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DETERMINATION OF PRODUCED AND CONSUMED ELECTRICITY OF A RESIDENTIAL BUILDING USING A GRAPHICAL USER INTERFACE

DOLOČITEV PROIZVEDENE IN PORABLJENE ELEKTRIČNE ENERGIJE STANOVANJSKEGA OBJEKTA Z UPORABO GRAFIČNEGA UPORABNIŠKEGA VMESNIKA

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Abstract

The primary objective of this paper is to present a graphical user interface for the calculation of electricity produced by a photovoltaic system and electricity consumed by a heat pump. The produced electricity is determined by a multi-year average of measurements of the global and diffuse power density of solar radiation for several places in Slovenia, while consumed electricity is determined based on the required heat for heating a residential building and domestic water. The calculation of produced and consumed electricity is validated by measurements on a real system. The developed graphical user interface enables simple user inputs of the photovoltaic system, heat pump, and the considered residential building, and provides a comprehensive technical analysis for installing both systems at the same location.

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Povzetek

Glavni cilj tega prispevka je predstavitev grafičnega uporabniškega vmesnika za izračun proizvedene električne energije s fotonapetostnim sistemom in porabljene električne energije s toplotno črpalko. Predvidena proizvedena električna energija je določena z večletnimi povprečji meritev globalne in difuzne gostote moči sončnega sevanja za več krajev po Sloveniji, medtem ko je poraba električne energije določena na podlagi toplote za ogrevanje stavbe in sanitarne tople vode. Izračun proizvedene in porabljene električne energije je ovrednoten z meritvami na realnem sistemu. Izdelan grafični uporabniški vmesnik predvideva preproste uporabniške vnose fotonapetostnega sistema, toplotne črpalke in obravnavanega objekta ter podaja celovito tehnično analizo za postavitev obeh sistemov hkrati.

1 INTRODUCTION

An increasing number of households are opting for alternative heating solutions for residential buildings in a bid to achieve a higher level of self-sufficiency. One example of a modern solution is the use of a heat pump for heating a building and sanitary water, which increases the share of renewable energy sources (RES). Additionally, the necessary electricity for operation of the heat pump can be produced by a photovoltaic (PV) system installed on the residential building itself. This increases the level of self-sufficiency of the household. The decision to invest in a combination of a PV system and a heat pump for heating purposes is simpler if it is supported by appropriate forecast calculations. To this end, investors can use a graphical user interface that calculates produced and consumed electricity for any residential building based on simple user inputs. Based on the idea of the described graphical user interface, this paper is divided into two parts: a calculation of electricity production using a PV system, and electricity consumption with a heat pump. The authors [1] found that the electricity produced by the PV system is directly dependent on the solar radiation received and the apparent position of the Sun in the sky. One option is to rely on local measurements from previous years to predict solar radiation at any point on Earth [2]. In Slovenia, these measurements are provided by ARSO (Environmental Agency of the Republic of Slovenia) [3]. Many authors, such as [1–2, 4–7], present different models for determining solar radiation of any surface on Earth based on knowledge of the power density of solar radiation on a horizontal surface and geometric relationships between the Earth and the Sun. The requirements of the methodology for calculating the energy performance of buildings and providing their own RES for the operation of systems in buildings [8] are set out by the Rules on the Efficient Use of Energy in Buildings (PURES) [8]. The requirements are followed and explained by the Technical Guidelines for Construction TSG-1-004: 2010 Energy efficiency [9].

The latter also provides a methodology for calculating the electricity required to operate a heat pump. By conducting this research, the authors are pursuing a goal of creating a graphical user interface in the Matlab software package. The established methods for calculating the production and consumption of electricity and the search for simplification were taken into account, which would also meet user input restrictions and ensure the greatest possible automation of the calculation. Existing graphical user interfaces in the field of PV systems, such as [10], are primarily intended for PV system sizing or daily solar radiation forecasts, as described by the authors [11]. In the field of inspection of buildings, in terms of heating, the KI Energija programme [12] stands out, which also follows the PURES. In addition to the above, the RETScreen clean energy management software package [13] is available on the market, which deals with technical and financial energy efficiency analysis. After reviewing the literature, it was found that the proposed graphical user interface represents an innovative approach to evaluating the considered systems and user information.

This paper consists of four sections. The first section provides an introduction to the research topic. The second section describes the methodology of production and consumption of electricity, while the third section presents the results of the graphical user interface and the validation with measurements. The fourth and final section discusses the conclusions of the paper.

2 METHODOLOGY

The first subsection covers the basics of solar radiation, the calculation of solar radiation on the surface, and the necessary geometric connections between the Sun and the Earth. The second subsection deals with the calculation of the electricity required for the operation of the heat pump.

2.1 Production of electricity – PV system

The power density of solar radiation at the edge of the Earth's atmosphere and the Earth's average distance from the Sun is called the solar constant, which is approximately 1366 W/m^2 [14, 15]. Horizontal surfaces on Earth receive two types of solar radiation: direct solar radiation $I_{\mathrm{b,h}}$, which does not experience a significant change in direction on the way through the atmosphere [2], and diffuse solar radiation $I_{\mathrm{d,h}}$, which results from the scattering of sunlight in the atmosphere [16]. The greater the scatter, the smaller the direct component of solar radiation and vice versa [16]. The sum of direct and diffuse solar radiation is the global solar radiation on the horizontal surface I_{h} and is given by (2.1) [2].

$$I_{\mathrm{h}} = I_{\mathrm{b,h}} + I_{\mathrm{d,h}} \tag{2.1}$$

In addition to global solar radiation, an arbitrarily directed surface also receives reflected radiation $I_{\mathrm{r,c}}$, which results from the reflection of global solar radiation from the environment [2]. The total radiation on any surface is thus the sum of direct, diffuse and reflected solar radiation on any surface expressed by (2.2) [2].

$$I_{\mathrm{c}} = I_{\mathrm{b,c}} + I_{\mathrm{d,c}} + I_{\mathrm{r,c}} \tag{2.2}$$

To calculate the solar radiation of an arbitrarily oriented surface at any location on Earth, it is necessary to understand the geometric relationship between the Earth and the Sun in a selected period of time. The distance of the Earth from the Sun changes throughout the year. The Earth is closest to the Sun at the winter solstice (21 December) and furthest from the Sun at the summer solstice (21 June). At that time, the declination takes its extreme values, representing the angle between the conjunction of the centres of the Earth and the Sun and the plane of the Earth's equator. The declination for an individual day of the year is calculated according to (2.3) [6].

$$\delta = 23{,}45 \cdot \sin\left[\frac{360 \cdot (284 + n)}{365}\right] \tag{2.3}$$

The apparent current height of the Sun in the sky is described by the solar altitude angle α [1]. The solar altitude angle is the angle between direct sunlight and the horizontal surface of the Earth, calculated by (2.4) [4].

$$\alpha = \sin^{-1}\left(\sin L \sin\delta + \cos L \cos\delta \cos h\right) \tag{2.4}$$

The angle between the direct sunlight and the normal of the considered surface is called the incidence angle of the Sun i [5] and is calculated by (2.5) [7].

$$i = \cos^{-1}\begin{pmatrix} \sin L \sin\delta \cos\beta - \cos L \sin\delta \cos\gamma \\ + \cos L \cos\delta \cos h \cos\beta + \sin L \cos\delta \cos h \sin\beta \cos\gamma \\ + \cos\delta \sin h \sin\beta \sin\gamma \end{pmatrix} \tag{2.5}$$

As previously mentioned, the total solar radiation I_c as well as the solar irradiation H_c (expressed by (2.6)) received by any surface is the sum of direct, diffuse and reflected solar irradiation, taking into account the corresponding inclination factor for each radiation component (2.7), (2.8) and (2.9) [2].

$$H_c = R_b B_h + R_d D_h + R_r\left(B_h + D_h\right) \tag{2.6}$$

$$R_b = \frac{\cos i}{\sin\alpha} \tag{2.7}$$

$$R_d = \frac{1 + \cos\beta}{2} \tag{2.8}$$

$$R_r = \frac{\rho(1 - \cos\beta)}{2} \tag{2.9}$$

2.2 Consumption of electricity – heat pump

The main goal of a building heating system is to provide internal thermal comfort [8]. The most popular heating devices or heat generators currently on the market are so-called heat pumps, which use the temperature of the environment to produce heat for heating and are electricity operated. The electricity required for operation of a heat pump is calculated by (2.10) [9].

$$E_{HP} = \frac{Q_{HP}}{COP} \tag{2.10}$$

The indoor design temperature T_i = 20 °C was used to calculate the daily heat required for heating. The author in [9] assumes that this value is the same as the indoor design temperature for determining the annual heat required for heating residential buildings. The required daily heat $Q_{NH,n}$ is calculated by (2.11).

$$Q_{NH,n} = \left(Q_{trans,n} + Q_{v,n}\right) - \eta_{NH}\left(Q_{i,n} + Q_{s,n}\right) \tag{2.11}$$

Transmission heat losses occur due to the heat transfer through building structures [9]. Heat transfer through building structures occurs due to the temperature difference between indoor and outdoor air, with heat passing through three heat transfer mechanisms (convective heat transfer, conductive heat transfer, and radiation). Indoor heat is transferred to the inner surface of a building envelope by radiation and convection. Heat is transferred to the outer surface through the layers of building structures, and is then re-transferred by radiation and convection to the surrounding air. Heat transfer by radiation and convection is combined and presented by internal α_i and external α_e convective heat transfer coefficient. The thermal transmittance of a building structure is expressed by (2.12) by considering all three heat transfer mechanisms [37, 38].

$$U = \frac{1}{\frac{1}{\alpha_i} + \sum_{j=1}^{n} \frac{d_j}{\lambda_j} + \frac{1}{\alpha_e}} \tag{2.12}$$

According to [17], the external convective heat transfer coefficient α_e is 25 W/m^{2}K for all heat flow directions. However, the internal heat transfer coefficient α_i is 7.69 W/m^{2}K in the horizontal direction of heat flow, 10 W/m^{2}K in the upwards direction of heat flow, and 5.88 W/m^{2}K in the downwards direction of heat flow. The coefficient of specific transmission heat losses of an entire building envelope is determined by (2.13).

$$H_t^{'} = \frac{\sum_{j=1}^{n} U_j A_j}{\sum_{j=1}^{n} A_j} + 0{,}06 \tag{2.13}$$

The last term in (2.13) represents an increase in the thermal transmittance of the building envelope by 0.06 due to the influence of thermal bridges [9]. Transmission heat losses for a given day of the year are then calculated by (2.14).

$$Q_{\text{trans,n}} = H_t \left(T_i - T_{e,n}\right) t \tag{2.14}$$

The coefficient of specific transmission heat losses H_t is calculated by (2.15) [8, 9].

$$H_t = H_t^{'} \cdot A \tag{2.15}$$

Ventilation heat losses for a given day of the year are calculated by (2.16).

$$Q_{v,n} = H_v \left(T_i - T_{e,n}\right) t \tag{2.16}$$

The coefficient of ventilation heat losses is calculated by (2.17).

$$H_v = 0{,}34 \cdot k \cdot V_{\text{neto}} \tag{2.17}$$

The heat gains of internal sources Q_i are due to the movement of people, the operation of devices, and lighting in the room. For residential buildings, the usable area of the building A_u is simplified to 4 W/m^2 [9]. Heat gains due to solar radiation on a given day $Q_{s,n}$ are calculated by (2.18).

$$Q_{s,n} = H_{c,n} \cdot F_s \cdot F_c \cdot F_f \cdot A_{\text{window}} \cdot g \tag{2.18}$$

It was assumed that there is no shading of windows with external obstacles (shading factor F_s = 1) and that blinds are not in use during the heating period (blinds factor F_c = 1). The window frame factor specifies the proportion of glazing on the entire window surface. In the event that the window frame factor is unknown, the value F_f = 0.7 is assumed after [9]. The efficiency of heat gains η_{NH} by the monthly method is given by (2.19).

$$\eta_{NH,m} = \frac{1-\gamma_{H,m}^{a_H}}{1-\gamma_{H,m}^{a_H+1}} \tag{2.19}$$

The ratio between heat gains and heat losses $\gamma_{H,m}$ is given by (2.20), where the parameter m represents the month of the year.

$$\gamma_{H,m} = \frac{Q_{i,m}+Q_{s,m}}{Q_{trans,m}+Q_{v,m}} \tag{2.20}$$

The dimensionless parameter a_H is given by (21).

$$a_H = 1+\frac{\tau}{15} \tag{2.21}$$

The time constant of the building τ, presented in (2.21) is given by (2.22) according to a simplified method.

$$\tau = \frac{50\cdot V}{H_t+H_v} \tag{2.22}$$

If the heat pump is also used for domestic water heating, the heat output of the heat pump is calculated by (2.23) according to the simplified calculation.

$$Q_{HP} = Q_{NH}+Q_w \tag{2.23}$$

The heat required to calculate the domestic hot water Q_w presented in (2.23) is calculated by (2.24) [9], where the specific annual energy consumption for domestic hot water q_w presented in (2.24) is 12 kWh/m^2/year for single-family houses [9].

$$Q_w = \frac{q_w}{365} d_w A_u \tag{2.24}$$

3 RESULTS AND DISCUSSION

3.1 Validation of electrical (PV system) and thermal model (heat pump) with measurements

Validation of the electrical model or methodology for calculating the electricity production of the PV system was performed based on measurements on a real PV system in the vicinity of Krško, Slovenia. The PV system consists of six single-crystal PV modules (72 PV cells) with an average selected efficiency of 15 %. The PV system is oriented to the south (a_w = 0 °) at an inclination angle of β = 30° with a total area of 6.75 m^2. To confirm the electrical model of the graphical user interface, a comparison was made between the results of the electrical model and the measurements on the presented PV system (Figure 1).

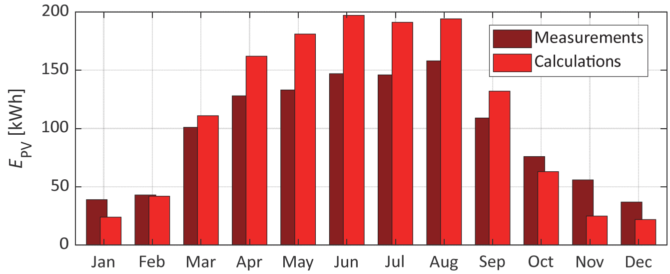

Figure 1: *Validation of electrical model (production of electricity from PV system) with measurements.*

Figure 1 shows that there are minor deviations in February, March and October. Significant deviations can be observed in the summer months from 17-26 %. The annual deviation between the calculated and measured electricity production is 12.72 %. The deviations are a consequence of measurement data of global and diffuse solar radiation, constant efficiency of the PV system, disregard for shading of surrounding buildings and that of degradation of the PV system, which occurs with the increase of the lifetime of the PV system. Validation of the thermal model or methodology for calculating the electricity consumption of the heat pump for heating the building was performed on the basis of measurements on a real residential building in the vicinity of Maribor, Slovenia. The residential building has a heating volume of 553.6 m^3, using an air-to-water heat pump. To confirm the thermal model of the graphical user interface, a comparison was made between the thermal model results and the measurements on the presented residential building (Figure 2).

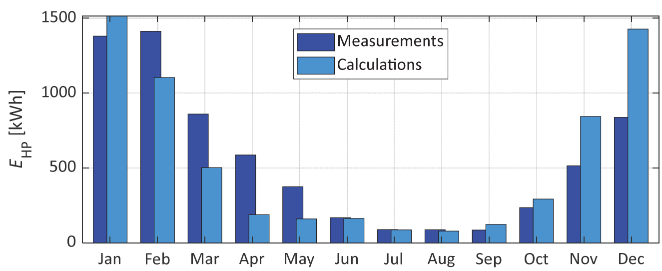

Figure 2: *Validation of thermal model (consumption of electricity by heat pump) with measurements.*

Figure 2 shows minor deviations in the summer months, when only domestic hot water is heated. A significant deviation can be seen when comparing individual months, while the annual deviation between the calculated and measured electricity consumption is only 2.25 %. The deviations are due to the simplification of the calculation of electricity consumption (neglect of heat losses of the heating system and hot water system) and the assumption of constant values of internal design temperature and a number of air exchanges (depending mainly on the living habits of residents).

3.2 Presentation of graphical user interface

The created graphical user interface is divided into four tabs. The first tab presents the data entry for calculating solar radiation and electricity production of the PV system (Figure 3). The user has the option of choosing between eleven locations across Slovenia, which are evenly spaced. Based on the choice of location, relevant meteorological data are determined, namely, a multi-year average of half-hour power density measurements of global and diffuse solar radiation [3], and average daily temperature summarised after a typical meteorological year. The average daily temperature is also used in the calculation of building heat losses. The choice of location also prescribes the corresponding latitude L, used to calculate the solar altitude angle α (2.5) and the angle of incidence of the Sun's rays i (2.6).

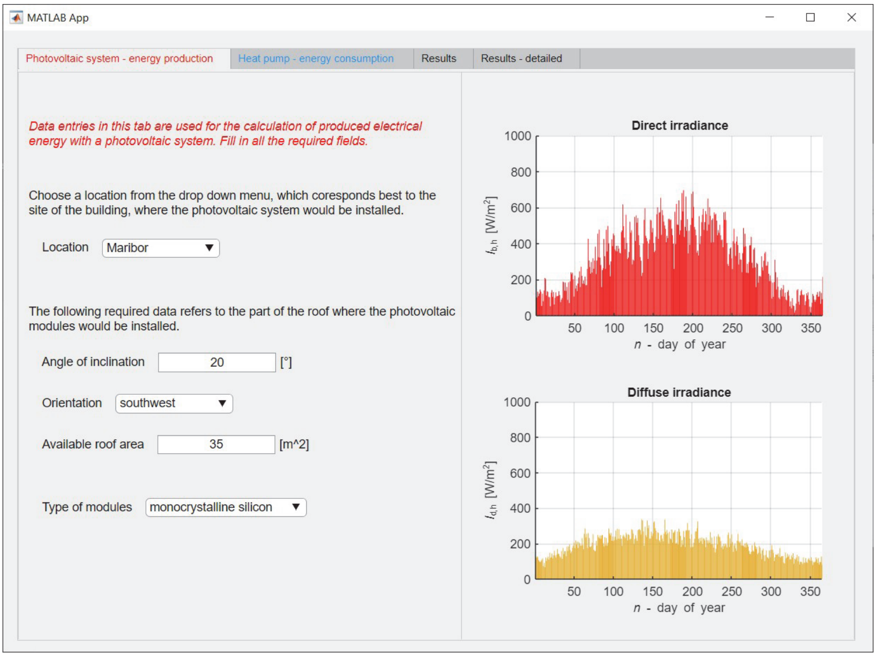

Figure 3: *First tab 'Photovoltaic system – production of electricity'*

The second tab represents the data entry for calculating the heat consumption of the heat pump. The second tab is divided into six sub-tabs for more detailed analysis. In the first sub-tab, shown in Figure 4, a simple or difficult data entry can be selected.

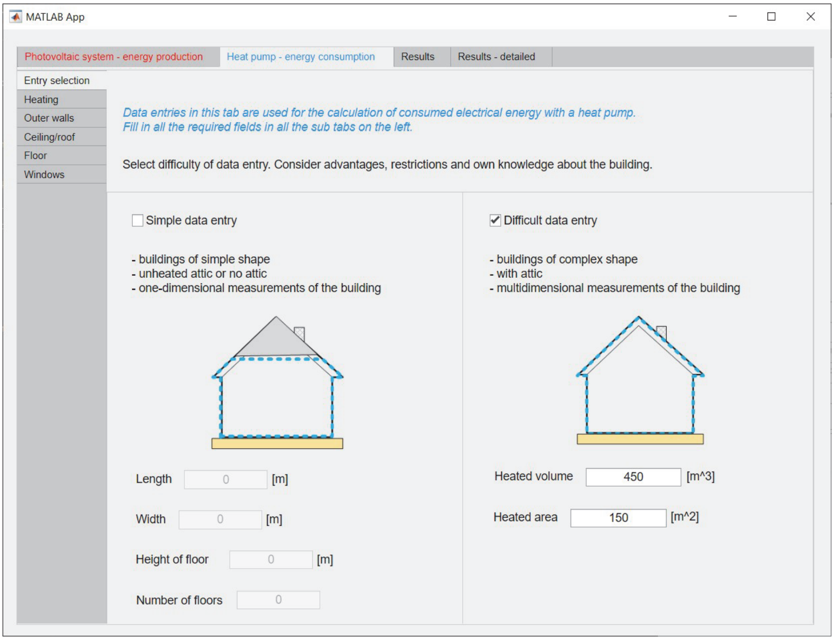

Figure 4: *Second tab 'Heat pump – consumption of electricity'*

Simple data entry is intended for buildings of simple geometric shape without an attic or with an unheated attic. Thus, the outer envelope of a building approaches the shape of a square, and the one-dimensional dimensions of a building can determine a building's gross heated volume and usable area. The required user entries are the length and width of the building, the height of the floor, and the number of floors. The difficult data entry is intended for buildings of complex shapes, which may also have an attic. In this case, the user must know the multidimensional dimensions of the building and determine the gross heated volume, usable area and areas of individual elements of the external envelope of the building. The calculation with difficult data entry is more accurate but requires better knowledge of the building. The 'Heating' sub-tab allows the selection of heat pump type, the outlet water temperature, and whether the heat pump includes domestic hot water heating. The 'Heat pump type' drop-down list offers air-to-water, water-to-water, and brine-to-water options. In the 'Outlet water temperature' drop-down list, the user selects between 35 °C and 55 °C, which corresponds to the type of heaters in the building. The type of heat pump and the outlet water temperature are necessary data for determining the heating number of the coefficient of performance (COP). The sub-tabs 'Outer walls', 'Ceiling/roof' and 'Floor' (shown in Figure 5) are intended to determine the composition of individual elements of a building's exterior envelope. The composition of the outer envelope is determined by the choice of materials and their thicknesses. Materials are divided into seven categories: walls, mortars, stone and earth, fillers, concretes, thermal insulators, and cladding.

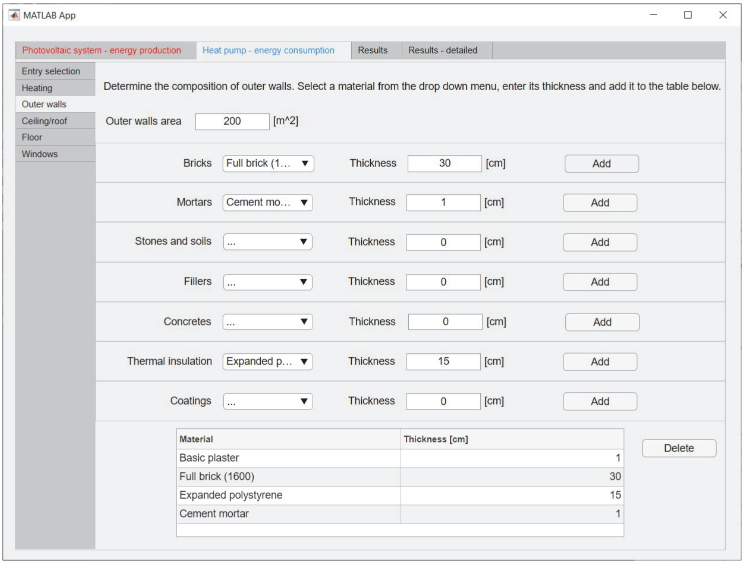

Figure 5: *Sub-tab 'Outer walls'*

The 'Windows' sub-tab (shown in Figure 6) allows entry of thermal transmittance of windows, the solar energy transmittance of glass *g*, a window area, and their orientation.

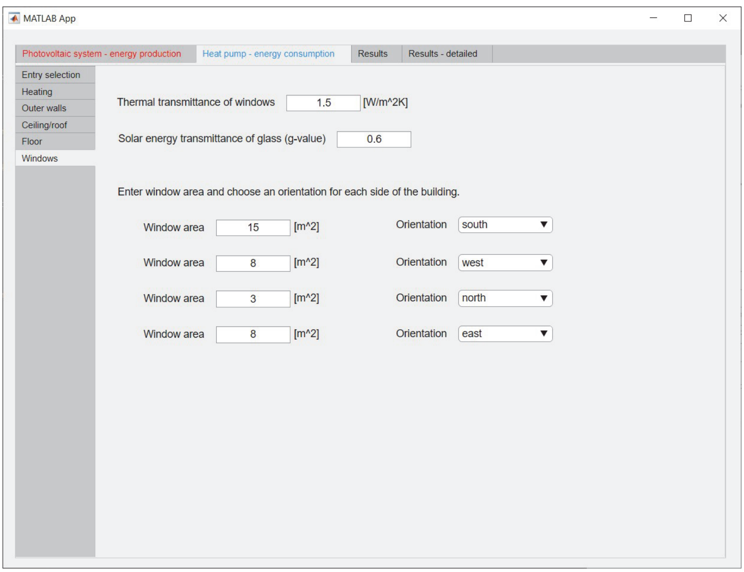

Figure 6: *Sub-tab 'Windows'*

The 'Results' tab (Figure 7) shows the calculated produced and consumed electricity on a monthly and annual basis, while the 'Results – detailed' tab (Figure 8) shows some additional calculated quantities.

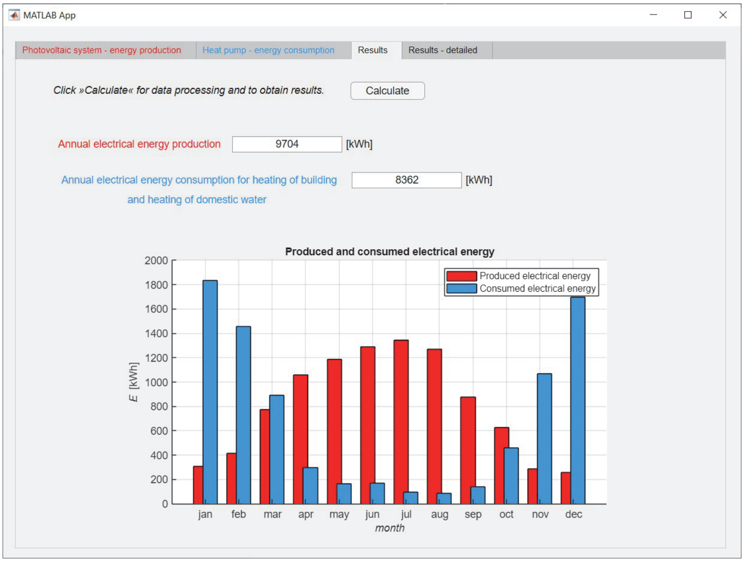

Figure 7: *Third tab 'Results – produced and consumed electricity'*

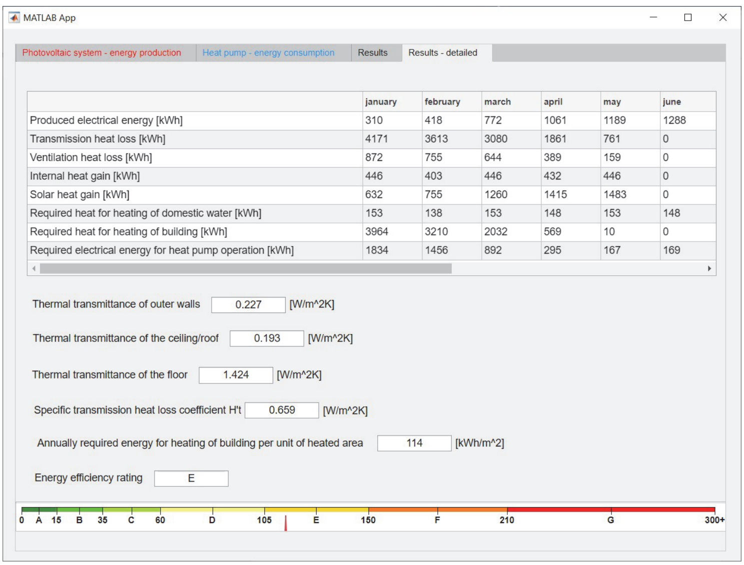

Figure 8: *Fourth tab 'Results detailed – energy efficiency rating'*

The tab 'Results – detailed' (Figure 8) shows the monthly and annual values of the following calculated values: produced electricity, transmission heat losses, ventilation heat losses, internal heat gain, solar heat gain, required heat for heating of domestic water, required heat for heating of the building, and required electricity for heat pump operation. Below the table, the calculated thermal transmittances of each element of the building envelope and the coefficient of specific transmission losses are displayed. Additionally, the annual required energy for heating of building per unit of heated area is calculated and shown, based on which the energy efficiency rating is determined. The criterion for determining the energy efficiency rating is determined based on [37]. In addition, the corresponding letter of the energy efficiency rating of the building is displayed, with the pointer showing the appropriate place on the colour scale of the energy classes.

4 CONCLUSION

This paper presents a graphical user interface for calculating electricity produced by a photovoltaic system and electricity consumed by a heat pump. The aim of the paper is to create an accurate tool to analyse the current and future technical view of residential buildings with a user-friendly and straightforward designed graphical user interface. Required meteorological data was obtained by the Environmental Agency of Slovenia, while other data were summarised according to technical guidelines for energy efficiency in buildings. The discussed methodology for the calculation of produced and consumed electricity was validated with measurements on a real system. In addition, it is essential to highlight the minimum deviations between the methodology results and measurements, which ranged from 2.25 % (for consumed electricity) to 12.72 % (for produced electricity).

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Nomenclature

(Symbols)	(Symbol meaning)
A	the area of the outer envelope of a building
a_H	dimensionless parameter
A_u	usable area of building
A_{window}	window area
B_h	direct solar irradiation on horizontal surface
d	layer thickness of the building structure
D_h	diffuse solar irradiation on horizontal surface
d_w	the number of days of hot water supply in a given period
E_{HP}	required electricity for the operation of the heat pump
F_c	blinds factor
F_f	frame factor

F_s	shading factor
g	solar radiation transmittance factor
h	hour angle
H_c	total solar irradiation on observed surface
$H_{c,n}$	total solar irradiation of observed surface for the selected day of the year
H_t	coefficient of transmission heat losses
H_t'	coefficient of specific transmission heat losses
H_v	coefficient of ventilation heat losses
i	incidence angle of the sun
$I_{b,c}$	power density of direct solar radiation on an inclined surface
$I_{b,h}$	power density of direct solar radiation on a horizontal surface
I_c	power density of total solar radiation on an inclined surface
$I_{d,c}$	power density of diffuse solar radiation on an inclined surface
$I_{d,h}$	power density of diffuse solar radiation on a horizontal surface
I_h	power density of global solar radiation on a horizontal surface
$I_{r,c}$	power density of reflected solar radiation on an inclined surface
k	number of air exchanges
L	latitude
m	consecutive month of the year
n	consecutive day of the year
η_{NH}	efficiency of heat gains
$\eta_{NH,m}$	efficiency of heat gains for the selected month of the year
Q_{HP}	heat produced for heating
Q_i	heat gains from internal sources
$Q_{i,m}$	heat gains from internal sources for the selected month of the year
$Q_{i,n}$	heat gains from internal sources for the selected day of the year
Q_{NH}	heat required to heat the building
$Q_{NH,n}$	heat required to heat the building for the selected day of the year
$Q_{s,m}$	heat gains due to solar radiation for the selected month of the year
$Q_{s,n}$	heat gains due to solar radiation for the selected day of the year
$Q_{trans,m}$	transmission heat losses for the selected month of the year
$Q_{trans,n}$	transmission heat losses for the selected day of the year

$Q_{v,m}$	ventilation heat losses for the selected month of the year
$Q_{v,n}$	ventilation heat losses for the selected day of the year
Q_w	heat required to heat hot water
q_w	specific annual energy use for hot water
R_b	inclination factor for direct solar irradiation
R_d	inclination factor for diffuse solar irradiation
R_r	inclination factor for reflected solar irradiation
t	time period
$T_{e,n}$	average daily outdoor temperature for the selected day of the year
T_i	indoor design temperature
U	thermal transmittance
V	gross heated volume of the building
V_{neto}	net heated volume of the building
α	solar altitude angle
α_e	external convective heat transfer coefficient
α_i	internal convective heat transfer coefficient
β	inclination angle
γ	azimuth angle
$\gamma_{H,m}$	the ratio between heat gains and heat losses for the selected month of the year
δ	declination angle
λ	thermal conductivity
ρ	reflection factor
τ	the time constant of the building