Research Article

SIMPLIFIED METHODOLOGY OF ECONOMIC EVALUATION OF HOUSEHOLD PV INSTALLATIONS IN CZECH REPUBLIC USING MONTE CARLO METHOD

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Abstract. *This paper deals with the design of a suitable, transparent, and reasonably accurate methodology for the economic evaluation of household photovoltaic (PV) installations in the Czech Republic. The basis of economic evaluations of household photovoltaic installations is a time model of energy balance from which cash flows result. Therefore, a specific methodology of the energy balance calculation is proposed to increase accuracy, while at the same time, reasonably increasing the energy balance model complexity by using the Monte Carlo method (probability model). Following the detailed analysis of the affecting factors and the compilation of the methodology for the energy balance calculation, the main stochastic parameters were specified. These specified stochastic parameters are estimated by the Monte Carlo method in multiple scenarios. The presented methodology of the energy balance calculation is also used for direct calculation where the mean values of the same specified stochastic parameters (without assumption of their probability) serve as the reference values for one scenario. Pros and cons of the designed methodology are demonstrated in a case study of an existing household photovoltaic installation. The mean values of the output parameters from the Monte Carlo method scenarios are then calculated for subsequent results comparison of both methods and also with the real (measured) values of the case study installation. Then a cash flows for each year of the installation's lifetime are stated, and the internal rate of return (IRR) as an economic evaluation criterion is calculated. The results show that IRR differs between methods by about 2.5% which may be crucial in such long-term projects on the verge of profitability. The accuracy of the application of the Monte Carlo method to the output parameters is then discussed in the conclusion where some possible recommendations for further work and project evaluators are indicated as well.*

Keywords

Economic Evaluation, Energy Balance, Household, Mean Values, Monte Carlo Method, Photovoltaic Installation, Prosumers, Simulation, Transparency.

1. Introduction

Attempts to integrate renewable energy sources into the energy grid can be found more and more frequently [1, 2]. This can be seen as a result of the development of these sources, their ever-increasing efficiency, and better availability. Thanks to this, they are integrated not only into the centralized installations but also into the installations in the households of the end consumers [3] who thus become prosumers (producers - consumers).

This increasing integration of renewables will bring new opportunities, but also new challenges related to, among other things, the effort to maintain the stability of the energy grid threatened by the fluctuations in the process of the generation of renewable electric energy [4]. For installations in the households of the prosumers, it is thus best to consume all the generated electric energy right in the place of production to prevent the destabilizations of the energy grid by fluctuations in generating electric energy as well as to eliminate transmission losses [5, 6].

Although the decision to install these renewables in the households of the end consumers is partly a moral decision to reduce the electric energy consumption of a particular household, it also needs to be economically viable [3].

The economic viability of these installations can be assessed in various ways, although in general, the most accurate expression of the impact of the installation on the energy savings of the household is crucial [5, 6] or [7]. This can be achieved primarily by the reduction of the household's grid consumption as compared to the state before the installation impacts (in case the environmental impact is not considered). That means the more generated electric energy will be consumed right in the household and not delivered to the power grid (which will be discussed in the case study section in more detail) will equipotentially increase the income from the installation. This is evaluated through the energy balance of the installation which consists of:

- Photovoltaic (PV) panels energy generation,
- Household energy consumption,
- Energy accumulation in BESS (Battery Energy Storage System) – in case it is integrated,
- Potentially excess energy supplied to the grid.

The enumeration of these individual components of the energy balance with adequate accuracy is thus the core of economic evaluations. Generally, there is a great deal of methodologies and methods of the economic evaluations themselves which are not always transparent or even unified. Currently, there is a trend in using increasingly complex methods, such as machine (or more specifically - deep) learning described, for instance, by [8, 9, 10], or Monte Carlo described by [11, 12] or [13] but these do not necessarily bring any considerably increased accuracy and definitely reduce transparency. Compared to that, there are quite transparent works that deal with mean values [14] or [15] which may not always include the complexity of the PV assessments [16].

This paper proposes a compromise alternative between increasing complexity and adequate accuracy of energy balance calculation with the use of the Monte Carlo Method (MCM) for stochastic factors expression with emphasis on transparency and simple applicability.

Due to the fact, that solar incident radiation (and followingly electric energy generation) varies in different countries and thus is difficult to formulate a universal methodology, the focus is paid on the Czech Republic. The Czech Republic was relatively slow in the integration of PV installations (especially in households) and after a huge initial rise of installed power (up to the end of 2013) caused by larger installations, there was stagnation. The rising trend in the installed power of PVs can be seen again from 2021 [17]. This is caused by increasing financial support, decreasing costs as well as increasing electric energy prices. Following this, the proper economic evaluation and related investment return period are gaining importance. The presented methodology may have a practical impact and can help stakeholders with an evaluation of further projects.

The risk assessment of each installation is quite specific and should be included in net present value calculations. On the other hand, inflation is a more or less general parameter and therefore for net present value calculations can be used any common prediction. The presented methodology with the use of internal rate of return as an evaluation criterion is most suitable for project comparison with each other while inclusion in specified net present value calculations is also possible.

2. Theoretical Background

As was indicated in the Introduction, the most accurate expression of the impact of the photovoltaic installation on the energy savings of the specific household is crucial for the economic evaluation. To achieve this there is a need to express the energy balance (in terms of methodologies or models) and its calculation (in terms of methods) as accurately as reasonably achievable. From an economic point of view, there are two situations:

- The power supply to the distribution grid (in case the production of the photovoltaic panels exceeds the consumption of a household + potential capacity of the BESS).
- The energy savings given by the difference between gross and net consumption from the grid (depend-

ing on the potential State of Charge of the BESS and actual PV generation).

Therefore, it depends not only on the amount of energy produced but also on the fact whether this energy is meant to be used for direct (indirect – from battery) consumption or to be supplied to the grid. The timing needs to be taken into account too. It can generally be said there is a need for an energy balance time model. It follows energy savings and the excess energy amount can then be deduced from the energy balance.

The complexity of the energy balance model is the most important part here. The more complex models are more computationally intensive, which does not necessarily mean they proportionately increase the accuracy as described by [16] for solar irradiation or by [18] directly for photovoltaic cells. Here a compromise seems to be the most advantageous solution.

In simplified calculations, the mean values [19] can be used. This method is computationally undemanding, but it will probably not be accurate enough especially for the installations functioning on the verge of profitability. A simple solution of integrating the Monte Carlo Method can provide higher accuracy with only a small increase in computational demandingness. The conditioning of the calculations, which is unique for each installation (country, region, etc.), is important here and it is described in detail in section 3.

3. Proposed Calculation Methodology

According to the central limit theorem, a normal distribution is considered for the expression of the expected probability density of the ambient temperature, solar energy, and electric energy consumption of the household when applying the Monte Carlo Method. In the case study, there will be also used the mean values of the probability distributions as a reference for calculated results. Therefore, mean values are considered to be the same model, but the mean values of the mentioned parameters are used instead of the stochastic ones.

The assumed time step concerning the increasing complexity of the calculation and data availability is 1 hour of the year which also seems to be short enough as mentioned by [16]. Only a one-year hourly energy balance is calculated, and the energy balances of other years are then expressed concerning the changing efficiency of the photovoltaic panels.

There is also assumed an integrated BESS, which can be omitted from the following equations in the case where the BESS is not available.

3.1. Energy Balance Time Model and Economic Evaluation Criterion

Equation (1) is proposed for the energy balance calculation based on the previously mentioned components.

$$\begin{gathered} E_i = (Q_{Si} \cdot x \cdot S_c) \cdot e_n \cdot e_{pv} - E_{ic}, \\ \textbf{If} \quad T_{ti} \quad \leq 25^{\circ}C \quad e_{pv} = e_{pvrated} \;, \\ \textbf{Otherwise} \quad e_{pv} = e_{pvrated} - (T_{ti} - 25) \cdot c_{T/e} \;, \end{gathered} \tag{1}$$

where E_i (kWh) is the hourly energy balance, Q_{Si} (kWh/m^2) is the hourly solar energy absorbed by PV panels, S_c (m^2) is the total cells surface, $e_n\,(-)$ is the inverter efficiency, $e_{pv}\,(-)$ is the photovoltaic efficiency, E_{ic} (kWh) is the hourly household energy consumption, $e_{pvrated}\,(-)$ is the rated photovoltaic efficiency, $c_{T/e}$ (1/K) is the temperature/efficiency coefficient and $x\,(-)$ is a number of PV panels. To derivation and calculation of the $Q_(Si)$ is dedicated section 3.1.1). The value of 25 °C and its impact on PV efficiency is discussed in section 3.1.2).

In addition to the energy balance the energy accumulated in the BESS (State of Charge) SoC_i (kWh) needs to be calculated for every step (hour). Three situations can occur:

- *If* $E_i \leq 0 \quad SoC_i = E_i \cdot \left(1 + \frac{1-e_{BESS}}{2}\right) + SoC_{i-1}$
BESS is discharging.
- *If* $E_i \leq 0 \quad SoC_i = SoC_{i-1}$
BESS is in the same state.
- *If* $E_i \geq 0 \quad SoC_i = E_i \cdot \left(1 + \frac{1-e_{BESS}}{2}\right) + SoC_{i-1}$
BESS is charging.

where $e_{BESS}\,(-)$ is the efficiency of the BESS charge/discharge cycle. In case the BESS has no free capacity left the excess of E_i is supplied to the grid and, conversely, in case the BESS is empty the lack of E_i is consumed from the grid.

The $CF\,(t)$ for every year is calculated from Eq. (2).

$$CF\,(t) = E_s\,(t) \cdot P_s\,(t) + (E_g\,(t) - E_n\,(t)) \cdot P_D\,(t)\,, \tag{2}$$

where $E_s\,(t)$ (kWh) is the annual amount of energy supplies to the grid, $P_s\,(t)$ (EUR/kWh) is the purchasing price of the supplied energy, $E_g\,(t)$ (kWh) is the annual gross consumption, $E_n\,(t)$ (kWh) is the annual net consumption, $P_D\,(t)$ (EUR/kWh) is the price of delivered energy from the grid and t (year) is the year of the project lifetime.

The internal rate of return (IRR) is proposed as an evaluation criterion thanks to the possibility of its comparison with other projects. IRR inclusion is shown in Eq. (3).

$$\sum\nolimits_{t=1}^{T_l} CF\,(t)\,.(1 + IRR)^{-t} - IN = 0, \tag{3}$$

where $CF(t)$ (EUR) are the annual cash flows, IN (EUR) is the initial investment costs, t (year) is the specific year during the lifetime of the installation and T_l (years) is the lifetime of the installation according to [20].

20,000 scenarios are demonstratively calculated here (due to the sufficient expression of observed phenomena – which is discussed later) by the Monte Carlo Method and 1 direct scenario by the mean values. The mean values of the Monte Carlo scenarios are then calculated and compared with the mean values calculation results and also with the real values in the first years of the installation's lifetime in the case study. For better transparency of the results of individual scenarios, including histograms of results and representation of probability distributions, see [21]. Our previous work [21] calculated only 10,000 scenarios by MCM, which led to a relatively large deviation in household consumption calculation. The impact of doubling the number of scenarios is discussed later as well.

1) Solar Energy Estimation

There are a lot of factors that can be included, as described, for instance, by [22]. For the purpose of the paper discussed in section 2 and Introduction, the following method with direct parametrization is selected.

According to [23], the intensity of incident solar radiation I $(\mathrm{kW/m^2})$ on the photovoltaic panel is calculated as the sum of the intensities of diffuse and direct solar radiation according to Eq. (4).

$$I = I_P + I_D, \tag{4}$$

where I_P $(\mathrm{kW/m^2})$ is the intensity of direct solar radiation which is not reflected or absorbed and re-emitted when passing through the atmosphere and I_D $(\mathrm{kW/m^2})$ is the intensity of diffuse solar radiation, which is reflected from particles contained in the atmosphere (water droplets, dust, etc.) and thus changed its direction, as described by [23].

When the sky is completely cloudy, only diffuse radiation falls on the surface of the photovoltaic panel, and when the sky is completely clear, it is the sum of diffuse and maximum direct radiation (for a specific hour of the day). According to [23], these components are calculated in Eq. (5) and (7).

$$\begin{aligned} I_P =& I_0 . \exp\left(-\frac{Z}{\varepsilon}\right) . (\sin(h) . \cos(\alpha) + \cos(h) . \\ & ssn(\alpha) . \cos(a - a_s)), \end{aligned} \tag{5}$$

where $I_0 = 1\ 360\ \mathrm{W/m^2}$ is solar constant, $Z(-)$ is the atmospheric pollution coefficient shown in Tab. 1, $\varepsilon(-)$ is the coefficient of the dependence of the height of the sun above the horizon and the altitude of the given place and is calculated in Eq. (6), $h\,(^\circ)$ is the height of the sun above the horizon, $\alpha\,(^\circ)$ is the angle of inclination of the sunlit surface from the horizontal plane, $a\,(^\circ)$ is the azimuth of the sun and $a_s\,(^\circ)$ is the azimuth angle of the normal of the illuminated surface, described by [23].

$$\begin{aligned} \varepsilon =& \frac{9.38076 \cdot \left[\sin(h) + \left(0.003 + \sin^2(h)\right)^{0.5}\right]}{2.0015 \cdot \left(1 - H \cdot 10^{-4}\right)} \\ & + 0.91018, \end{aligned} \tag{6}$$

where $H = 303$ m is the altitude of the installation [23].

$$\begin{aligned} I_D =& 0.5 \cdot (1 + \cos(\alpha)) \cdot I_{Dh} + 0.5r \cdot \\ & (1 - \cos(\alpha)) \cdot (I_{Ph} + I_{Dh}), \end{aligned} \tag{7}$$

where I_{Dh} $(\mathrm{kW/m^2})$ is the intensity of diffuse radiation incident on a horizontal surface calculated in Eq. (8), $r = 0.2$ is the albedo, and I_{Ph} $(\mathrm{kW/m^2})$ is the intensity of direct solar radiation incident on a horizontal surface calculated in Eq. (9), described also by [23].

$$I_{Dh} = 0.33 \cdot \left(I_0 - \left(I_0 \cdot \exp\left(-\frac{Z}{\varepsilon}\right)\right)\right) \cdot \sin(h), \tag{8}$$

$$I_{Ph} = I_0 \cdot \exp\left(-\frac{Z}{\varepsilon}\right) \cdot \sin(h), \tag{9}$$

Tab. 1: Assumed Z values.

Month	$\mathbf{Z_{city}}$
January	3.1
February	3.2
March	3.5
April	4.0
May	4.2
June	4.3
July	4.4
August	4.3
September	4.0
October	3.6
November	3.3
December	3.1

According to [23], the total theoretical (maximal) energy of the clear sky incident radiation on the panel during the day $Q_{Sdaytheor}$ $(\mathrm{kWh/m^2})$ is obtained by integration of I according to Eq. (10).

$$Q_{Sdaytheor} = \int_{\tau_r}^{\tau_s} I d\tau, \tag{10}$$

where τ_r (h) is the time of sunrise and τ_s (h) is the time of sunset. The theoretical time of direct sunlight (without clouds) is calculated in Eq. (11), as described by [23].

$$\tau_{theor} = \tau_s - \tau_r, \tag{11}$$

According to [24], to calculate the total actual energy of solar radiation incident on the panel during the day

Q_{Sday} (kWh/m^2), it is necessary to use the balance Eq. (12).

$$Q_{Sday} = \frac{\tau}{\tau_{theor}} \cdot Q_{Sdaytheor} + \left(1 - \frac{\tau}{\tau_{theor}}\right) \cdot Q_{Dday}, \quad (12)$$

where τ (h) is the number of hours of direct sunlight and Q_{Sday} (kWh/m^2) is the total daily energy of diffuse radiation incident on the panel and is calculated in Eq. (13), as described by [24].

$$Q_{Sday} = \int_{\tau_r}^{\tau_s} I_D d\tau. \quad (13)$$

The variable for the solar energy estimation is τ (h) which is estimated from the data obtained from [25]. The daily solar energy is flowingly divided to normal distribution to the hours of the solar day to obtain Q_{Si} (kWh/m^2). The presented equations for solar energy estimation are standardized for the Czech Republic.

2) Ambient Temperature Estimation

The efficiency of the photovoltaic panels is also influenced by their temperature, which creates a paradox that with the higher daily energy of solar radiation, the panel can produce less electric energy than at the lower daily irradiation energy due to a decrease in its efficiency with increasing temperature [26] which has a linear character expressed by the temperature/efficiency coefficient shown in the Tab. 3 for the specific case study.

Attempts to estimate the temperature of the panel more accurately would be computationally very demanding, as this temperature depends on a large number of factors, such as the ambient temperature, humidity, energy of incident radiation, wind speed, etc., which may again become a subject of an independent research study and is well described by [26]. Therefore, in the following calculations, the temperature of the panels is considered as the ambient temperature. It is assumed that the effect of peak temperatures will be mitigated in 1-hour calculation steps. For this purpose, it is necessary to express and calculate hourly ambient temperatures.

In reference [27] is deduced and quantified, based on the conclusions of [28], that the expected temperature at a specific hour can be calculated in Eq. (14) and (15), considering only hours of a day with a positive energy balance (solar day), when the temperature is approximately sinusoidal.

$$T_{ti} = T_{\min} + A \cdot \sin\left((\tau_i - \tau_{r+1}) \cdot B \cdot \frac{\pi}{180}\right), \quad (14)$$

where A and B are the supporting temperature constants.

$$A = T_{\max} - T_{\min}; B = 90/\left(14.5 - \tau_{r+1}\right), \quad (15)$$

where T_{ti} ($^{\circ}C$) is the ambient temperature in the i-hour, T_{min} ($^{\circ}C$) is the minimal temperature of the day, T_{max} ($^{\circ}C$) is the maximal temperature of the day and τ_i (h) is the hour of the day. The input minimal and maximal temperatures were obtained from the data from [25].

3) Household Consumption Estimation

The estimation of household consumption (considered for a family house) was performed based on the statistical annual consumption data by hours from the Sonnen customer analysis portal for the case study installation. Therefore, in the specific case study as a result of lower variability of consumption within the following groups, the days of the calendar year were divided into four typical groups, for which the standard deviations and mean values of consumption are subsequently calculated from a representative sample of days (1 per calendar week). This procedure assumes the knowledge of the consumption statistics at hourly intervals for the whole year (minimum). If these data are not available, the consumption estimation can be made based on the estimations or more complex models of the daily use of the individual appliances and the sum of their outputs as described for instance by [29].

Assumed groups of days of a calendar year:

- working week May – September,
- weekend May-September,
- working week October – April,
- weekend October-April.

This distribution takes into account the differences in consumption during the absence of people in the house during the working week and, conversely, the presence at weekends, as well as the differences between the heating and non-heating seasons.

In this paper, an estimation of the consumption of a household was performed based on the statistical data gathered from the Sonnen customer analysis portal.

4) Electric Energy Prices Estimation

The final price of electric energy for end consumers varies according to suppliers, tariffs, products, and distribution rates. Generally, it can be said that the end consumer's electric energy price is divided into the market part (unregulated) and the distribution part (regulated) [30]. Simply said their ratio according to [31] is more or less 1:1 for the households. This ratio will of course change with changes in the prices of both components which brings another uncertainty. On the other side, for rough and comparing calculations to distant future prices seems the assumption that electric energy price for end consumers will be double to its market component adequate. This assumption should be revalidated in the future.

For the proposed price analysis, a common contract concluded for 3 years with price fixation at the time of conclusion (with automatic extension for 3 years) is chosen and will be the most likely option for such evaluated installations.

Thanks to the price fixation for every three years, it is likely that the large price deviations from the future seasonal (caused by high PV penetration) and other EU electric energy market fluctuations during shorter periods (see Fig. 1) will be filtered out. Final assumed market prices are then shown in Fig. 2 with annual approximation. It is important to note that the prices are stated in EURs with 2020 value. Due to the primary assumed purpose of this evaluation method to compare projects with each other and followingly selected evaluation criterion, is effect of inflation omitted here.

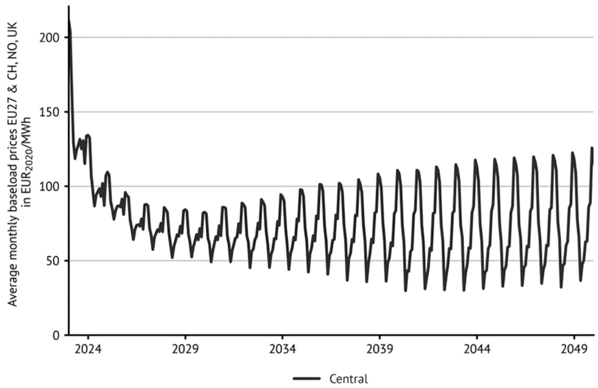

Fig. 1: Electric energy market component prices estimation (monthly) for baseload [32].

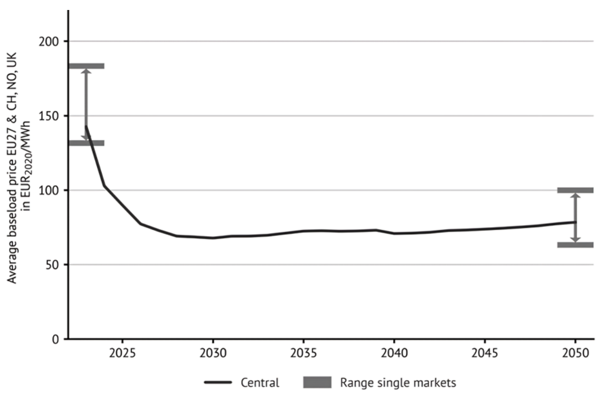

Fig. 2: Electric energy market component prices estimation (yearly) for baseload [32].

The purchase price for 1 MWh of electric energy supplied to the grid by photovoltaic panels in households is calculated according to the currently valid CEZ Group methodology as 40% of the market electric energy prices (excluding VAT), which are fixed for 3 years [33]. The assumed energy prices are shown in Tab. 2.

Tab. 2: Assumed prices for electric energy grid deliveries market component and supplies [32, 33].

Date	Market price (EUR_{2020}/MWh)	Supply price (EUR_{2020}/MWh)
1. 1. 2020	180	72
1. 1. 2023	150	60
1. 1. 2026	75	30
1. 1. 2029	68	27.2
1. 1. 2032	70	28
1. 1. 2035	72	28.8
1. 1. 2038	74	29.6
1. 1. 2041	70	28
1. 1. 2044	75	30
1. 1. 2020	180	72
1. 1. 2023	150	60
1. 1. 2026	75	30

4. Case Study

It is commonly assumed that the economic lifetime of the household photovoltaic installations is related to the lifetime of the installed photovoltaic panels. In most cases, it is 20 or 25 years (depending on manufacturers). In the presented case study, the lifetime is assumed 25 years and during this time the efficiency decreases linearly by 10% in the first 10 years and by another 10% in the remaining lifetime to 80% of the rated efficiency as noted in the manufacturer's list [34], which is also commonly referred by [35].

An existing installation was chosen for the case study thanks to the easy availability of parameterization, component prices, and the possibility of comparing the results with the real energy balance of the installation.

The subject of the case study is a family two-story house (with a habitable attic) with a total living area of approximately 350 m^2, with three permanent residents. The house is insulated with a 5 cm thick layer of polystyrene. Heating is provided by a gas boiler (floor heating on the ground floor, otherwise radiators), and water is heated by a combination of a gas boiler and electricity (usually generated by photovoltaic panels).

Important components and their selected technical parameters will be described in the next sections as well as the initial assumptions.

4.1. Assumptions

The following assumptions must be made for the unequivocalness of the calculations:

- Own sources financing (loan financing is not considered).
  - In the case of loan financing, there is a need to take into account the prediction of interest rates.
- The temperature of the panels is the same as the ambient temperature (generalized to hourly steps).
- Proper installation and no manufacturing defects.
- Panel inclination 45 ° and orientation to the south.
- The effect of weather conditions (instead of ambient temperature) is neglected.
- Zero residual value of components at the end of the installation lifetime.
- Installation lifetime is 25 years (reduction of panel efficiency after ten years to 90% and after twenty-five years to 80%) according to the manufacturer's data.
- The increasing installed power of the household during the lifetime of the installation is neglected.
- A perfectly symmetrical three-phase consumption and supply to the grid is considered.
- Commissioning as of 1 January 2020.
- Maximum BESS and inverter efficiency are considered.
  - In case the power/efficiency curve of the inverter is available, it should be included in calculations.
- DC appliances directly powered by photovoltaic panels are not considered.
- The CEZ Group is the electricity supplier (see energy prices estimation methodology).

4.2. Installation Components

Solarwatt ECO 60M panels in the number of 16 pieces are installed as photovoltaic panels. Selected technical parameters are shown in Tab. 3.

A battery-connected SONNEN Hybrid 8.13/5 inverter is installed as a monoblock. Selected technical parameters are shown in Tab. 4.

The K2 system is installed as a fastening system. Selected technical parameters are shown in Tab. 5.

Tab. 3: Selected technical parameters of the installed photovoltaic panels [34].

Rated power	**285 Wp (for 25 °C and 1 000 W/m²)**
Rated efficiency $\mathbf{e_{pvrated}}$	17.6 % (for 25 °C)
Operation temperature range	-40 ... +85 °C
Ambient temperature range	-40 ... +45 °C
Temperature/efficiency coefficient $\mathbf{c_{T/e}}$	-0.42 %/K
Photovoltaic cells	60 monocrystalline cells
Cell dimensions	157 × 157 mm
Total cells surface $\mathbf{S_c}$	1.47894 m^2
Total rated power	4.560 kWp

Tab. 4: Selected technical parameters of the installed photovoltaic panels [36].

Inverter	
Rated power	5.5 kW
Rated voltage	400 V
Rated frequency	50 Hz
Rated charging/discharging power	2.5 kW
Maximal efficiency	96 %
BESS	
Capacity	5 kWh
Usable capacity	4.5 kWh
Technology	$LiFePO_4$
Depth of discharge	90 %
Working cycles	10,000
Maximal efficiency	98 %

Tab. 5: Selected technical parameters of the installed fastening system [37].

Placement	Sloped roof
Photovoltaic panels	Suitable for all standard photovoltaic panels
Material	Stainless steel 1.4301
Connection to the roof	Screws connection

4.3. Total Price and Subsidy

The total price of the installation, including assembly, is 13,422 EUR incl. VAT and the non-refundable investment subsidy from the new green savings program for photovoltaic installations in households is 6,539 EUR (added to the first year of economic evaluation).

5. Results

In this section, the results of the calculations by the Monte Carlo Method as well as by the mean values are presented. All calculations are made in MS Excel. MS Excel toolbox Crystal Ball produced by Oracle company is used for the Monte Carlo Method inclusion.

In Tab. 6 the mean values calculated from the Monte Carlo scenarios, direct calculation results, and real (measured) energy balance of the installation in 2020-2022 are shown. The results of the energy balance are shown only for the first three years of the lifetime due to the commissioning of the installation and the subsequent possibility of comparison. The decreasing efficiency of the photovoltaic panels during the years is included in $CF(t)$ calculations and illustrated in Fig. 3.

Tab. 6: Results.

Parameter	Mean values from MC	Direct mean values calculation	Real (measured) values
$E_g(1)$	10,078 kWh	10,121 kWh	9,372 kWh
$E_n(1)$	6,376 kWh	6,267 kWh	5,692 kWh
$E_s(1)$	531 kWh	127 kWh	598 kWh
Total generation (1)	4,233 kWh	3,981 kWh	4,302 kWh
$CF(1)$	EUR 7,909	EUR 7,935	EUR 7,906
$E_g(2)$	10,078 kWh	10,121 kWh	11,834 kWh
$E_n(2)$	6,413 kWh	6,305 kWh	8,050 kWh
$E_s(2)$	526 kWh	126 kWh	468 kWh
Total generation (2)	4,191 kWh	3,941 kWh	4,252 kWh
$CF(2)$	EUR 1,357	EUR 1,382	EUR 1,396
$E_g(3)$	10,078 kWh	10,121 kWh	9,260 kWh
$E_n(3)$	6,450 kWh	6,344 kWh	5,677 kWh
$E_s(3)$	520 kWh	124 kWh	682 kWh
Total generation (3)	4,148 kWh	3,901 kWh	4,265 kWh
$CF(3)$	EUR 1,344	EUR 1,368	EUR 1,339
IRR	9.46 %	EUR 9.72 %	

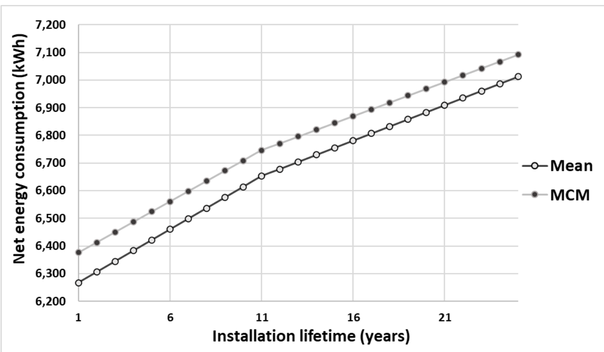

Fig. 3: Net consumption during the installation lifetime – method comparison.

6. Discussion

It is important to note here again that the energy balance calculation or even the photovoltaic project evaluation itself has no unified methodology (except general assessment principles), see [38, 39]. There are a lot of factors that affect the energy balance (mentioned in sections 3.1.1) – 3.1.4)) and their inclusion, or the degree of inclusion depends directly on the project evaluator. Moreover, these parameters are to some extent unique for each installation. A lot of papers which are dealing with energy balance calculations or subsequent problems where there is a need for the energy balance calculation of the photovoltaic installations are not transparent and/or they use only a very simplified energy balance model and/or they don't take into account the whole household, which increases the difficulty of finding relevant references. Furthermore, the verification of the results as well as the accuracy evaluation can be complicated.

The proposed methodology in this paper is not the most complex one but it includes all the main affecting factors (with some above-mentioned simplifications, discussed in sections 3.1.1) – 3.1.4)). However, the methodology in combination with [21] is fully transparent and it tries to analyze the accuracy of different methods of enumeration of the included stochastic factors. Following this, the energy balance data were obtained from an existing photovoltaic installation in the Czech Republic, commissioned at the end of 2019, which is not common and is valuable for comparison with reality. Then the parametrization of the presented equations tailored to the situation in the Czech Republic (and followingly to a specific case study) is carried out to make the paper more readable, and transparent and maintain its potentially practical impact on PV projects evaluation utilization in reaction to current renewable energy situation in Czech Republic. In general, the presented equations (of incident solar radiation) are much more complex. This geographically focused type of study is not particularly unusual, see [40, 41].

Thanks to the measured and relevant data acquisitions the calculations can be simply verified and deviations in results quantified. Furthermore, the proposed integration of the Monte Carlo Method can be evaluated. These results should be valuable for further studies where the model and methodology of the energy balance calculation need to be selected.

7. Conclusion

As is obvious from Tab. 6 the application of the MCM is more accurate when it comes to the energy supplies to the grid as well as to the total energy production using the photovoltaic panels. There is increased accuracy by 5% in total generation and even more in grid supplies. On the other hand, there can be very similar results by MCM and mean values in household energy consumption which additionally quite differs from the measured values. It is important to notice that the weather conditions are rather stochastic in nature, but household energy consumption has a rather deterministic character. This can be seen in Tab. 6 in more detail. Total PV panels production varies relatively little between years and the advantage of MCM application is obvious, household energy consumption can differ by $\sim 20\%$ the very next year and MCM application is not very beneficial in comparison to simple mean values calculation. In addition, there can occur any hardly predictable "black swans" such as the COVID-19 pandemic and subsequent lockdowns (this is most likely the case of E_g (2) deviation) which can have a significant impact on household consumption.

The division of the computational steps into hours seems to be optimal and, likely, any further reduction of the computational steps would not have a dramatic effect on accuracy. The situation is similar for several simulation scenarios, perhaps the number of scenarios might be reduced here (below 10,000), and carrying out a sensitivity analysis might be worth further consideration in this sense. Our previous work [21] assumed 10,000 scenarios and the only more visible difference with doubling the number of scenarios is in the relatively imprecise calculation of household consumption where seems to be sufficient mean values method.

Concerning previously mentioned results, there can be made final recommendations to future evaluators:

- Use MCM and proposed calculation methodology for PV panel's electric energy generation calculation,
- Verify the real reduction in PV panels generation declared by the manufacturer during years (assumed PV panels degradation in case study probably does not coincide with a real decline in electric energy generation),
- Use the greatest possible household consumption statistics with the application of the mean values calculation method or use any more complex behavioral model mentioned for instance in section 3.1.3).

Despite the above reservations, it seems that the proposed methodology of calculation, also improved by the integration of the MCM, met the set goal which was the formulation of transparent methodology and reasonably increasing the energy balance calculation accuracy (except for the household energy consumption which was discussed above). The IRR differs between methods by about $\sim 2.5\%$ which may be crucial in such long-term projects on the verge of profitability. But it is important to notice again, that the final internal rate of return will be strongly affected by market and distribution electric energy prices (and their ratio) which are very difficult to predict.

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Author Contributions

Martin Vins conducted the research, designed the methodology, collected the data, tested it for the case study and wrote the manuscript. Mikulas Gangur helped shape the research and supervised the project.

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