & for\ the\ 10th\ and\ 20th\ year \end{cases} \quad (4)$$

In order to account for the benefits of electricity generation from the PV installation for each year, several production data must be obtained from the simulations run in the PVsyst. Those parameters are the annual amounts of energy at the nth year of operation: available from the PV system – $E_{avilPV,n}$, consumed from the PV system by the user – $E_{consPV,n}$, injected to the grid - $E_{inj,n}$, purchased from the grid – $E_{pur,n}$. Additionally, for the Net Metering support scheme amount of energy recovered from the grid – $E_{rec,n}$ – is taken into consideration, and for the Feed-In-Tariff support scheme the amount of energy sold to the grid – $E_{sold,n}$. As those amounts vary each year due to PV system performance, the small letter “n” denotes the year of operation. All of the above parameters are expressed in kWh/year.

As the PV panels are ageing, their performance gradually deteriorates over time. To compute the amount of energy available from the PV system at the nth year of operation, the initial yield in corrected by annual degradation factor D:

$$E_{availPV,n} = E_{avail,1} \times (1 - D)^n \quad (5)$$

Energy available from the PV system would cover the instantaneous energy demand of the facility, or in case of the surplus production, this energy would be injected into the grid. This surplus amount of electricity is simulated and computed in the PVsyst software by subtracting the hourly production profile from the hourly demand profile.

$$E_{inj,n} = E_{availPV,n} - E_{consPV,n} \quad (6)$$

If the PV system works under the FIT support scheme, the energy injected to the grid is sold and the quantity of energy needed to cover the demand is purchased from the grid.

$$E_{pur,n(FIT)} = E_{dem,n} - E_{consPV,n} \quad (7)$$

However, if the PV system works under the NM support scheme, a user can store virtually the surplus energy which was injected into the grid and collect it later, at a reduced amount, to meet the ongoing demand. According to the Polish Energy Law, For the installations with the capacity up to 10 kWp, for each 1 kWh injected into the grid, the prosumer will receive the maximum of 0.8 kWh. In case of the micro-installations between 10 and 50 kWp the ratio is 1 to 0.7 [31]. Amount of the recovered electricity is calculated in the following way:

- for the $PV_{cap} \leq$ 10 kWp:

$$E_{rec,n} = \begin{cases} 0.8\,E_{inj,n} & if\ (0.8\,E_{inj,n} + E_{consPV,n} \leq E_{dem,n} \\ E_{dem,n} - E_{consPV,n} & if\ (0.8\,E_{inj,n} + E_{consPV,n}) > E_{dem,n} \end{cases} \quad (8)$$

- for the 10 kWp $< PV_{cap} \leq$ 50 kWp:

$$E_{rec,n} = \begin{cases} 0.8\,E_{inj,n} & if\ (0.8\,E_{inj,n} + E_{consPV,n} \leq E_{dem,n} \\ E_{dem,n} - E_{consPV,n} & if\ (0.8\,E_{inj,n} + E_{consPV,n}) > E_{dem,n} \end{cases} \quad (9)$$

With a constraint for the maximum amount of annually recovered electricity is:

$$E_{rec,n} \leq E_{dem,n} - E_{consPV,n} \quad (10)$$

The annual amount of electricity purchased from the grid in the Net-Metering scheme is then:

$$E_{pur,n(NM)} = E_{dem,n} - E_{consPV,n} - E_{rec,n} \quad (11)$$

In the next step, electricity flows will be translated to monetary values, in order to carry out the economical evaluation. The annual cost of purchased electricity is composed of variable part – dependent on the electricity imports, and fixed part. It is calculated as follows:

$$C_{e.pur,n} = \begin{cases} E_{pur,n(NM)} \times p_{e,pur,var} + p_{e,pur,fix} & for\ NM \\ E_{pur,n(FIT)} \times p_{e,pur,var} + p_{e,pur,fix} & for\ FIT \end{cases} \tag{12}$$

Where $C_{e.pur,n}$ is the annual cost of electricity purchased in the n^{th} year, $p_{e.pur,var}$ is a variable price of the electricity, given in €/kWh and $p_{e.pur,fix}$ is fixed component of the electricity price, given in €.

To assess the profitability of the investment, it is crucial to know how much money does the PV system save, thanks to the mitigated need of purchasing a part of the electricity from the grid. The amount of saved electricity again depends on the support scheme.

For FIT mechanism, the mitigated cost of electricity purchase in the n^{th} year is calculated by the equation:

$$C_{e.save,n(FIT)} = E_{consPV,n} \times p_{e,pur,var} \tag{13}$$

Additionally to the saved electricity, in the FIT scheme the PV system's owner can also sell the surplus energy. The annual income from the transaction is given by the equation:

$$I_{e.sold,n} = E_{inj,n} \times p_{e,sold} \times (1 - tax_{e.sold}) \tag{14}$$

In the NM scheme, the annual profit from the saved electricity is calculated by the equation:

$$C_{e.save,n(NM)} = (E_{consPV,n} + E_{rec,n}) \times p_{e,pur,var} \tag{15}$$

The cash flow, summarizing the cash inflows and outflows for the system working under the FIT support scheme in the n^{th} year is calculated by:

$$CF_{n(FIT)} = C_{e.save,n(FIT)} + I_{e.sold,n} - OPEX_n \tag{16}$$

For Net Metering support scheme, the cash flow for the n^{th} year is computed by the equation:

$$CF_{n(NM)} = C_{e.save,n(NM)} - OPEX_n \tag{17}$$

As mentioned at the beginning of the chapter, the leading financial parameter, in respect to which the system size will be optimized, is the NPV. Its formula goes as:

$$NPV = \sum_{n=1}^{N} \frac{CF_n}{(1+r)^n} - CAPEX \tag{18}$$

To compute the IRR, one must equal the NPV formula to zero, and solve it for the discount rate.

$$0 = \sum_{n=1}^{N} \frac{CF_n}{(1+IRR)^n} - CAPEX \tag{19}$$

To calculate the DPP, the below equation must be solve for the year at which the initial investment equals the discounted cumulative cash flow.

$$\sum_{n=1}^{DPP} \frac{CF_n}{(1+r)^n} - CAPEX = 0 \tag{20}$$

Lastly, to calculate the LCOE, the lifetime costs of CAPEX and OPEX of the investment are divided by the discounted amount of electricity produced over this period. As the O&M costs are incurred every year, they need to be discounted for the future, in contrary to the CAPEX which is buried only once, at the beginning of the investment.

$$LCOE = \frac{CAPEX + \sum_{n=1}^{N} \frac{OPEX_n}{(1+r)^n}}{\sum_{n=1}^{N} \frac{E_{avail,1} \times (1-D)^n}{(1+r)^n}} \tag{21}$$

2.2 Building's electricity demand estimation method

Prior to designing the PV generation system, determination of the building's electricity consumption in needed. As the building is not yet in operation, a bottom-up method of estimating the demand and creating the load profiles has been adopted.

The method required creation of a table which contains all electrical appliances to be found in the facility, their quantities and power ratings. The next step is to determine how frequently, at which hours and for how long the individual equipment is to be used. To gather this data and obtain a reasonable approximation, a series of interviews should be conducted with the building's users. Once the data is collected, the individual electricity demands should be placed on a 24-hour timeline, with 30 min timestep.

In order to create the load profiles for the whole year, the method introduces a simplification, which assumes that energy consumption between the individual days of the specific month does not differ significantly. Thus, instead of modelling each day independently, a monthly estimates are created. As the building's electricity demand is assumed to be similar for the working days of the week an "average working day of the month" is created, for each month separately. Similarly, the consumption profile is assumed similar through the weekends, resulting in the creation of an "average weekend day of the month". This results in modelling separately 12 average working days and 12 average weekend days – one of each per each month. By taking 5 times the average working day of the specific month and adding to it twice the average weekend day of the specific month weekly profiles are created. Monthly profiles are assembled from the weekly profile. This operation is later repeated for each month separately, enabling the production of a 24-hours energy demand timeline profile for each day of the year.

3. Case study description and preliminary analysis

The building under study is a warehouse planned to be build the city of Miszewo, in Poland. The building's roof has dimensions of 18.5x38m, a tilt of 8° and is oriented 23° to the West from the South.

3.1 Load profiles and electricity demand

Estimated load profiles of the average days of specific months are presented in figure 3.1, and show the hourly variations of electricity demand throughout the day. It can be seen how the demand changes depending on the season, with the demand higher during winter months than summer ones.

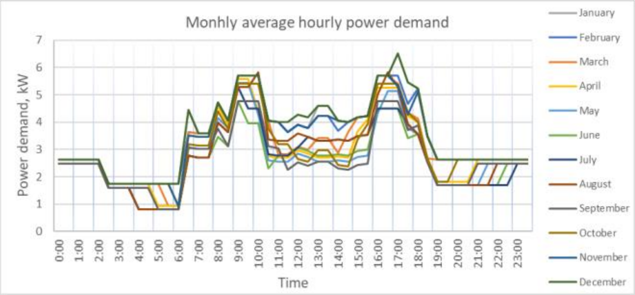

Figure 3.1. Load profiles of the average days of the months

Figure 3.2 presents monthly demand on the aggregated level. The average monthly consumption is of around 2200 kWh/a, with a total yearly electricity demand of 27.3 MWh.

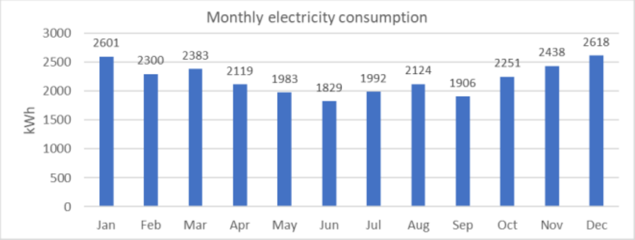

Figure 3.2 Monthly electricity demand

3.2 Effects of snow cover on soiling loss and albedo

As discussed in the literature overview, modelling the snow cover is agreed to be an extremely difficult task. For these reasons certain simplification and assumptions were taken to adjust the model. As the snow starts to fall in the studied region of Poland from mid-December and ends around February, soiling from snow and values of albedo were adjusted accordingly. It has been assumed that the PV panels will be covered under the snow for 50% of time in January, and for 30% in December and February. Values of albedo were set for 0.8 for the months were snow is present and 0.2 for the times when it is not. The monthly setting are demonstrated in table 3.1

Table 3.1 Monthly values of albedo and soiling from snow

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Soiling from snow	50%	30%	0%	0%	0%	0%	0%	0%	0%	0%	0%	30%
Albedo	0.8	0.8	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.8

3.3 Preliminary analysis

Before committing to a specific design of the system, a preliminary design was done. This step allowed to determine the most suitable tilt of the PV panels and approximate the optimal capacity range of the system, for both NM and FIT support schemes. At this stage, generic components were used in the PV system simulations. A discount rate of 4% and a 25-year project lifetime were assumed.

As during the preliminary design only selected capacities were tested, results of the simulations, presented on figure 3.3, indicate only the range in which lies the optimal capacity of the PV system. Boundaries of the solution are determined by the two point, adjacent to the point with the highest NPV. The range, in which the maximum NPV should be sought for, was marked with a red line.

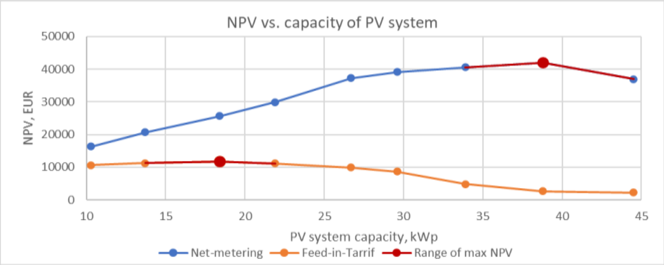

Figure 3.3 Monthly electricity demand

Results of the preliminary simulations show that for a scenario in which:

- the legislation will change so that the **NM** support mechanism will also cover the companies, the optimal capacity is somewhere within the range of **34 kWp to 44 kWp**
- the legislation remains unchanged, offering the **FIT** support mechanism to the companies, the optimal capacity is somewhere within the range of **13 kWp to 22 kWp**

The optimal tilt for the system operating under NM and FIT in those ranges is respectively 41° and 39°.

A lifetime average annual cost of covering the facility's electrical demand was computed, and plotted on figures In the baseline option, with no PVs, the average discounted annual electricity expenditures would be of around 4000 EUR. The base case is benchmarked against various capacities of the PV system. The showing the cost structure and the annual cost saving ratio.

It can be seen on figure 3.4 that the for NM option, that the maximum annual cost saving ratio can be expected at the levels close to 45%, and falls within the previously approximated optimal capacity range.

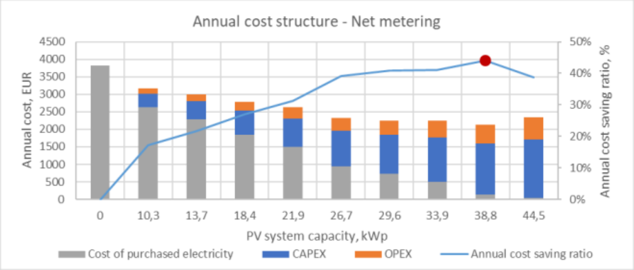

Figure 3.4 Annual cost structure of different system capacities– case of NM

Results for FIT are demonstrated in figure 3.5. The average annual costs of CAPEX, OPEX and the costs of purchased electricity are reduced by the profit from the electricity sold to the grid. The annual costs will be lowest for a capacity that is between 13.7 to 21.9 kWp, similarly to the NPV study, with the annual cost saving ratio of around 12%.

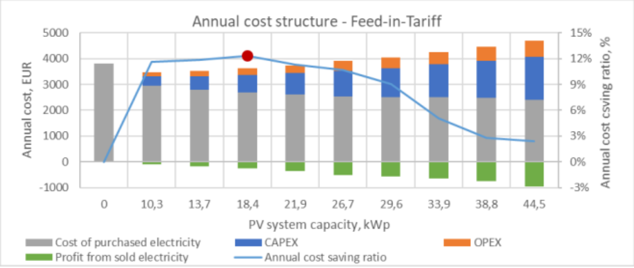

Figure 3.5 Annual cost structure of different system capacities– case of FIT

4. Results and discussion

Based on the optimal ranges found in the preliminary design, a detailed performance simulations of the selected components were carried out in the PVsyst software. Economic evaluation of each configuration was computed and plotted on the below graphs. Results illustrate the relationship between NPV and the nominal power of the PV system. Each point on the charts represents an individual system configuration of the PV panel and the inverter.

4.1 Results for the NM supported PV system

Results of the NM system simulations, presented in figure 4.1, show that the among the studied configuration, the one bases on the JA Solar JAP6-60/275 PV panel and a KACO Powador 36.0 TL inverter is financially the most attractive. The PV system of 36,3 kWp will generate over the 25 year of operation the NPV of around 51 000 EUR.

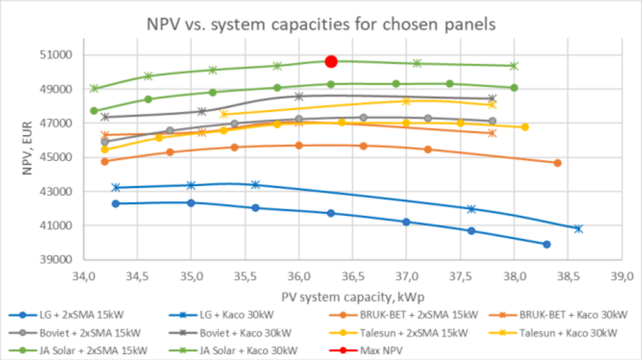

Figure 4.1 NPV vs. system capacities - for NM support scheme

It can be seen on the below figure 4.2, that there is a conflict between the highest NPV and the highest IRR. Such situation is common for a mutually excluding options, which is the case. This means, that even though the internal rate of return is slower, the added monetary value by the end of the project's lifetime will be bigger. The IRR of the optimal configuration is predicted to be slightly over 17%.

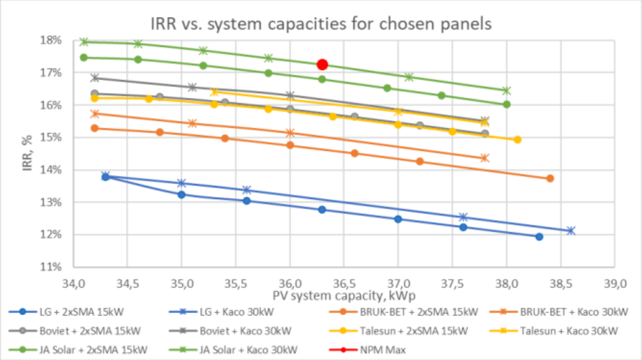

Figure 4.2 IRR vs. system capacities - for NM support scheme

The optimal configuration would require 132 PV modules inclined at 41° in respect to the horizon. The designed system is expected to have a specific annual yield of 1017 kWh/kWp in the annual bases, resulting in the 36,9 MWh of produced electricity during the first year. The amount surpasses the electricity demand, however due to the NM compensation mechanism, the surplus electricity injected into the grid can be later partially recovered. This allows to achieve a staggering 96.88% of solar fraction, being the percentage share of the electricity provided from PV in the total project's lifetime electricity consumption. Performance ratio is estimated for a 85.7%.

From the financial side, the initial investment would be of around 31 000 EUR, and the average discounted running costs of the system close to 300 EUR/year. The system will offer substantial energy savings – the average annual cost is projected to be around 1800 EUR/year, in comparison to the baseline 3800 EUR/year, where no PVs are installed. Under those performance conditions, the system will pay off in a little bit over 6 year. The LCOE of the system is 0.048 EUR/kWh.

The energy profiles of the first 2 years of PV system production were plotted in figure 4.3, assuming that the installation will start operating in January 2020.

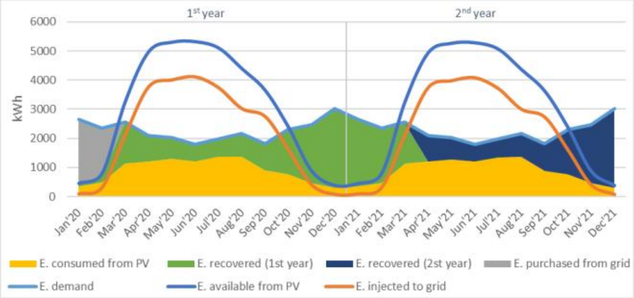

Figure 4.3 Energy profile of the facility – NM case

It can be seen that during the first two months of operation, it will be necessary to purchase additional electricity from the grid to cover the demand. However, later, due to the appropriate sizing of the installation, energy shortages will be covered with energy recovered from the grid.

4.2 Results for the FIT supported PV system

Results of the simulations for FIT supported system, presented in figure 4.4 indicate that the optimum system should be bases on the JA Solar JAP6-60/275 PV panels and a KACO Blueplanet 20.0 TL3 inverter. The optimal PV system, marked with the red dot, has 21.4 kWp of nominal power, and will generate the NPV of around 12 500 EUR, over the entire lifetime of the investment. It can be noticed that the NPVs for the FIT option are around 3 to 4 times smaller than for the configurations working under NM.

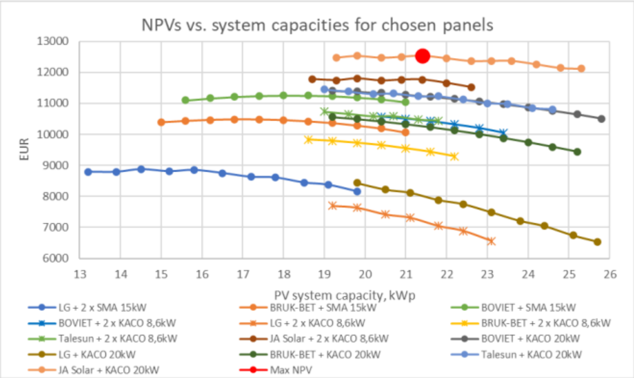

Figure 4.4 NPV vs. system capacities - for FIT support scheme

The designed system produces 21.8 MWh of electricity per year with a specific annual yield of 1016 kWh/kWp. The amount is lower than the 27.3 MWh electricity demand, as FIT doesn't allow for recovering surplus electricity injected into the grid. The surplus is sold to the grid at the average market electricity price from the previous quarter. Those prices are however much lower than the purchasing prices for the consumers. For this reason the designed system is smaller than the one for NM option. As a consequence, the solar fraction is much smaller, covering approximately 32% of electricity demand directly from the PV system. The remaining part is bought in this case from the grid. Performance ratio is slightly smaller, averaging 80.9%.

The initial investment would be of a little over 18 000 EUR, and the average discounted running costs of the system close to 180 EUR/year. The system will offer a slight reduction energy savings – the average annual cost is projected to be around 3300 EUR/year in comparison to the baseline 3800 EUR/year where no PVs are installed. Looking at the figure 4.5, the IRR is projected at the level of 10%. Under those performance conditions, the system will pay off in a little bit over 11 year. The LCOE of the system is 0.049 EUR/kWh.

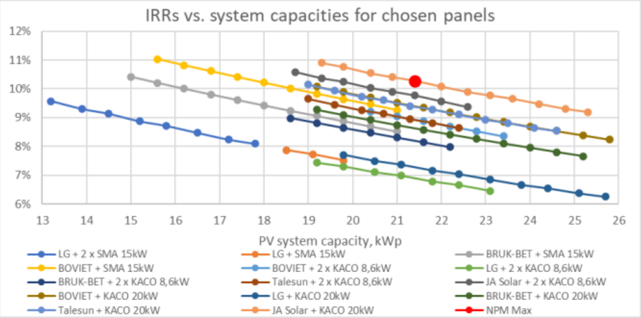

Figure 4.5 IRR vs. system capacities - for FIT support scheme

As seen from figure 4.6, the system working under FIT support scheme will require purchases of electricity from the grid in every month. In fact, in this case we can only talk about the reduction in electricity spending, which is highest during summer months. The surplus electricity injected into the grid can only be sold to the grid, not stored in it.

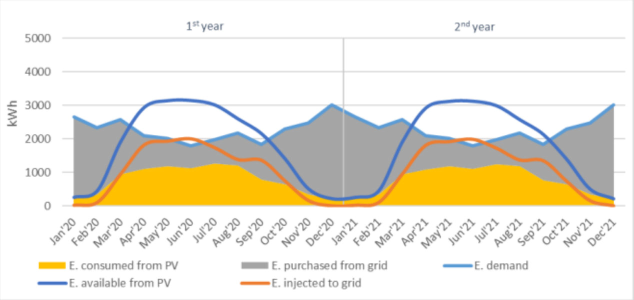

Figure 4.6 Energy profile of the facility – FIT case

4.3 Sensitivity analysis

In order to determine how changes of individual variables could affect the two most important for the investor financial indicators of the model – NPV and DPP, a local sensitivity analysis was conducted. A one-at-a-time technique was used, in which only one parameter at a time has been changed and the rest was kept constant. The chosen parameters were changed in the range of ±20% with a step of 5% points. Variables selected for the analysis that were common for both systems were: CAPEX, OPEX, electricity demand, price of purchased electricity and a discount rate. Additionally, a net metering ratio (a maximum ratio of the energy recovered from the grid to the energy previously injected – currently 0.7) was tested for NM option, and the influence of the price of sold electricity and the income tax were analyzed for FIT scenario.

Sensitivity analysis on NPV and DPP for NM case were plotted respectively on figures 4.7 and 4.8. It can be noted, that the most influential variable is the price of purchased electricity. With the 20% increase of electricity prices, the NPV would grow by 35%, and the DPP would fall from 6.3 to 5.1 years.

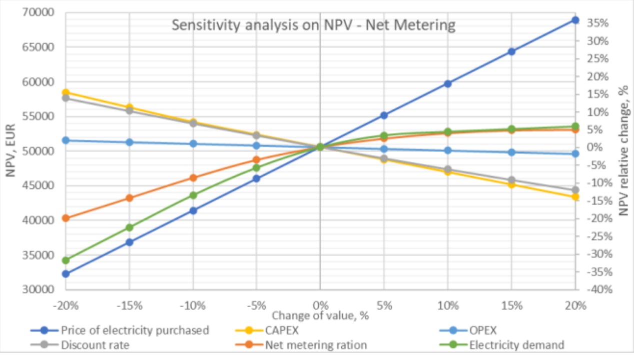

Figure 4.7 Sensitivity analysis on NPV for the system optimised for NM

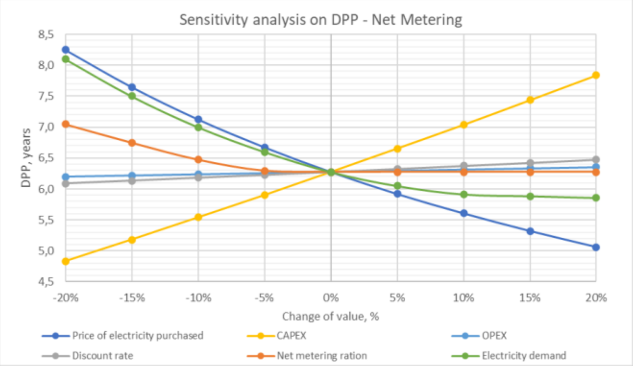

Figure 4.8 Sensitivity analysis on DPP for the system optimised for NM

The second variable that is likely to positively influence the NPV is the decrease of CAPEX. Over the last decade the prices of solar PV system components were falling, and the tendency is likely to continue for at least some time. According to the sensitivity analysis, every 5% drop in CAPEX would increase the NPV by approximately 4% and reduce the DPP by roughly half a year.

Influences of changes in electricity demand and on the net metering ratio depend on the direction of a change. With the 20% increase of both, the NPV will slightly grow, by just 5%, and the DPP will decrease by half a year. However, if the percentage of the energy that can be recovered from grid will decline in the future the effects will be much more pronounced. Same stands true for the decline of facility's energy demand, although the effects will be even more noticeable on both NPV and DPP. It is hard to assess the risk connected to the change of those parameters, as it is difficult to estimate the direction in which they will possibly shift in the future.

Additional simulations were performed to determine what change in individual parameters would turn the investment's NPV to 0. One case that would make it happen, would be a 55% decrease in energy demand to the level of 11 900 kWh/year. Also if the price of electricity would drop below 0.1 EUR/kWh, the investment would not be able to pay itself off. The last instance, under which the NPV would become negative, would be caused by decrease of NM recovery ratio from the current 70% to below 6%. This in practice means that in the absence of NM support scheme, the designed PV system would not be financially viable.

Looking at the range of NPV relative change for the FIT case, shown in figure 4.9, it can be concluded that the system optimized for FIT is more vulnerable to changes of the selected variables. The ±20% variations of electricity purchase price would change the NPV in a range of ±50%. As the tendency indicates that the electricity prices will grow, it is likely that the final NPV of the system will be higher than predicted at the moment. In such case, judging from the figure 4.10, it is possible that the DPP will be less than 10 years, especially when looking at the influence of CAPEX.

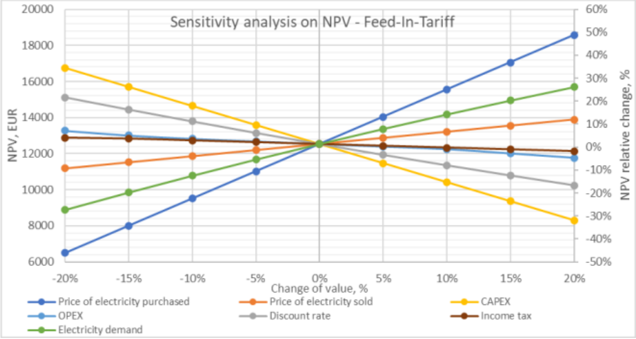

Figure 4.9 Sensitivity analysis on NPV for the system optimised for FIT

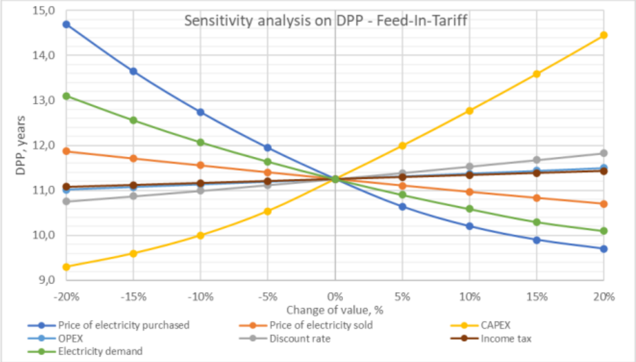

Figure 4.10 Sensitivity analysis on DPP for the system optimised for FIT

Only through the decrease of initial capital expenditure by 10%, the system optimized for FIT would pay off 1.5 years earlier. This would also increase the NPV by 20%.

The increases of both facility's electricity demand and the prices of electricity sold to the grid have a positive, linear influence on the system's attractiveness. However, as the line of electricity demand is steeper than the one of the selling price, it can be concluded that the prior has a more significant influence on the system's NPV. The analysis also shows that the increase of both OPEX and income tax negatively affects the financial performance, though the influences are marginal.

Similarly as for NM, additional simulations were carried out for the FIT system to determine under which conditions the NPV of the investment would equal 0. It turned out that if the facility's energy demand drops by 70%, to around 7 800 kWh/year, the investment will end with a negative NPV. Another case could be a drop in electricity prices below 0.13 cents/kWh. Simulations have shown, that even if the FIT support system was terminated, and the utility would not offer any compensation for the energy injected into to grid (price of sold electricity would equal 0 cents/kWh), the designed system would still be financially viable. In such pessimistic case, the cumulative NPV after 25 years of operation would reach approximately 6 000 EUR – slightly less than a half of that is forecasted for when the FIT support mechanism stays unchanged.

5. Conclusions

The purpose of this paper was to find the optimal configuration of the rooftop PV generation system for the warehouse located in the northern part of Poland. Due to the current alterations in the Polish energy law regarding support for the solar installations, and the still uncertain direction of those changes, optimization of the studied system has been done in respect to the two possible regulatory outcomes – continuation of the Feed-In-Tariff support scheme or adoption of the Net-Metering support mechanism.

One of the important parts of this paper was conducting a preliminary study, based on generic components. Results obtained during this step were valuable, as they narrowed down the search range for the optimal PV system size. Results of the preliminary study also showed the scale of influence which policy has on the system's NPV. Comparing installations with the same nominal power, the NM supported system generated significantly larger NPVs. For the capacity of 20 kWp the NM system generated twice higher NPV than the installation supported by FIT, and for the capacity of 40 kWp the difference was 5-fold bigger. At their optimal configurations, the annual cost saving ratio would be close to 45% for the NM case, and maximally of around 12% for the system optimized for FIT.

Results of the detailed simulation pointed out the optimal setups of the PV generation system. In case the Polish lawmakers decide to stay with the FIT support mechanism, the optimal system should be composed of 78 PV modules from JA Solar, connected into the 20 kWac inverter from KACO New Energy. The nominal power of the PV installation would be of 21,4 kWp and the modules should optimally be inclined by 39° in respect to the horizon. With such system, on average, 32% of facility's electricity consumption would be covered from PVs. The initial investment of around 18 000 EUR would be paid off in a little over 11 years, generating over 25 years of operation an NPV of 12 500 EUR, at an internal rate of return close to 10%. However, if the upcoming amendments in the energy law adapt the NM support mechanism, then the optimal installation would be nearly twice as big. Precisely, it should have a nominal power of 36.3 kWp, based on 132 JA Solar modules connected the 30 kWac KACO New Energy inverter. The optimal inclination of the modules in respect to the horizon would be 41°. With such system the facility would cover nearly 97% of its electricity demand from solar energy. Initial investment would be of around 31 000 EUR, and by the end of the project's lifetime the system would generate an NPV of around 50 500 EUR, at the IRR of 17.25%

Sensitivity analysis showed that the three parameters that most affect the NPV of the tested PV systems are: prices of electricity, facility's electricity demand and CAPEX. With the rise of the first two parameters and the fall of the third one, the NPV increased. The global trends suggest, the prices of electricity will most likely rise in the future. As the amount of electrical devices around us grows continuously, the building's need for electricity is also presumably keep growing. During the last 10 years, the prices of PV modules and inverters have fallen significantly and are expected to fall further. If the above predictions prove to be true, systems NPV will be higher than currently estimated. This reduces the risk of investment, positively influencing the moods of investors and hopefully encouraging them to expand more extensively their PV systems portfolio.

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