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FACULTY OF ELECTRICAL ENGINEERING

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UNIVERSITY „GOCE DELCHEV” - SHTIP
FACULTY OF ELECTRICAL ENGINEERING

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PREFACE

The Faculty of Electrical Engineering at University Goce Delcev (UGD), has organized the International Conference ***Electrical Engineering, Informatics, Machinery and Automation - Technical Sciences applied in Economy, Education and Industry-ETIMA.***

ETIMA has a goal to gather the scientists, professors, experts and professionals from the field of technical sciences in one place as a forum for exchange of ideas, to strengthen the multidisciplinary research and cooperation and to promote the achievements of technology and its impact on every aspect of living. We hope that this conference will continue to be a venue for presenting the latest research results and developments on the field of technology.

Conference ETIMA was held as online conference where contributed more than sixty colleagues, from six different countries with forty papers.

We would like to express our gratitude to all the colleagues, who contributed to the success of ETIMA'21 by presenting the results of their current research activities and by launching the new ideas through many fruitful discussions.

We invite you and your colleagues also to attend ETIMA Conference in the future. One should believe that next time we will have opportunity to meet each other and exchange ideas, scientific knowledge and useful information in direct contact, as well as to enjoy the social events together.

The Organizing Committee of the Conference

ПРЕДГОВОР

Меѓународната конференција ***Електротехника, Технологија, Информатика, Машинство и Автоматика-технички науки во служба на економија, образование и индустрија-ЕТИМА*** е организирана од страна на Електротехничкиот факултет при Универзитетот Гоце Делчев.

ЕТИМА има за цел да ги собере на едно место научниците, професорите, експертите и професионалците од полето на техничките науки и да претставува форум за размена на идеи, да го зајканува мултидисциплинарното истражување и соработка и да ги промовира технолошките достигнувања и нивното влијание врз секој аспект од живееењето. Се надеваме дека оваа конференција ќе продолжи да биде настан на кој ќе се презентираат најновите резултати од истражувањата и развојот на полето на технологијата.

Конференцијата ЕТИМА се одржа online и на неа дадоа свој допринос повеќе од шеесет автори од шест различни земји со четириесет труда.

Сакаме да ја искажеме нашата благодарност до сите колеги кои допринесоа за успехот на ЕТИМА'21 со презентирање на резултати од нивните тековни истражувања и со лансирање на нови идеи преку многу плодни дискусии.

Ве покануваме Вие и Вашите колеги да земете учество на ЕТИМА и во иднина. Веруваме дека следниот пат ќе имаме можност да се сретнеме, да размениме идеи, знаење и корисни информации во директен контакт, но исто така да уживаме заедно и во друштвените настани.

Организационен одбор на конференцијата

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Прва меѓународна конференција ЕТИМА
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COMPLEX EVALUATION MODEL OF A SMALL-SCALE PHOTOVOLTAIC INSTALLATION PROFITABILITY

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Abstract: *Number of small-scale photovoltaic installations grows rapidly every year. A decade ago, this was motivated solely by the attempt to reduce greenhouse gas emissions, because the investment itself was not economically viable. Nowadays, the table is turning. Small-scale installations are becoming profitable, if selected wisely. Therefore, the article discusses, what are the factors that need to be taken into consideration when selecting the photovoltaic installation, what data must be collected beforehand and how to proceed in their analysis. To sum up, the article provides an in-depth methodology for the small-scale photovoltaic installation assessment that is aimed to be used in household's or small commercial consumer's profitability appraisal of such an investment.*

Keywords— *photovoltaic systems; profitability; price; electricity consumption; electricity generation; renewable energy sources support; energy storage; optimization; standard consumption diagram*

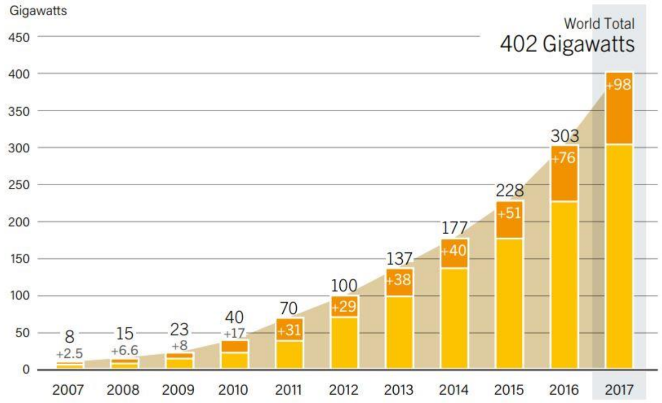
Introduction

Renewable energy sources (RES) development is a major tool in climate change combat within the power engineering sector. These technologies however represent a significant shift that may be seen like a threat both in terms of grid technologies and in terms of finances. Despite these assumptions, the photovoltaic (PV) market is growing rapidly. This is naturally connected with obligations of states under the international law to decrease their carbon footprint. Some countries focus on large-scale projects in sunny locations. [1] These are not suitable for each geographical region. This might be seen in the European trend of small-scale household installations. They have several advantages. Firstly, they usually do not occupy land and could easily be installed on the rooftop. Secondly, they are financed by private entities and do not require a complicated state administration. Although, support schemes might still be relevant in terms of profitability in some regions or for some consumer categories. Thirdly, they constitute a much less significant threat for the electricity grid since they are spread all over the grid and thus their generation output is usually different and distributed to various node areas. And finally, if optimized properly, a majority of the generated electricity could be consumed in a real time or stored in an energy storage device. Thus, the amount of transported electricity would be minimalized. However, battery systems are still very expensive and unprofitable. Therefore, the real-time consumption supported by some support schemes such as net metering constitutes a way forward in many European countries. [2]

Household customers usually do not know what factors to take into consideration when selecting the PV installation. Nevertheless, the market is quite competitive and there are many PV suppliers, installers and many companies operating on various markets connected with both electrical appliances and energy services that offer turnkey projects. PV design optimization is a complicated process and large-scale project designers usually use various expensive softwares.

On the other hand, household customers deciding upon the PV installation usually follow the recommendations of the supplier. However, these do not necessarily have to be relevant. There are many factors that should be considered, and an in-depth analysis should always be performed before an installation purchase. Choosing a suitable PV installation is crucial for the profitability of an investment. Too expensive installation with an overly set installed capacity would cause the investment not to return at all, because the majority of electricity would not be utilized and would only be sent to the grid as a surplus. An installation with an insufficient installed capacity would not be profitable either, because the installation costs and the equipment costs would not be proportional to the energy savings related to low installed capacity. As the findings show, the starting point of each PV optimization should be the electricity consumption, i.e. both its curve and its volume should be considered. It is important to understand that households' consumption peaks are usually located before and after the working hours, whereas the PV generation peak is located during the working hours. On the other hand, in case of the small commercial consumers it is vice versa. This has a significant impact on the amount of surplus electricity that cannot be consumed in a real time and thus creates a need for a battery storage, what makes the installation far more expensive. The conclusion is that the consumption data allows for the PV installation optimization that leads towards the profitability maximization.

Due to the above mentioned, the aim of the article is to identify a small-scale PV installation profitability assessment methodology that would be clearly answering the question, what PV installation is the most profitable for a specific electricity consumer. However, the article only discusses Slovak market conditions and focuses mostly on the household customer categories. Nevertheless, the proposed methodology may be used for other small-scale customer categories, too.



Global PV Capacity and Annual Additions, 2007-2017. [3]

Methodology

Categorizing the final consumer

First of all, a detailed consumption data is needed. As it was already stated above, the PV generated electricity is utilized in the most profitable way only when consumed immediately without any energy storage solutions. Thus, it is important to adjust the PV installation according to the consumption volume and its curve.

There are two options in defining the consumption of a specific electricity consumer. First and much more accurate approach is to collect a real data. The easiest would be to collect these from a smart meter or its online database. Another option might be to use the data collected by the consumer himself. However, this data might not be that accurate. Second option, used if the real data is unavailable, is to use the standard consumption diagram (SCD) provided by the local distribution system operator. These usually divide the small-scale final consumers into several categories according to their load profiles. Basic categories usually distinguish residential and commercial customers. This also applies to SCDs used by Západoslovenská distribučná a.s. (ZSD). Seven consumer categories are defined by ZSD. Three of these are specified for households, three for commercial customers and one for public lighting. [4] The load profile is then combined with the annual consumption volume in order to calculate a consumption diagram of the particular final consumer. This procedure results in a complex consumption data covering all hourly, daily and monthly details. These constitute a solid platform for the optimization.

Defining the PV technology

Secondly, the PV technology should be defined. Each PV panel type has different results under different conditions. Therefore, it would not be correct to select one of the existing PV technologies and to use it solely. Hence, the calculations are based only on an installed capacity, an efficiency and a surface area of the considered panel. The respective details can be found in datasheets and are used in further process in order to calculate exact amounts of electricity generated by the PV installation. This method allows for a simple and quick technology comparison. Nevertheless, polycrystalline panels are globally used the most. The reason is economical. They are the cheapest to produce and majority of PV producers focus only on this technology. However, it is important to state that their efficiency is slightly lower. [5]

When assessing the profitability, the installation investment (Pi) is a cornerstone. This price is however made up of two items. A panel price (P1P) defines the market price of one selected PV panel. An equipment price (Pe) defines the costs of a wiring, switchgear, inverter, installation work and connected fastening material. All this information can be found in a pricelist of a selected PV panel producer or installer. Market survey showed that the ratio among these two installation price components has usually an exponentially decreasing trend. Higher the panel number, lower the equipment price specified for an installed capacity unit, i.e. consumers installing a bigger PV installation have more favorable equipment price.

To sum up, installed capacity, surface area, efficiency, and complex price details of the specified panel must be gathered in order to proceed into the next stage of the analysis.

Collecting the radiation data

Another factor that needs to be considered is the amount of radiation (G). Naturally, radiation depends on the locality of installation and is affected by weather, shading obstacles, panel orientation etc. All these aspects need to be considered when calculating the PV production. To sum up, it is difficult to predict the radiation amounts. Therefore, various predicting softwares are used. Their calculations are usually based on historical data collected in a specific locality. It might be anticipated that their predictions may not be fully accurate. With a more accurate data more accurate results would be achieved. Majority of the respective softwares are provided only commercially. However, a sufficiently accurate data can be gathered from PVGIS software provided by the European Commission for free. [6] In addition to that, the respective software provides both hourly and monthly average radiation data inevitable for the complex PV production calculation.

Defining the PV installation

With the aforementioned consumption, solar radiation and PV panel data an optimization of the installation can be performed. Thus, the aim of this stage is to define the most profitable PV installation for a specified electricity consumer. This is achieved by consumption and production simulations performed in order to assess the profitability of a PV investment.

The first step is to identify the hourly production values of a selected panel within an average day of each month (E_{1P}). Primary input of this calculation is the hourly radiation amounts of an average day within the month. Other inputs are related to the selected PV panel, i.e. the surface area (S), performance factor (p_F) and efficiency (η). The performance factor represents losses related to an inverter efficiency, dust, snow, wiring and switchboard losses, shading, panel orientation etc. The number usually fluctuates around 0,8 and can be set precisely if needed. The temperature coefficient (c_t) represents monthly adjustments of the calculation related to the temperature disturbances of the PV production. The installed capacity of the PV panel may only be achieved under standard test conditions (STC). Usual datasheet STC temperature is defined to be 25° C. Each deviation influences the PV production. Therefore, it is important to cover a performance increase or decrease related to the temperature. [7]

$$E_{1P} = G * S * p_F * c_t * \eta * t \tag{1}$$

$$\eta = \frac{P_{TC}}{S * G_{TC}} \tag{2}$$

The above stated formulas had to be adjusted, because these results are required to be collected not only for each single hour of the average day in the month, but for each single relevant installed PV capacity that can be considered, i.e. a cumulative hourly production value of the whole PV installation (E_{PV}) needs to be defined for various installed capacities. Thus, an equation (3) was introduced. The number (n) represents the installed capacity of the PV installation. Here it is important to understand that the installed capacity is adjusted by simply increasing or decreasing the amount of PV panels in the installation. A small-scale installation is according to Slovak law an installation with an installed capacity of up to 10 kW. [8] If standard polycrystalline panels with a 270 Wp installed capacity are considered, their number should not exceed 37. Therefore, the simulation data should cover a PV production of 1 to 37 panels. However, if other panels are considered, the number of panels should be altered accordingly.

$$E_{PV} = n * E_{1P} \tag{3}$$

Next step is to define hourly surplus electricity (ΔE) values. These again need to be calculated for each single hour of an average day of the month and for each single relevant installed PV capacity. The surplus electricity represents the amount of electricity that cannot be consumed by the consumer in a real time and thus needs to be sent to the grid or to be stored in an energy storage device or to be utilized in other way that is always more expensive for the consumer than the real time consumption. In order to define the respective data, hourly consumption values (E_C) of an average day in a month are needed. With these details, the amount of surplus electricity generated in a PV installation can be identified for each single hour of 12 average days representing the average conditions of the respective month. The comparison needs to be at least this complex, because both the consumption and the PV production are significantly different throughout the year. The most accurate method would be to calculate these numbers for each single hour of the year based on real consumption data from previous years and on exact solar radiation predictions defined for a concrete upcoming year and its weather conditions. Consumption is largely dependent on household's habits, heating and cooling needs that usually remain very similar throughout the years. The PV generation is mostly affected by the radiation amounts and the weather character. These are predictable with only a certain amount of accuracy. Thus, a prosumer energy optimization always requires an in-depth analysis.

$$\Delta E = E_{PV} - E_C \tag{4}$$

Result of the calculations is a specific number of charts with 12 average days, each with 24 values representing the hourly consumption, production and surplus data. The number of charts depends on the number of considered PV panels. Such complex data allows for daily, monthly and yearly sums of PV production, consumption and surplus and thus constitute a solid platform for comparison of PV installation options.

However, defining the installation's scale is just a part of the optimization process. Potential prosumer has several choices when deciding upon the installation. Three major ones can be distinguished under conditions of the Slovak market. Firstly, opting for a cheapest option, installing solely a PV installation and thus relying only on a real-time consumption of the PV generated electricity. Secondly, increasing the investment and spending extra money on energy storage in order to utilize a higher portion of generated electricity. Commonly used are battery systems usually sold in a bundle with the PV installation. And thirdly, subscribing to a novel service on Slovak market offered by Západoslovenská energetika, a.s. (ZSE), a virtual battery. Respective service provides a theoretical storage of PV generated electricity that cannot be utilized in a real time. It is basically a net metering allowing prosumers to virtually use the surplus electricity generated by their PV installation in periods when their PV generation is insufficient. This is in fact done only through invoicing, i.e. no physical energy storage is included.

Major tool used for analyzing the profitability is a profitability index. It compares the investment costs with the future earnings arising from the investment and thus mathematically expresses the investment suitability. [9] Higher the profitability index, higher the ratio of future cash flows in comparison to its costs. For the purposes this article, the investment represents all the PV installation costs and the future earnings represent the electricity savings related to the PV installation. However, these are significantly different for the above mentioned three scenarios and thus the next step has to be divided into three options.

Real-time consumption scenario

The optimization is crucial especially in case of an installation without a physical or virtual energy storage, because the lack of flexibility in the utilization of the PV generated electricity constitutes a significant barrier in the use of the PV installation. As it was stated above, the installation investment (P_i) can be divided into two elements, the panel price (P_{1P}) and the equipment price (P_e). However, this does not concern a case when only bundles provided by a supplier or installer are considered. Then, the division would be irrelevant and only the provided bundle installations and their costs would be considered. Due to the fact that the aim of the methodology is the profitability index comparison of potential PV installations, the installation price has to be defined for each of the potential installed capacities (n).

$$P_i = n * (P_{1P} + P_e) \tag{5}$$

Renewable energy sources (RES) are often subject to a state support. This concerns PV installations, too. Thus, in case of an investment contribution eligibility, it is important to include this fact in the calculations. This can be done by simple deducting the contribution from the installation price. However, it is important to keep in mind that the contribution may change according to the installation details, usually according to the installed capacity and thus may be different for various considered PV installations.

Next step is to identify the annual savings (P_s), i.e. the financial value of electricity savings. For this purpose, the hourly PV generation data and hourly surplus electricity data connected to each considered scale of the PV installation are used. These numbers are needed to identify the real time consumption within each hour. These amounts are subsequently summed and multiplied by the electricity price (P_{1kWh}) set by a tariff relevant for the particular customer. All the electricity generated in times when the production is higher than the consumption constitutes a surplus that does not provide any electricity savings for the prosumer and is only donated to the electricity supplier, in other words absolutely worthless for the prosumer. Therefore, the optimization needs to ensure its minimizing.

$$P_s = (E_{PV} - \Delta E) * P_{1kWh} \tag{6}$$

The last step is to define the profitability index (PI) for each single assessed installed capacity of the PV installation. These are then compared and the highest is selected as the optimal installation for the real-time consumption scenario.

$$PI = \frac{P_s}{P_i} * 100\% \tag{7}$$

Accumulation scenario

The most frequently used energy storage technology connected with the small-scale PV power plants is the Lithium-ion (Li-Ion) battery storage. Method used in assessing the accumulation possibilities is very similar to the first scenario. However, several adjustments needed to be done. The profitability analysis is slightly more complicated, because it does not only compare various PV installed capacities, but it also compares various battery capacities. In spite of the fact that the Li-Ion batteries are usually sold as preset products and thus cannot be sized to specific capacities, the methodology is aimed towards selecting the most profitable battery capacity irrespective of the offered products. However, assessing the standardized capacities only is an option, too.

When defining the installation investment (P_i) the accumulation price needs to be considered, too. A price of 1 kWh battery storage (P_{1B}) can be defined after an up to date market analysis. With this value, battery system investments related to each considered capacity can be identified by multiplying the respective 1 kWh price with a specific number of kWh (x), i.e. considered capacity. Naturally, this constitutes an accuracy deviation, because higher battery capacities are usually connected with discounts, i.e. the price / capacity ratio is not entirely linear. However, this method can be easily adjusted for standardized offered products and thus to ensure more accurate results. Moreover, the described method can be used for other energy storage technologies, too.

$$P_i = n * (P_{1P} + P_e) + (P_{1B} * x) \tag{8}$$

Major difference in comparison with the real-time consumption scenario is related to the energy savings calculation. The difference is that the electricity that cannot be consumed in a real time has to be divided into two categories, the electricity that can be stored in the battery (ΔEB) and the electricity that cannot be utilized (ΔED), because there is not a sufficient battery capacity in a relevant time, i.e. the electricity donated to the supplier. Their definitions are pretty straight. The surplus electricity, or in other words the electricity that cannot be consumed in a real time, represents the electricity that can be utilized up to a point when the battery capacity is reached. All the subsequently generated electricity that cannot be consumed in a real time is donated to the supplier without any remuneration. Both values can be defined from the hourly consumption, PV production and battery capacity data. This difference results in an adjustment to the annual savings (Ps) formula that needs to include the PV generated electricity stored in a battery.

$$P_s = (E_{PV} - \Delta E + \Delta E_B) * P_{1KWh} \tag{9}$$

After both the installation investments and the annual savings are defined for each considered number of PV panels and for each considered battery capacity option, the profitability indexes for individual combinations can be identified and the highest can be selected using the same technique as in the previous scenario.

Virtual battery scenario

A precondition of the virtual battery service is a smart meter capable of measuring both the amount of electricity purchased from the electricity supplier and the amount of electricity send back to the grid in times when the PV generated electricity is not needed. This allows ZSE to motivate potential prosumers to opt for one of their PV installations by offering a service consisting of a virtual storage of the surplus electricity. The idea is to allow customers to utilize the surplus electricity sent to the grid later when the PV installation does not provide enough energy. This is however performed only financially via an annual electricity invoice. Price representing the annual amount of the virtually stored surplus electricity is deducted in the settlement invoice from the costs of the consumed grid electricity. This means that the service subscription is not reflected in the monthly bill and the customer is monthly charged in the same manner as any other customer without the respective service. On the other hand, the deduction does not include the whole electricity price, but only one of its components, the electricity supply. This represents approximately only 30 to 40 % of the electricity price, depending on customer´s tariff. In addition to that, the service in question is a subject to a monthly fee of 2 €. All these characteristics have to be included in the methodology.

Firstly, the installation investment (P_i) has to be identified for each considered PV installed capacity. This is done in the same manner as in the real-time consumption scenario.

Secondly, the annual savings (P_s) definition has to be distinguished into two variants. First for a case when the electricity sent to the grid is fully utilized in the virtual battery service, as described in equation (10). Second in case this is not possible. Here, the surplus electricity has to be divided into two categories, the electricity that can be virtually stored (ΔE_{VB}) and the electricity that cannot be virtually stored and has to be donated to supplier (ΔE_D). The reason is that the amount of PV generated electricity sent to the grid can only be deducted from the annual electricity price up to the amount of consumed grid electricity. Thus, if the amount of electricity sent to the grid is higher than the amount of grid electricity consumed, only a part of the surplus electricity sent to the grid can be utilized in the virtual battery service. The amount of virtually stored electricity under the second variant can be defined as a portion of consumed electricity that does not include the real-time consumption of PV generated electricity. The rest of the surplus electricity represents the amount that is only donated to the supplier and thus does not stand for any electricity savings. This is expressed in formulas (11) and (12).

$$E_{VB} = \Delta E \tag{10}$$

$$E_{VB} = E_C - (E_{PV} - \Delta E) \tag{11}$$

$$E_D = E_{PV} - E_C \tag{12}$$

The next step is to sum the hourly electricity amounts of the real-time consumption, of the virtual storage and of the donated surplus in order to calculate their annual values. This data is subsequently used for the annual savings identification. In this process, electricity price per kWh (P_{1kWh}) has to be known together with its component representing the electricity supply price

($P_{SC\text{-}1kWh}$). Moreover, the flat rate subscription fee of 24 € per year (P_F) has to be deducted from the savings.

$$P_s = [(E_{PV} - \Delta E) * P_{1KWh}] + [E_{VB} * P_{SC-1KWh}] - P_F \tag{13}$$

Finally, the last step is to calculate the profitability index for each considered PV panel capacity using the same formula as in both previous scenarios in order to identify the most profitable installation.

Conclusion

The aforementioned methodology results in three profitability indexes. Each of them represents a specific option for the potential prosumer. Profitability index is a universal financial characteristic that is widely used to compare investments. Thus, it can be used to identify, which of these options is the most profitable.

PV optimization service is globally offered by dozens of companies that have either developed their own software or use a licensed version of another provider. The main advantage of the discussed approach is the fact that it is tailor-made for the purposes of the current Slovak market and that it can be easily adjusted according to existing conditions, in other words extended to include novel services, price fluctuations, PV or accumulation technologies etc. In addition to that, the defined process is a methodology and thus can be included in a software that could after providing customer's data, answer the question, which PV installation is optimal.

On the other hand, a significant drawback represents the fact that it is fully dependent on the consumption and production data. These are rarely fully accurate. However, novel weather and solar radiation prediction softwares are being developed every year. Therefore, it might be assumed that the amount of error will only decrease in the future. With more accurate data a more accurate optimization may be performed with the respective methodology.

To sum up, a complex assessment model was developed in order to quickly and easily define an optimal small-scale PV installation for a potential prosumer under conditions of the Slovak market.

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