Parking Lot Roofing with PV Panels: Solution for the Specific Use of Photovoltaic Source

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***Abstract*—Photovoltaics (PV) is one of the solutions that contributes to the diversification of energy sources and in addition to reasonable integrating into the grid positively affects the energy security and self-sufficiency. The use of photovoltaics for combined use with the aim of eliminating the depreciation of valuable/agriculture land is starting to be a relevant and discussed topic. The paper illustrates a specific case of the integration of photovoltaics for the needs of a parking lot and powering an associated railway station. The designed parking lot type park and ride at the railway station in Nové Košariská in Slovakia and the related technical and economic analyses in variant scenarios were chosen as a model case of study.**

***Keywords*—photovoltaics, photovoltaic source, photovoltaic power plant, storage, parking lot, innovations, simulations, power plant, self-sufficiency, software, return**

I. Introduction

The gradual increase in the share of renewable energy sources (RES) in the energy mix is a global trend. The European Union (EU) responds to global trends and at the hand of directives and regulations obliges member states to adopt measures that would meet these goals. The adoption of Directive 2001/77/EC on the promotion of electricity produced from renewable energy sources in the internal market was the basis for these activities [1]. Slovakia responded to this directive with several steps and legislative documents, such as the Concept for the Use of RES (2003), the Government Program Statement (2002-2006), the National Strategy for Sustainable Development and the Energy Policy of the Slovak Republic (2010). Slovakia was committed to significantly increasing the share of RES in energy mix. The plan was to achieve a 19 % share of renewable sources in year 2010, from the initial state (5.2 TWh of electricity) represented by a share of 16 % of its consumption in 2006, 24 % in 2020 and around 27 % in 2030. According to current sources [2], electricity produced from RES accounted for 22.9 % of the total electricity production in the Slovak Republic in 2022. Compared to 2021, the total share of RES in electricity production increased by 1.6 %. Across the entire monitoring period in the RES energy mix dominates hydropower, up to 71 % of the installed capacity in 2023. In the PV sector in the recent period, there have been two significant increases in installed capacity. As shown in Fig. 1, the first significant increase in installed PV capacity at the turn of 2010/2011. It was contributed by large state subsidies mediated by the Slovak Innovation and Energy Agency. The European Investment and Structural Funds also played a role in this increase and simultaneously synergistically supported research in this area in Slovakia [3].

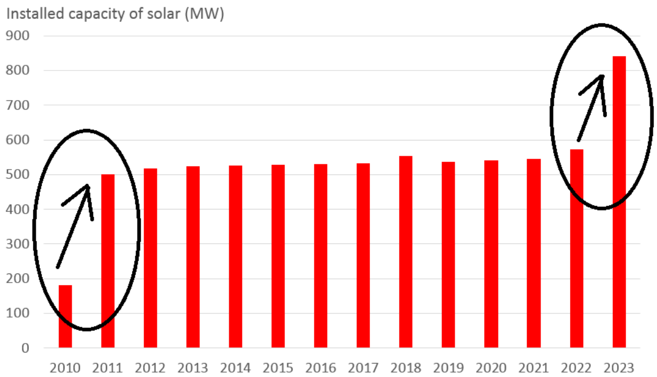

Fig. 1. Overview of the development of the installed capacity of PV sources in Slovakia in years 2010-2023 [4, 5, 6].

The second significant increase in the share of installed photovoltaics occurs in 2022/2023. The reason for this increase is the increased interest of industry and households in the energy transformation, which was motivated by the energy crisis, the military conflict in Ukraine and various grant schemes [7].

Renewable energy currently represents a 23 % share in the Slovak energy mix with the potential for further growth. Photovoltaic production contributes to the RES mix with a share of approximately 3%. It is necessary to look for other solutions for its effective integration into the functioning of the electricity transmission and distribution system.

Full utilization of PV which represent the supplied by power adequate to the installed capacity is on average 4 hours per day which is reflected on lower return on investment compared to conventional sources. Despite that currently is a greater dynamic increase in new installations. These activities also bring new problems and research challenges. The unpredictability of supplies and the associated impacts on the grid are the subject of many research projects. In addition to conventional solutions represented by large-scale power plants implemented and rooftop installations, the more

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massive introduction of PV also brings various unconventional compositions. Panels as part of skylights and facades [8] are not only progressive application. A wide range of applications can be found in the world, for example: 1 km long solar road (communication from solar panels) in Tououvre au Perche in Norway [9], or PV fields located on the sea surface in Jipyeong Reservoir (South Korea) [10], Kyocera (Japan), Kayamkulam (India) and Sungrow (China) [11, 12]. In addition to saving land, the placement of panels on the water surface brings another significant benefit. Heat dissipation and cooling of the panels and the associated positive impact on the efficiency of the installation are the advantages of such a solution. In addition to the fact that the PV installation sensitively integrated into the structure of the relevant building increases its architectural value and brings energy savings, another important fact should be mentioned. In connection with the expansion of photovoltaic installations, the protection of valuable agricultural land [13] and the search for adequate solutions are increasingly discussed topics. Recently, the so-called agriphotovoltaics, which represents a shared platform between the use of land for cultivation and the production of electricity by PV panels [14].

Photovoltaics integrated into the new or renovated buildings in accordance with the EU regulation No 305/2011 [15] or its transposition into the legislation of the member states of the community is one of the ways to reduce the carbon footprint or achieve the basic requirement - energy consumption of the building close to zero. In addition to integrating photovoltaics into a newly built or renovated building and striving to achieve consumption close to zero, it is important to analyze other potential loss points and find energy savings opportunities. Identify of heat losses points, redesign of lighting to be more energy efficient and prevent unnecessary electricity consumption (appliances in stand-by mode, demand lighting, etc.) are other options for eliminating unnecessary consumption [16].

A photovoltaic parking lot equipped with an accumulation system represents a microgrid or a local energy system [17, 18]. The currently increasing share of microgrids places increased demands on the control and stability management algorithms. The dynamics of imbalances between energy supply and demand caused by unexpected load changes can affect frequency changes in the microgrid, which can result in damage of microgrid components or blackout. We will achieve the elimination of undesirable effects through high-quality design activities and the use of available simulation tools [19]. With a reasonable setting of the volume of installed photovoltaics (number of panels), accumulation system and intelligent control, such a system represents an important element of the smart grid of the future [20]. By optimally using the energy obtained for the car the consumption of the location of the car park (security systems, night lighting) and charging electric vehicles, which are zero-emission demand appliances, we obtain an object which positively affects energy sustainability. Such solution provides shade and protection for cars against the environmental influences - sun, rain and snow and at the same time is photovoltaic car park an important supporting element for a smart electricity grid [21]. Saved land for other uses is another benefit. In Europe a whole range of such solutions already exists. The largest project of this type is the Disneyland car park in Paris with 82 000 installed panels, shade for 11 200 cars, and an installed capacity of 36.1 MW at area of 20 hectares. The ambition of the paper is to use a model case to show the methodology for designing PV parking system, taking into account current technical and economic contexts in Slovakia, and to illustrate the variability of solutions using alternative solutions for the photovoltaic parking.

II. Photovoltaic Source Design

Current Slovak legislation [22-25] distinguishes between photovoltaic devices and photovoltaic sources. This division is determined by the installed capacity and the installation location. The scope of the design activity and permitting processes [3] also depends on this. The design of a photovoltaic source/power plant in generally consists of the following steps:

- selection of the location,
- mapping the amount of solar radiation impact in given location,
- analysis of electricity demand,
- analysis of the consumer's consumption diagram (Fig. 2 shows the real consumption of the object selected for analysis and design purposes),
- selection of compatible components,
- simulation of systems with selected components and selection of the most efficient combination of components,
- tuning the system according to the consumption diagram,
- analysis of the generated electricity,
- analysis of profitability and return.

A. Location and conditions for the design

The location for the PV source design was selected by taking inspiration from the project for the renovation of the Slovak railways (SR) stations and the construction of integrated transport terminals and a network of parking lots. The project for the renovation of the railway station in Nové Košariská and the design of the adjacent parking lot is in the design process (preparation of documentation for a building permit) [26]. The ambition of the study is to bring added energy value to the parking lot by designing the supporting structure of the photovoltaic power plant above the aforementioned parking lot.

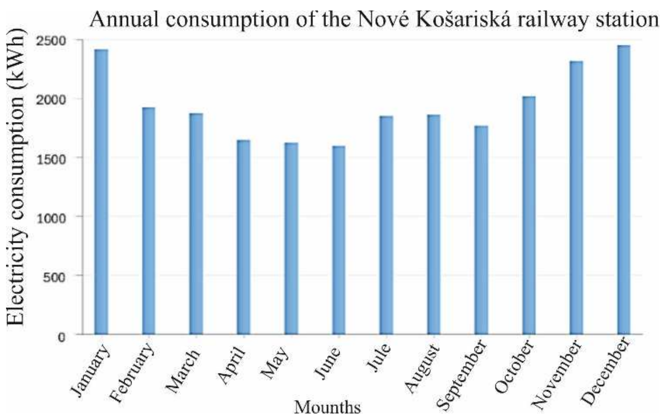

Fig. 2. Annual development of energy consumption in the associated railway station.

It was determined that the optimal structure for the proposed systems is a roof slope of 17°, orientation to the south-west and a roof area of 117.2 m^2. Such activity also gives for the SR a certain kind of green smart reference. The key to the design of the PV source is mapping local solar conditions and analyzing the demand for electricity and the consumption diagram. The PV geographic information system PVGIS was used to determine the amount of solar energy in this case. Data on annual 15-minute power peaks were provided by the SR. The selected consumption point has a total annual consumption of 23 351 MWh.

We see on the monthly diagram of electricity consumption that the profile of electricity consumption in the winter months is greater than in the summer months. This is caused by heating devices that are used for heating and it can also be caused by longer operation of lamps.

B. *Simulations of proposed PV systems*

Simulations of variants were carried out using the PV*SOL software. This software has libraries of components considered in this work. Another database implemented in PV*SOL is a database of hourly data on weather, solar radiation impact on locations from 1996 to the present [27]. In the interactive part of the software, it was necessary to plot the location of photovoltaic panels, their angle and azimuth.

III. Analysis of Variant of Proposed PV Systems

Four variants were selected for the case study demonstration. The variants differ in the number of panels, the possibility/impossibility of energy storage or an added charger for an electric car. The following is a brief description of the individual variants.

A. *Variant 1*

The design condition are considered with the aim of the smallest possible investment in the basic system. This system consists only of photovoltaic panels, inverter, dynamic supply management, cabling and assembly components. The total number of installed panels is 18 with total area of 35.1 m^2 with an installed power of 7.38 kWp. The specific annual electricity yield is 1145.52 kWh/kWp. One inverter with a nominal power of 8 kW was used. Another system parameter that the system should meet is the minimum amount of surplus electricity supplied to the grid. This requirement is ensured by dynamic management of electricity supplies to the grid. The total electricity produced from the photovoltaic power plant is used at the point of consumption for 61.1 % and the rest is supplied to the power limiter, which limits 24.4 % of the electricity and the remaining 14.5 % is supplied to the grid in the form of surplus. For a realistic view of the situation of mounted photovoltaic panels 3D view of the photovoltaic power plant was generated. In this variant, less than three parking spaces are covered by the shadow comes from the photovoltaic panels. This is a small system that would be more suitable to be applied to the roof of the railway station itself. This variant was analyzed for the illustrative purpose of implementing a small local source of up to 10 kWp.

The photovoltaic panel connection system is connected into 2 strings with the panels in each string connected in series.

The economic analysis of the first variant of the photovoltaic power plant design was calculated based on an initial investment of 4 649.40 €. The payback period of the system designed in this way is estimated based on calculations to be 5.1 years. The analysis was calculated for a period of 25 years. In the case of replacement of worn components, the investment in maintenance and the replaced component must be deducted from the resulting amount in the 25th year of operation of the system. The price of surpluses in the calculations of financial economy is considered to be 0.03 € and the price for the purchase of electricity is 0.17 €. Such prices are defined in all variants in the simulations.

B. *Variant 2*

The condition of supplying the smallest possible surplus to the grid is again met in the second variant. We consider a system consisting of the same panels as in the first variant with a larger number of panels (42) with a total area of 82 m^2 and an installed capacity of 17.22 kWp. The specific annual energy yield is 1160.84 kWh/kWp. A battery system with a nominal capacity of 20 kW with a total capacity of 41 kWh is also consider. The number of batteries in this system is 10 with a capacity of one battery of 100 Ah. To limit the supply of surplus to the grid, dynamic control of electricity supply to the grid is used. The total generated electricity is used at the point of consumption by 71.96 %.

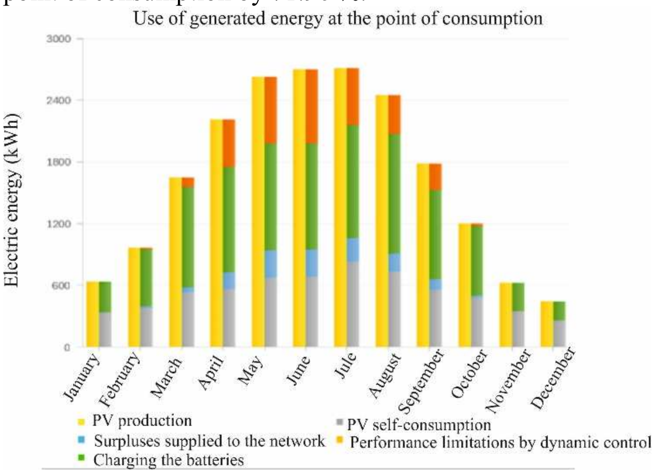

Fig. 3. Use of generated electricity for variant 2.

The remaining energy is lost in the form of charging losses, namely 5.74 % in the form of surpluses, which are limited by dynamic control and only 6.48 % of the energy produced by the power plant is transferred to the grid. Electricity consumption was reduced by 61.5 %. In Fig. 3 it can be seen that surpluses to the grid are almost zero in the winter months and at a possible minimum in the summer. The largest amount of electricity produced by the system is stored in the battery system and subsequently consumed as needed. The initial investment costs of variant 2 are 17 047.80 € with a payback period of 6.8 years. The total gross profit excluding service costs and replacement of spare components is 51 887.60 €. After deducting service costs, replacement of the inverter or one panel of €1806, and also the double replacement of the battery system cells in the total amount of 15 200 €, the total gross profit is 34 881.60 €.

C. *Variant 3*

PV system with a battery system shown in Fig. 4, which is also equipped with a charging station for electric cars is considered in this variant. By adding a charging station for 2 electric cars, the number of installed panels had to be increased to cover the additional electricity consumption.

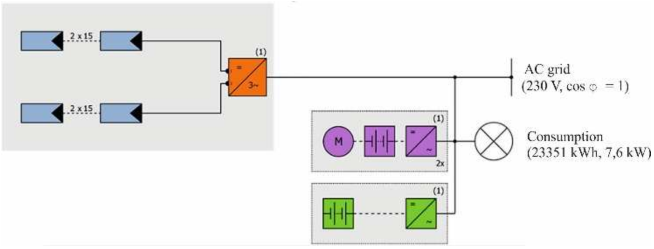

Fig. 4. Principle diagram of the photovoltaic power plant system for var.3.

The number of installed photovoltaic panels is 60 with a total installed power of 24.6 kWp with a total area of 117.2 m[2]. The specific annual yield is 1160.77 kWh/kWp. The topology of variant 3 and the connection of the panels is shown in Fig. 5.

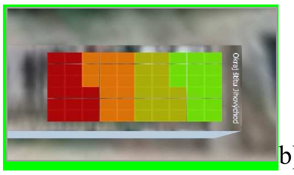
b)

Fig. 5. The connection of panels into 4 strings for 3rd variant.

One inverter with a nominal output power of 20 kW is used. For the added 2 charging stations for electric cars, it was necessary to increase the number of installed panels. The percentage ratios of electricity flows are almost identical to those in variant 2. The total electricity produced by the power plant is used at 72.76 %. The expected development of consumption for variant 3 is shown in Fig. 6.

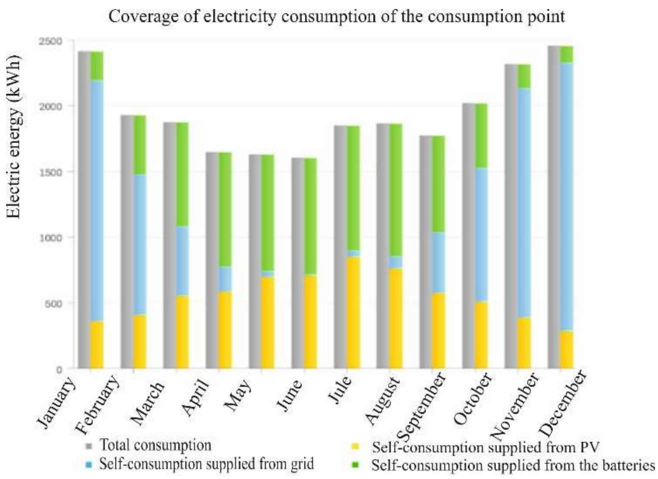

Fig. 6. Use of generated electricity at the point of consumption for var.3.

The initial investment costs in variant 3 of the proposed system are 24 354.00 €. Their payback period is based on 6.7 years, as illustrated in Fig. 7. The total gross profit excluding service costs and replacement of spare components is 75 271.97 €. After deducting service costs, replacement of the inverter, possibly damaged panel 1806 €, and also the double replacement of battery system cells in the total amount of 15 200 €, the total gross profit is 58 265.97 €. From an environmental perspective, the system designed in this way will reduce CO_2 emissions by 10.672 kg/year. And the railway station will consume “green electricity”.

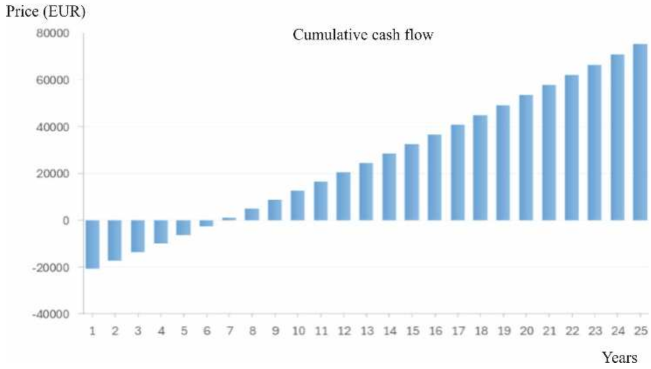

Fig. 7. Development of cumulative cash flow over 25 years for variant 3.

D. *Variant 4*

This variant has the same parameters as variant 3, with the difference that the panels are tilted at an angle of 35° by means of an additional structure. The nominal power 25 kW of the inverter is different. An additional structure installed on the roof structure is required to fix the panels. Thus, the roof tilted at 17° would be preserved, but each row of panels would be tilted by another 18°.

The total energy generated by the system in variant 4 of the design is 29 156 kWh, which is 2 % more production than in the system proposed in variant 3. The total initial investment is 11 % greater due to the use of an additional structure and a more powerful inverter. From an economically practical point of view, we decided to evaluate variant 4 as an inefficient system. Thus, the simulation of this system was only partially completed. Fig. 8 demonstrates the energy ratios in the fourth variant.

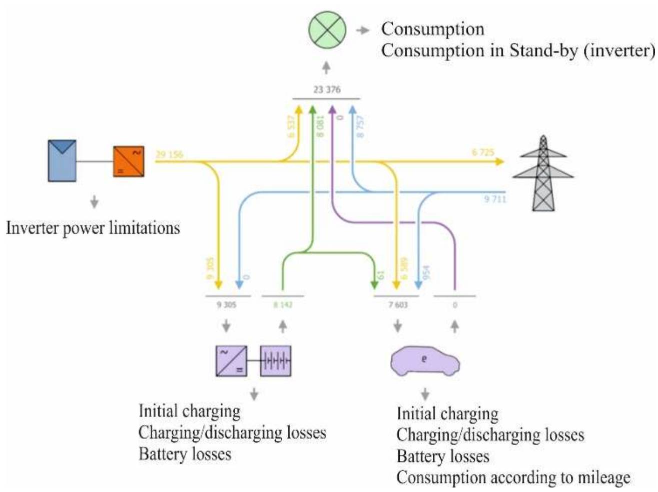

Fig. 8. Diagram of electricity flows in kWh variant 4.

IV. More Detailed Analysis of the Selected Variant

The evaluation of variant solutions requires a multi-criteria approach, we took into account the initial investment and its return in this case. It should be added that these two criteria may not always be decisive, e.g. if there was a requirement that the entire parking lot be covered with panels, which would monitor the effect of protecting cars from direct sunlight and other weather influences, and the PV return, or surpluses to the grid, would not be the primary monitored parameter. From the point of view of optimizing the parameters price vs. return, the third variant was selected and designed into a practical form. This variant can be evaluated as an optimal due to the low investment, medium-fast return and high rate of use of the generated electrical energy. The panel system is located on the raised structure of the parking lot roof. The battery system should be located in a ventilated room, ideally in the technical premises of the railway station. A detailed analysis from an energy point of view is provided in Tab. 1, or Fig. 9.

TABLE I. SUMMARY TABLE OF SIMULATION RESULTS

PV generator		
PV generator output	17.22	kWp
Specific annual yield	1 160.84	kWh/kWp
Plant utilization factor (PR)	91,38	%
Shading yield reduction	0.1	%
Assumed PV energy generated	20 014	kWh/year
Direct self-consumption	6 339	kWh/year
Battery charging	9 214	kWh/year
Inverter output limitations at the feed-in point	3 164	kWh/year
Energy feed-in	1 297	kWh/year
Share of self-consumption	77.7	%
Reduced CO_2 emission	7 348	kg/year
Consumer	23 351	kWh/year
Standby consumption (Inverter)	25	kWh/year
Total consumption	23 376	kWh/year
Covered by PV	6 339	kWh/year
Covered by battery net	8 065	kWh/year
Covered by grid	8 972	kWh/year
Share covered by solar energy battery system	61.6	%
Battery charging (Total)		
Battery charging	9 214	kWh/year
Battery charging (Grid)	9 214	kWh/year
Battery power to cover consumption	0	kWh/year
Charging/discharging losses	8 065	kWh/year
Battery losses	969	kWh/year
Cycle load	221	kWh/year
Total consumption	6	%

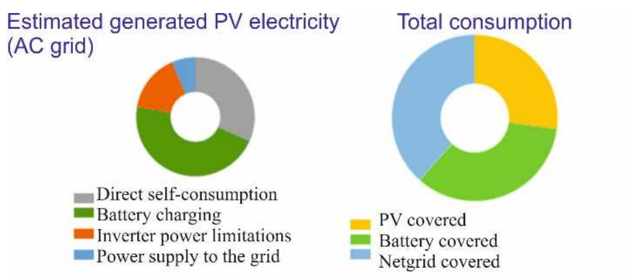

Fig. 9. Graphical interpretation of energy ratios for the optimal variant.

V. CONCLUSION

The paper provides a comprehensive view of the specific method of incorporating photovoltaics in an urbanized area. The current trend in the use of renewable energy sources is their integration into the existing infrastructure with the aim of reducing the consumption of the given unit, land use and increasing the architectural value of the relevant object. Many such solutions already exist in the world, with the PV parking lot being a symbiotic combination of comfortable parking in the shade with the benefit of generated electricity produced by shading PV panels. The work was focused on the use of PV for the parking lot at the railway station in Nové Košariská. Four system variants were developed, from the system with the smallest size and investment to the system that was excluded from a more detailed evaluation due to too large an investment and a high rate of return of 9.8 years.

The optimal variant of the photovoltaic power plant system in the parking lot concept was developed into a practical form with appropriate technical and financial evaluation.

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