VARIANT SOLUTIONS FOR A PARKING LOT COVERED WITH PHOTOVOLTAIC PANELS

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Abstract

The photovoltaic system is a relevant energy source that, in addition to the well-known negative impacts on the grid, bring specific added value. Photovoltaic panels are valuable element in progressive building architecture. Such incorporation of photovoltaics brings potential eliminating the take-up of valuable land. The use of panels for parking lot roofing is a symbiotic solution that saves agricultural land and protects parked cars from various external environmental influences. The ambition of the paper is use a model example and in variants solutions show the technical and economic context. Designed parking lot in Nove Kosariska, retrofitted with a PV system in four alternative solutions is presented in this paper.

Key words

Photovoltaics, parking, smart, microgrid, battery, PV system, microgrid.

Introduction

Growing energy consumption requires new sources and new approaches. Almost 100 % newly installed sources in the world's in the last year was based on renewable energy, with China leading the way in their construction. This dynamic trend is influenced for some renewable sources by simpler technical and economic implementation and therefore the ability to respond to growing electricity consumption, more accessible than traditional sources, i.e. gas, coal or nuclear power plants.
In Slovakia, in 2024, practically 100% of the newly connected 280.16 MW of electricity generation capacity consisted of RES, specifically photovoltaic (PV) power plants [1]. Although this acceleration, even exceeds the goals set out in the National Energy and Climate Plan, photovoltaic production contributes to the renewable energy sources (RES) mix with a share of approximately 3% and renewable energy currently with 23 % share in the Slovak energy mix. This increase and its dynamics will not be enough to meet the needs of industrial decarbonization to which we are committed.
Such dynamic increase in the share of connected RES sources across European countries has other reasons as well. The main driving force are the activities of the European Union in the form of regulations and directives. Greater use of energy from renewable sources is an important part of the package of measures needed to reduce greenhouse gas emissions and comply with the 2015 Paris Agreement and the EU climate and energy policy framework (2020 to 2030).

The main legislative instrument driving the development of renewable energy is the currently valid Directive (EU) 2023/2413 of European Union (EU), which replaced Directives 2018/2001 and its previous versions [2].
The reason for this was to update the energy rules in the framework of the European Green Deal and the "Fit for 55" package, which aim to ensure that these rules are in line with its objective of carbon neutrality by 2050 and its target of reducing net greenhouse gas emissions by at least 55 % by 2030 compared to 1990 levels. These rules were also amended to implement the REPowerEU plan, which aims to reduce the EU's dependence on Russian oil and gas.
In addition to legislative instruments that influence using subsidies the creation of new RES installations (with photovoltaics playing a primary role in Slovakia), this dynamic growth also has other reasons. Recently, we have been observed a significant increase in small installations, e.g. on the roofs of family houses.
Among reasons for the growing number of photovoltaic sources is the implementation of European Directive 305/2011 into national legislation, as well. The aforementioned directive obliges member states of EU to develop measures to ensure that newly constructed and renovated buildings have a carbon footprint close to zero [3].
Newly created PV installations must take into account not only the technical aspect of the cooperation of an unpredictable source with the network, but also follow the architectural solution and urban planning, or, for example, choose solutions that eliminate the use of useful agricultural land.
Research is not only academic in nature but have also seen real applications, e.g. PV module as part of skylights and facades [4], a cycle path or a road made of PV panels [5], PV panels placed on the water surface of a sea or lake [6-8] and integration of PV power plants into greenhouses and plantations known as agriphotovoltaics [9].
Using panels as a replacement for a parking lot roof is one such solution. Parking lot which uses PV panels, brings a whole range of benefits:

•The panels covering the parked cars use the space, which, by replacing a conventional roof, brings added value in the form of an electric energy generator.

•The cars are protected from adverse weather conditions, especially rain, snow, or strong direct radiation,

•the multifunctionality of the solution represents the existence of a source for powering the parking lot's own consumption or support for charging electric cars,

•for the company that implements smart PV parking, brings an increase in its image in relation to sustainable transport and energy,

•a parking lot equipped with photovoltaic panels contributes to reducing CO_2 emissions and a positive impact on climate change,

•as simulations in variant forms show, the chosen parking lot solution with photovoltaic panels is also an economical solution with reasonable economics, i.e. costs vs. revenues.

PV parking roof supplemented with battery storage, control and optimization systems, or a charger for electric vehicles connected to a conventional grid, we consider as a microgrid or a distributed source of electrical energy [10, 11].
The main task in designing process is to optimize the number of panels, their inclination, battery storage capacity and control system to eliminate unwanted impacts on the network, optimize production and consumption, as well as the economic return on the system. The presence of electric vehicles makes the system a demand-driven appliance and can be an important element of the smart grid of the future [12].

Photovoltaic source design

The procedure for designing a photovoltaic source or power plant has already been developed in detail and published in several studies [13]. In general, various simulation tools (e.g. Photovoltaic Geographical Information System (PVGIS), PV*SOL, SolarEdge Designer) are used for design, while it is necessary to take into account the relevant location and its climatic and weather conditions, the energy consumption of the given object and economic context. Likewise, the complexity of the permitting processes depends on the installed capacity and the relevant legislation of the country. Based on installed capacity, in the case of Slovakia legislative, we distinguish photovoltaic devices and photovoltaic plants [14]. In Slovakia, photovoltaic sources include small electricity sources (up to 10.8 kW) and local sources. A device for generating electricity from solar energy, most often located directly on the roof structure or the perimeter shell of a building (building), whose output is fed directly into the distribution system, is understood as a photovoltaic power plant under Slovak legislation.

Location and conditions for the design

The aim of this paper is to demonstrate using analyses of variant solutions, the usefulness of such an approach and given the current price of energy, the economic advantage of a solution. We were inspired by the project of integrated transport terminals in the Bratislava agglomeration and associated parking lots. The subject of the research is the designed parking lot in Dunajska Luzna, which is in the project phase for documentation for the zoning decision [15]. Retrofitting the parking lot with a roof consisting of solar panels will make it possible to partially cover the consumption of the associated railway station, will introduce an interesting urban element into the environment, and last but not least, such a system can be retrofitted with a charger for electric vehicles, which are an important element in the concept of a microgrid and intelligent network of the future.

The PV geographic information system PVGIS was used for mapping local energy conditions and estimated yield of an energy source. Accepting the location of parking and results from PV-GIS for optimal PV source condition is a roof slope of 17°, orientation to the south-west. The amount of generated electricity depends on the number of panels and the availability of solar radiation. The southern parts of Slovakia are considered the most suitable for the installation of PV sources and, as can be seen in Fig. 1, the availability of radiation for the studied location follows a standard Gaussian curve.

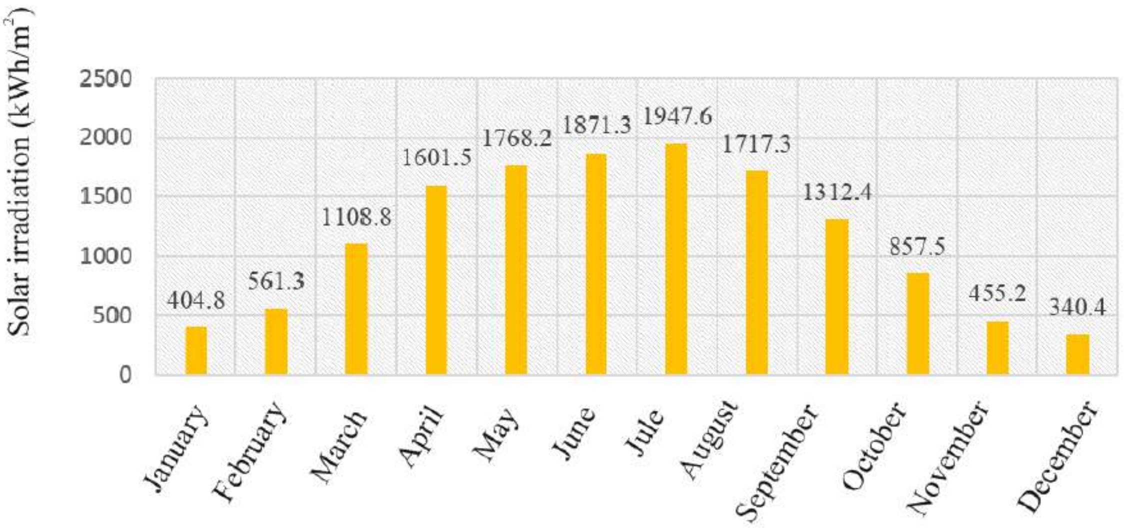

Fig. 1 Irradiation of the surface of panels in a selected location in Nove Kosariska.

With regard to balanced production and consumption it is important to set up the system, especially the number of panels, the sizing of inverters and batteries based on the consumption profile of a given point of consumption (railway station). Consumption data was provided to us by the Slovak Railways company in the form of a 15 min power maximums while a total annual consumption is 23 351 MWh. The consumption profile as well as other details about the consumption point is the aim of another study [13]. PV*SOL software was chosen as a software tool for variant analyses of PV systems. This software environment works with a database of meteorological data, it is possible to very intuitively "build" different types of PV system compositions (batteries, car chargers, etc.) and its outputs contain both technical and economic data [16].

PV*SOL software outputs do account for the degradation of photovoltaic panels, which is a critical factor for long-term performance analysis. This feature allows for the simulation of a gradual decrease in panel efficiency over the system's lifespan, typically modeled as an annual percentage. By incorporating this degradation rate, the software provides a more realistic and accurate projection of energy yield and financial returns over 25 or more years. Therefore, the simulation results represent a dynamic long-term performance trend rather than a static output for a single year. This approach ensures that the model reflects the real-world behavior of a solar power system.

Analysis of variant of proposed PV systems

It is standard in technical practice that each investment action has a so-called pre-project preparation and implementation documentation. In the initial stages of each project, a technical and economic assessment is made, mostly for various scenarios, starting with a minimalist variant and ending with a maximalist solution. In our paper, we present selected alternative solutions for smart parking, which differ not only in the number of panels but also in the possibility of energy accumulation or charging electric vehicles.

Variant 1

The first alternative solution is a small system consisting of 18 panels, which minimizes overflows into the distribution network with dynamic supply management. The area of the PV roof is 35.1 m^2 with an installed power of 7.38 kWp and annual electricity yield is 1145.52 kWh/kWp. This configuration corresponds to covering only three parking places. The total electricity produced from the photovoltaic device 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. Presented small system would also be suitable for installation directly on the roof of the station and was chosen and analyzed for illustrative purposes. This variant represents a small system up to 10 kWp, the advantage of which from a legislative point of view is that it is easier to implement from the point of view of permitting processes. From a technical point of view, a series-parallel connection of the panels into two strings was chosen.

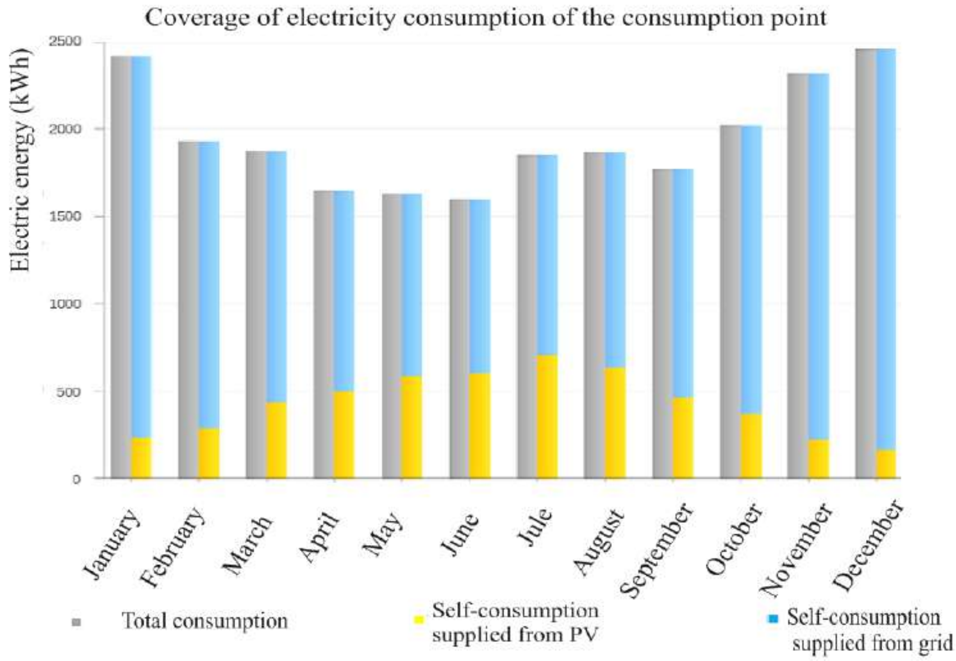

Fig. 2 Energy consumption ratios in the investigated variant 1.

The economic analysis takes into account the initial investment in the value of 4 649.40 € with a payback period 5.1 years. More detailed data on the economics of the solution for the first and last 5 years are presented in Table 1.

Table 1 Cash flow for the first 5 years after the payback year and the last 5 years of the mapped period of variant 1.

	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**
Investments	-4 649,40 €	0,00 €	0,00 €	0,00 €	0,00 €
Feedback rate	30,12 €	30,14 €	29,84 €	29,55 €	29,25 €
Savings from electricity consumption	848,86 €	876,14 €	884,82 €	893,58 €	902,42 €
Annual Cashflow	**-3 770,42 €**	**906,28 €**	**914,66 €**	**923,12 €**	**931,68 €**
Cumulative cash flow	-3 770,42 €	-2 864,14 €	-1 949,48 €	-1 026,36 €	-94,68 €

	Year 21	**Year 22**	**Year 23**	**Year 24**	**Year 25**
Investments	0,00 €	0,00 €	0,00 €	0,00 €	0,00 €
Feedback rate	24,95 €	24,70 €	24,46 €	24,21 €	23,97 €
Savings from electricity consumption	1 056,50 €	1 066,97 €	1 077,53 €	1 088,20 €	1 098,97 €
Annual Cashflow	**1 081,45 €**	**1 091,67 €**	**1 101,99 €**	**1 112,41 €**	**1 122,95 €**
Cumulative cash flow	16 052,11 €	17 143,77 €	18 245,76 €	19 358,17 €	20 481,12 €

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 €. The above calculation of financial flows in this case does not take into account the potential replacement of damaged components and must be deducted from the given amount in the event of such intervention.

Variant 2

Due to the realization and optimal setting of production and consumption at a given location, the number of panels was increased and battery storage was added in the second variant. The solar roof in this variant is composed of 42 panels with area 82 m^2, installed capacity of 17.22 kWp and specific annual energy yield is 1160.84 kWh/kWp.
In the electricity flow diagram of the 2nd variant of the system shown in Fig. 3 one can see out the reduction in the total electricity consumed from the grid if it is compared to the 1st variant. It is also interesting that by adding a battery system it is able to increase the number of panels and store the excess electricity that is produced outside the peak consumption points in a battery storage and then consume it when needed. However, the surplus is not fully utilized and so dynamic control is installed, which limits the power supplied in the form of surpluses to the grid.

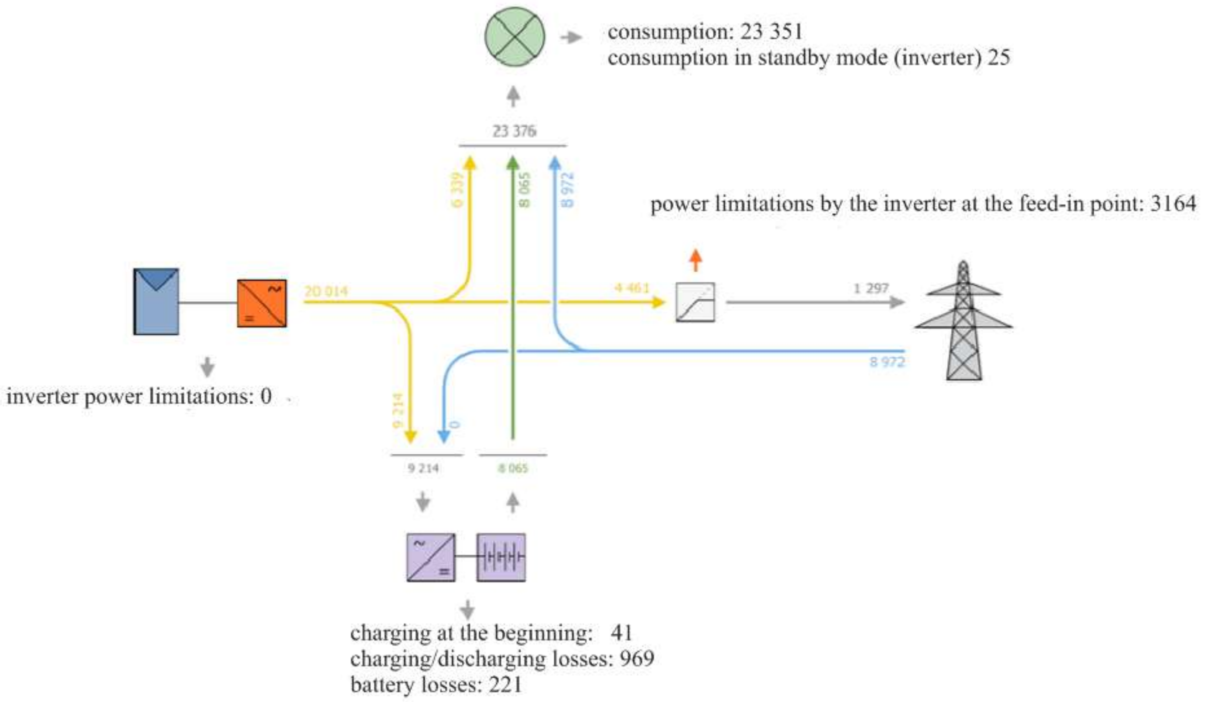

Fig. 3 Electricity flow diagram in kWh (2nd variant).

A battery system with a nominal capacity of 20 kW with a total capacity of 41 kWh is also consider. 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 % and a closer overview of the production is provided in Fig. 4. 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. 4 it can be seen that surpluses to the grid are almost zero in the winter months and at a possible minimum in the summer. Fig. 5 shows the energy ratios from a consumption perspective.

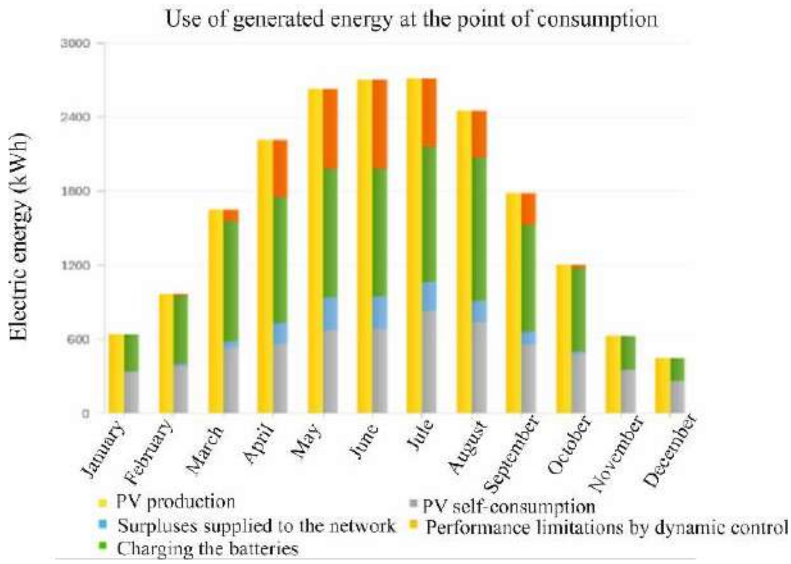

Fig. 4 Use of generated electricity (2nd variant).

The investment in variant 3 is 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 €.

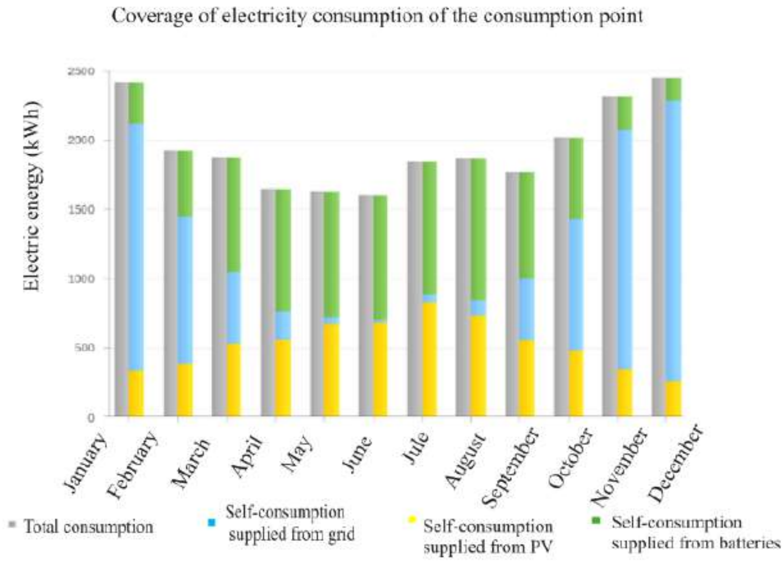

Fig. 5 Energy ratios in variant 2 from a consumption perspective.

Variant 3

The system comprises two photovoltaic arrays rated at 2.41 kWp each (grey), which supply direct current to a central inverter (orange). The inverter converts the generated DC electricity into alternating current that can be delivered to the public AC grid (230 V, cos φ = 1) or used to meet local demand, represented by the lamp symbol, with an annual consumption of 23,351 kWh and a maximum load of 7.6 kW. The model also incorporates two electric vehicle charging stations (purple) and a battery storage unit equipped with a charge controller and inverter (green), allowing for enhanced system flexibility and optimized energy management.

Due to increased charger consumption, the number of PV panels was increased from 42 to 60 with a total installed power of 24.6 kWp and the specific annual yield is 1160.77 kWh/kWp. The composition of this assembly can be seen in Fig. 6.
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. 7.

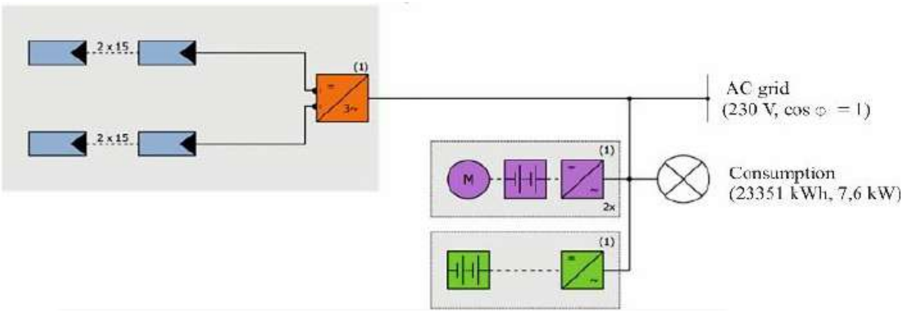

Fig. 6 Principle diagram of the photovoltaic power plant system for var.3.

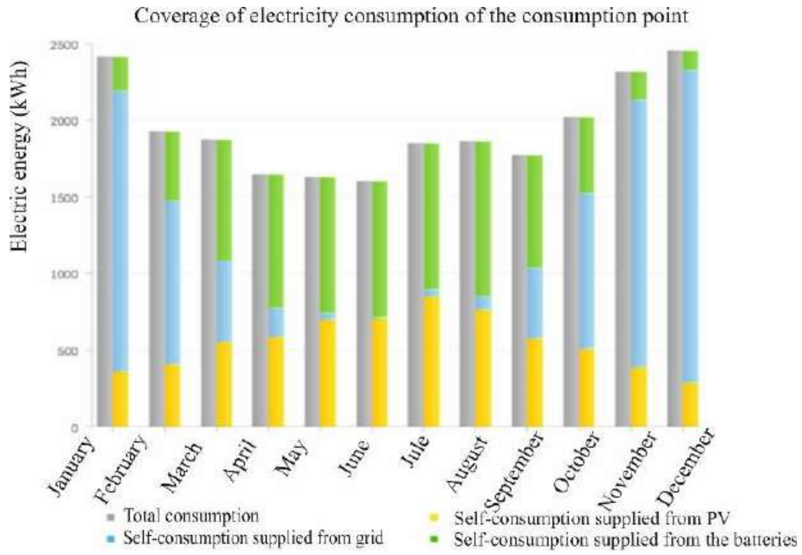

Fig. 7 Use of generated electricity at the point of consumption for var.3.

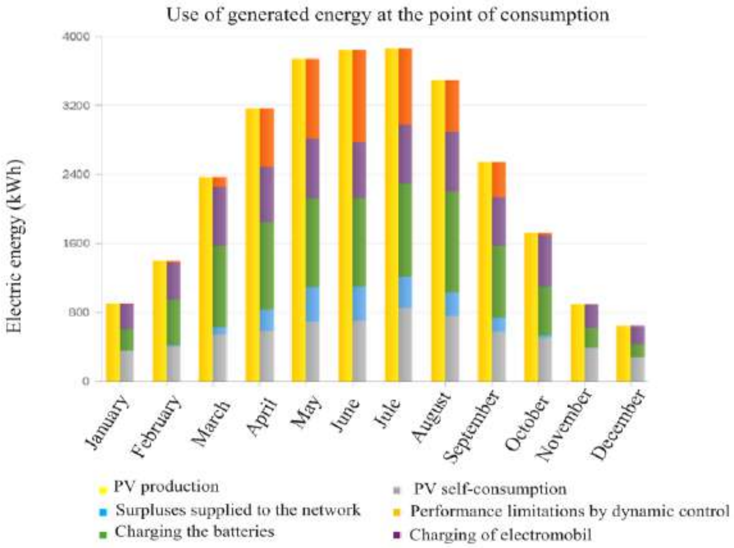

Fig. 8 A more detailed look at the use of generated electricity for variant 3.

The initial investment costs in variant 3 of the proposed system are 24 354.00 € with payback period on 6.7 years. 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 €.

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 support 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.

More detailed analysis of the selected variant

When choosing the optimal option in such a case, it is not always possible to focus only on the relationship between investment and return. Sometimes, even the architectural design of a building may not allow us to install the panels at the optimal angle and orientation. Other times we have to look at the investor's request, who wants to cover the entire parking lot area. And we often have to resort to compromise solutions, such as accepting increased flows into the grid or not using all the generated energy.
Within the variants that are the subject of this paper, we choose variant 3 as the optimal one for acceptable investment, return, minimal network flows, and optimal consumption and we recommend it for implementation in the given project. We recommend placing the battery system in an air-conditioned room, using the available space at the railway station. In Table 2, we also present a detailed energy analysis of the selected optimal solution.

Table 2 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

PV generator		
PV generator output	17.22	kWp
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	%

Conclusion

Building of containment parking lots is way to increasing the share of low-emission public transport. If such a parking lot is supplemented with photovoltaic panels, intervention can provide a more valuable urban element, which can also serve as a local energy source. The presented alternative solutions for the parking lot, which is part of the integrated transport terminal, provide guidance on finding the optimal option. Presented 4 variants were differing in the number of panels, their inclination, and the possibility/impossibility of accumulating or recharging electric vehicles. They also differed in investment amount, return and energy indicators. As part of the technical and economic assessment, option 3 was chosen as the proposed option, with a return of 6.7 years.

Given the expected increases in energy prices and the overall societal climate, it can be expected that the volume of PV installations will increase and such solutions that save valuable agricultural land will be on the rise.

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