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Increasing photovoltaic self-consumption for objects using domestic hot water systems

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Abstract: The technique of estimating the expected decrease in electricity consumption from the grid and using PV energy for the taken load schedule based on archival data for 5 years is refined. With full self-consumption (SC), the reduction of consumption from the grid can be increased by 9.5%–30.7% for a year according to the rated PV power. Consumption should increase when PV generation exceeds a certain value. A discrete time control of the power of an electric storage boiler (ESB) is proposed based on the deviation of the storage battery (SB) state of charge from a given schedule with a heating concentration during hours of high PV generation. In the considered application, it is possible to increase SC by up to 21%. Reducing the load in the evening allows us to use SB energy to reduce consumption from the grid at night. The possibility of complete photovoltaic SC when the ESB is used with an air conditioner is substantiated. Limitations for air conditioner energy consumption according to PV generation are determined. The system's 24h model of energy processes is supplemented with a thermal model. The standard use of ESB with water temperature maintenance was also considered for comparison. ESB power control allows you to reduce daily energy consumption from the grid by 1.7–2 times. When combining an adjustable ESB with an air conditioner, it is possible to reduce consumption from the grid by 1.466–1.558 times at minimum and increase consumption from the grid by 2–5% at maximum air conditioner consumption.

Key words: 24h simulation, boiler power regulation, consumption redistribution, deviation of state of charge, temperature regime mode, warm water consumption schedule

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1. Introduction

The use of renewable energy sources (RES) is a global world trend in the development of mankind. This is because "… fossil fuel-based energy generation contributes to increased greenhouse gas emissions, leading to climate change in both developed and developing countries" [1]. According to the International Renewable Energy Agency (IRENA) data in 2022 "… some 300 GW of renewables were added globally, accounting for 83% of new capacity compared to a 17% share combined for fossil fuel and nuclear additions. Both the volume and share of renewables need to grow substantially, which is both technically feasible and economically viable" [2]. Involving low-carbon technologies will solve the problem of ensuring energy independence and local consumers'safety.

By scenarios of IRENA [2] to 2050 the rate of RES in the world energy balance will be 77%, and use of RES will increase in all sectors of final consumption. It makes especially relevant the task of maximum RES energy use on consumption. This shifts the focus from exporting the maximum electricity, produced by local photovoltaic systems (PVSs), to the grid to the maximum self-consumption (SC) of local objects (LO). Depending on the ratio of income from the sale of electricity generated by photovoltaic plants and the cost of electricity consumed from the grid, increasing their consumption may be beneficial for owners of small PVS. This will reduce the load on electricity distribution grids. Thus, SC is an important model for using local RES, especially in the absence of feed-in tariffs. At the same time, increasing the degree of use of renewable energy to reduce the cost of consumed electricity while reducing exports to the grid, up to its complete elimination, is a relevant task.

The review paper [3] summarizes existing studies on the SC of energy by PVS for residential systems. Two main options for increasing SC are being considered. These are energy storage and load management (or demand management). The development of this work is presented in [4]. It is noted that in power grids with high PV penetration, increasing SC can also reduce the load on the grid if the peak power of PVS is reduced. At the same time, energy storage is considered as the main way to increase SC, since the demand management power in the surveyed households is less than 4%. In [5] it is noted that the solution to the problems of energy balance in residential buildings with PVS is to reduce the injection of energy into the grid and increase its local consumption.

The work [6] indicates that on average the largest share (65%) of energy consumption in residential buildings is for space heating, and 15% is used for heating domestic water. This is also stated in work [7], where it is noted that lighting and heating, ventilation and air conditioning are the main components of the total energy consumption of buildings. This circumstance determines the direction of most work.

The use of a tank for storing hot water with storing electrical energy in the form of heat is considered in [8–10]. In this case, it is possible to directly use electricity for heating. Thus, the article [9] examines the effect of energy storage in batteries and heat accumulation in a hot water tank. It is argued that the strategy of replenishing excess renewable electricity into a storage tank with a single day's supply of domestic hot water can be technically and economically more efficient than using electric batteries to reduce the annual mismatch. Optimization of photovoltaic SC using hot water systems is presented in [10]. Excess PV production is stored in a hot water tank as thermal energy. When the reservoir is full, excess photovoltaic energy is sold to the grid. The authors highlight the great potential of electrified hot water systems to harness PV energy through energy management. However, using an additional storage tank is not always possible. And the sale of excess photovoltaic energy to the grid remains. This will take place when PV generation is a maximum.

Many researchers associate water heating with the use of heat pumps (HP). Thus, in [6] the use of active control by an HP is considered. In this case, the active HP controller prevents the heat pump from running when the uncontrolled load is already high. The goal is to reduce peaks in home energy consumption (peak smoothing). The heat pump is switched on when energy is produced by local RES (maximizing own consumption of renewable energy).

An analysis of the results of the year-round operation of a hybrid PVS with an HP for heating water in a residential building in Krakow was carried out in [11]. It has been shown that the use of an HP with operating time control leads to an increase in monthly SC values from 7 to 18%, and annual values up to 13%. But not up to 100%, and at the same time the generation of excess energy to the grid is maintained.

The work [12] shows that when using air HP water heaters, reducing energy consumption by 28% for a year is possible by controlling the compressor speed. This allows energy consumption to be coordinated according to available photovoltaic energy or to shift consumption to off-peak hours. However, as the authors note, when assessing the energy consumption of an entire home grid with PV and a battery, the financial decision to install a battery depends little on the HP control system.

The use of HP allows you to reduce energy consumption by using environmental energy. This is important for the period when PV generation is low. But during the period of high PV generation, excess energy remains. Ultimately, increasing the degree of PV energy use is achieved by reducing the required PV installed power and battery with their correct selection.

In [13] a system with a combination of two types of energy storage: a boiler room and a battery is considered. The boiler system consists of two parts connected in series (the main boiler and the preheating boiler). The main boiler provides the required temperature level using renewable or grid energy. The preheat boiler stores energy that is not used to load and feed the main boiler. The practical application of this solution has not been sufficiently developed, and the generation of excess energy into the grid remains.

The work [5] proposes two-level management of energy consumption at home to increase the SC of PVS and reduce energy costs in households. The first level includes the rescheduling of replacement devices for operation during hours of excess PV generation. The second layer uses a multi-objective strategy to optimize the energy exchange between the energy storage system and the smart home EV. Planning results showed that the proposed strategy allows increasing SC and reducing grid consumption by 17–41% and 27–78%, respectively, depending on the proposed scenarios. At the same time, an electric car has not yet become a mandatory attribute of the LO.

Appliance runtime scheduling is presented in [14] as one of the most effective Home Energy Management System (HEMS) strategies to help homeowners reduce their energy bills and promote grid stability. In this case, it is possible to shift the operating time of household appliances to the period of high PV generation. Energy storage systems are useful for charging during periods of low prices, as well as when there is an excess of photovoltaic energy. Discharge is possible during periods of high prices and shortages of PV power. In work [15] proposes a HEMS structure that takes into account the multiple uncertainties associated with RES power generation and load profiles. The work [16] considers demand management as a key component of both microgrids and Smart Grid technologies. Demand management can be achieved by carefully controlling requirements while maintaining customer confidence. Much of the solutions reviewed in the study aim to help households manage their electricity plan.

In work [17] the potential of demand management by shifting the timing of electricity demand is presented. The case study of a household dishwasher demonstrates the possibility of increasing renewable electricity consumption while simultaneously delivering financial savings to the consumer. It is also possible to reduce demand during peak hours by more than 60%. The authors of work [7] note that devices of everyday use can be divided into non-movable and mobile (demand shifts over time) loads. Electric dishwashers, washing machines, and clothes dryers are examples of moving loads. It is noted that most existing methods involve controlling only moving loads. The authors of [7] believe that important loads such as lighting and heating, ventilation and air conditioning can be continuously controlled through dimming, thermostatting and/or fan speed control. Thus, active demand management with consumption regulation is promising.

In work [18] an experimental prototype device using a variable average power auxiliary load (VAPL) and a grid-connected inverter for an off-grid system is described. An electric boiler can be used as a VAPL to heat water. The adjustment is carried out using the PWM method. The problem of controlling the excessive power of a renewable energy source is solved without affecting the state of charge of the battery (SîC) of the autonomous system. The considered system is somewhat specific and the goal of research is to assess the possibility of such a solution. At the same time, the use of an electric boiler to provide warm water is typical, so its use for systems with RES to ensure energy balance looks promising.

Work [19] presents an intelligent energy management system that integrates an energy controller and an IoT middleware module for efficient demand management. Since air conditioning systems account for more than 50% of electricity consumption in Pakistan, energy management with regulation of air conditioner consumption is considered.

In [20], thermoelectric models of an electric boiler and a heat pump are considered to evaluate their power and flexibility as active loads for demand management. It is shown that the elasticity of installations of this type can be sharply limited due to their continuous operation. However, management decisions are not considered.

Increasing the degree of RES use is possible under the PV generation forecast [21]. Work [22] presents a solution for a solar-wind system using a PV generation forecast with the formation of a SoC(t) graph of the battery. The generation forecast data of one of the web resources is used [23]. The problem of increasing the degree of use of RES for LO consumption is being solved to reduce energy consumption from the grid when PV generation deviates according to the forecast and load – according to the calculated value. This solution is used when the PV generation is insufficient to supply the LO load and the missing energy is consumed from the grid. One of the possible ways to reduce electricity costs is the use of solar water heaters (SWH) [24, 25]. Study [25] comprehensively assesses the technical, economic, and environmental impact of SWH systems in South Africa. As shown in [25], "... using SWHs can reduce CO_2 emissions by 75–77% for the evacuated tube system and 69–76% for the flat plate system annually, depending on the location".

For the central part of Europe, in particular Ukraine, when designing small PVS, an important issue is the correct choice of parameters. On the one hand, low generation of PV during the autumn-winter-spring period implies an overestimation of the PV power, which requires high capital costs. On the other hand, with high PV generation, there is a significant surplus of energy for export to the grid. The problem is getting worse when energy generation into the grid is limited or eliminated. In this case, switching from the MPPT mode to reducing PV generation is used [26]. Limiting the export of energy to the grid is provided by hybrid grid inverters for local PVS with batteries [27].

In work [28], a technique for calculating the PVS with a battery for SC of LO is considered. The expected indicators are assessed using archival PV generation data [29] by days over 5 years. A simplified model of energy processes in the system in a daily cycle is used. It is shown that incomplete use of PV energy for consumption is inevitable. The solution comes down to finding a compromise – to choose the value of the installed PV power, at which the degree of PV energy use for consumption is $k_{\mathrm{PV}} = W_{\mathrm{PV}L}/W_{\mathrm{PV}} \geq 0.88$ ($W_{\mathrm{PV}L}$ is the consumed PV energy, W_{PV} is the total PV energy) without a significant reduction in the degree of decreasing in costs for consumed electricity from the grid. The incomplete use of PV energy at certain intervals and for charging the battery is not taken into account. Indicators are determined for months of the year by averaging; there is no assessment of indicators for the year.

A preliminary assessment of the effectiveness of solutions in systems with RES is usually carried out using mathematical modelling in 24-hour mode, in particular, using Matlab [30, 31]. This concerns the study of energy processes in electrical circuits of PVS using archival data of the generation of PV [32]. To consider temperature conditions in the boiler, the mathematical model [20] can be used. This creates opportunities for the implementation of a general model for studying energy processes in PVS, taking into account the warm water supply system.

Thus, the use of active demand management in combination with energy storage is promising for increasing the degree of SC. One of these elements is an electric heat storage boiler. It is obvious, that the full use of PVS energy for SC without exporting excess energy to the grid requires ensuring a balance of generated and consumed power, or excess consumption. At the same time, it looks promising to use an adjustable boiler in a warm water supply system in combination with additional seasonal air conditioning, which is a typical use for many LOs. Taking into account changes in PV generation and energy consumption of the air conditioner, the control system must function according to a certain law. A possible option is control with the formation of a SoC battery schedule.

Concerning PVS with batteries for SC of LOs without exporting excess electricity to the grid, there are insufficiently studied questions regarding:

- techniques of PVS calculating for SC with an assessment of expected indicators for the year. The use of archival data on PV generation at a location point over a long period will increase reliability;
- the feasibility of increasing the degree of PV energy use, which should be confirmed by an appropriate assessment of the expected consumption indicators from the grid for the year;
- compliance with the degree of SC to the current PV generation value;
- the ability to control consumption when using an adjustable electric storage boiler with constant total consumption of the LO, as well as a boiler in combination with an additional seasonal load – air conditioning unit;
- implementation of boiler power control to form the battery SoC(t) schedule. This will link consumption with actual PV generation and will help reduce energy consumption from the grid during evening peak demand hours.

The solution to this set of issues requires additional study with evaluation of the results.

2. Purpose and objectives of the research

The purpose of the research is to increase the degree of energy use by PVS with batteries for SC of LOs to reduce the cost of electricity consumed from the grid when using a regulated load – an electric boiler.

Problems to solve:

- clarify the technique for calculating the degree of PV energy use for SC of LOs and the degree of reduction in electricity consumption from the grid when choosing PVS parameters;
- assess the possibilities of managing LO consumption to increase the degree of PV energy use and reduce energy consumption from the grid;
- study the possibilities of using an adjustable electric boiler for LO with a constant average load schedule at time intervals with constant LO consumption, as well as when using a boiler with an additional seasonal load – air conditioning;
- justify control with power regulation of the boiler heating element taking into account the temperature regime;
- perform a 24-hour simulation of the system, taking into account the control and temperature conditions of the boiler for various implementation options.

3. Materials and research methods

The technique of calculating the PVS parameters with the assessment of the expected indicators is based on the processing of archival data PV generation $P_{\text{PV}}(t)$ for the location point represented by the European geosystem [29]. To increase the reliability of the results of calculating PVS indicators with batteries, PV generation data were used for all days over 5 years. To ensure the possibility of comparing the results, the calculation was performed for the load graph $P_L(t)$, adopted for analysis in [28].

The expected values of the degree of PV energy (W_{PV}) used for consumption (k_{PV}) and the degree of reduction in energy consumption from the grid (k_E) are estimated. For the calculations, a refined mathematical model of energy processes in a PVS with an SB was used over time intervals during the day. The calculation of indicators is carried out by the energy values for all days for 5 years, without averaging.

When determining the possible value of k_E from the condition of the full consumption of PV energy, it is accepted that when the W_{PV} value of the limit value $W_{\text{PV}B}$ is exceeded, the consumption of the PV increases by the corresponding value ($W_{\text{PV}}\_W_{\text{PV}B}$). The $W_{\text{PV}B}$ value is determined by excluding energy consumption from the grid during the daytime, including peak load hours. This means that consumption must be controlled according to the W_{PV} value.

An analysis of the possibilities for increasing k_{PV} and k_E was performed for an object with a constant schedule of average load power over time intervals. At the same time, for the accepted consumption schedule [28], the use of PV with an installed power of 0.7 kW is considered, when the increase in consumption for the full use of PV energy in the maximum generation mode does not exceed 35%.

The functioning of the system was considered at $W_{\text{PV}} \geq W_{\text{PV}B}$, which occurs in the summer when PV generation is above the monthly average. To provide warm water, an electric boiler is used as a heat storage element. In this case, the load graph $P_L(t)$ takes into account the energy consumption of the boiler, taking into account the accepted schedule of warm water consumption volumes during the day. A boiler with power control of the heating element is being considered. A condition is set that the temperature of the water in the boiler as it is consumed should not drop below a certain value. This makes it possible to exclude heating of the boiler in the morning and evening while concentrating the energy consumption of the boiler during the hours of maximum PV generation and to redistribute energy consumption during the day.

The mathematical model for describing the processes in the boiler is made using the first law of thermodynamics and uses the accepted assumptions [20]. The power of the heating element is regulated with a discrete interval of 0.5 hours and is tied to the formation of the $\mathrm{SoC}(t)$ graph of the battery. The $\mathrm{SoC}(t)$ graph is taken to be exponential, which ensures a minimum value of $\Delta\mathrm{SoC}/\Delta t$ in charging mode with a constant battery voltage and a decrease in the deviation of $\mathrm{SoC}(t)$ relative to the taken value. Eliminating the heating of the boiler and reducing consumption in the evening allows you to use the stored battery energy at night. Regulation of boiler power based on $\mathrm{SoC}(t)$ deviation ensures regulation of LO consumption taking into account the actual PV generation and load deviations. The total energy consumption of the LO is constant.

The use of an adjustable boiler in the presence of an air conditioner involves ensuring energy consumption is regulated by the generation of the PV. This takes into account the possibility of changing the energy consumption of the air conditioner with the same PV generation but under different climatic conditions. To assess the possibility of application, limits have been introduced to regulate the energy consumption of the air conditioner depending on the energy of the PV, when almost its complete consumption is achieved. To take into account the actual parameters of the boiler and air conditioner used concerning the considered load schedule, appropriate conversion factors are used.

The mathematical model of energy processes in a PVS with a battery in combination with a model of temperature conditions in a boiler is made according to well-known principles. The measurement error of the SoC value is taken into account ±5%. When modelling, two options for object consumption were considered under the same conditions and the same warm water consumption schedule, which makes it possible to compare indicators.

4. Research results

4.1. Assessment of the degree of reduction in electricity consumption from the grid by increasing the degree of use of PV energy for self-consumption of LO

The results and data of work [28] are used, where the technique for calculating the installed capacity of PV for SC of LOs is considered with the assessment of indicators based on archival data of PV generation by day over 5 years. The corresponding graph of the maximum average load power (P_{LC}) by time intervals is shown in Fig. 1 for summer [28]. The base power value of the PV is 1 kW, and the installed power $P_{\mathrm{PV}R}$ is determined by the value of the coefficient $m = (0.65 - 1.0)$ to the base power. The degree of PV energy use for consumption [28] is

$$k_{\mathrm{PV}} = W_{\mathrm{PV}L}/W_{\mathrm{PV}}, \tag{1}$$

where $W_{\mathrm{PV}L}$ is the PV energy used for consumption and W_{PV} is the total PV energy.

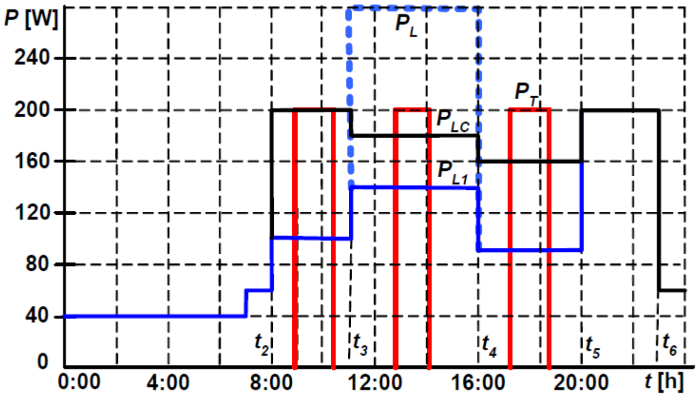


Fig. 1. Load consumption schedule for LO per day

The $W_{\mathrm{PV}L}$ value is determined by the condition of excluding energy consumption from the grid during the daytime, including morning and evening peak loads [28]

$$W_{\mathrm{PV}L} \le W_{\mathrm{PV}B} = \frac{W_{L25} + W_{L56}/(\eta_C \cdot \eta_B)^2}{\eta_C}, \tag{2}$$

where η_B and η_C are the efficiency of the battery and energy converter, and W_L is the energy consumed by the LO load at the corresponding time intervals.

The degree of reduction in costs for electricity consumption from the grid at one rate of payment tariff [28]

$$k_E = W_L / W_g, \tag{3}$$

where W_L is the energy consumed by the LO load, and W_g is the energy consumed by the LO from the grid.

Refinements have been introduced into the calculation technique [28]. This concerns the incomplete use of PV energy in the interval (t_4, t_5), when the battery is fully charged, and the value is $P_{\mathrm{PV}45} > P_{L45}$. If energy generation into the grid is not used, then PV generation is reduced in comparison with the MPPT mode ($W_{\mathrm{PV}M}$) due to the condition of ensuring power balance [26]. Analysis of the graphs of PV generation at a given value of P_{L45} shows that with some simplification for the assessment, we can accept: $k = 0.75$ at $0.5W_{L45} < W_{\mathrm{PV}M45}$ and $k = 1$ at $0.5W_{L45} \ge W_{\mathrm{PV}M45}$. Also, the limitation on the energy that the battery can consume during charging is not taken into account, taking into account the value of its energy capacity $W_B = U_B C_B$ (U_B is the battery voltage, C_B is the battery capacity (Ah)). W_B value is 1126 Wh (44 Ah at voltage 25.6 V). Meaning of W_{PV} and $W_{\mathrm{PV}L}$

$$W_{\mathrm{PV}} = \mathrm{W}_{\mathrm{PV}M24} + kW_{\mathrm{PV}M45} + W_{\mathrm{PV}M56}, \tag{4}$$

$$W_{\mathrm{PV}L} \le W_{\mathrm{PV}B} = \frac{1}{\eta_C}\left(W_{L24} + (W_{L46} - \Delta W_{B46}) + \Delta W_{B24}\right), \tag{5}$$

where ΔW_{B46} is the energy released when the battery is discharged at the interval (t_4,t_6) and ΔW_{B24} is the energy required to charge the battery.

The $W_{\mathrm{PV}B}$ value is determined at the maximum energy value that the battery can supply in the interval (t_4, t_6) with a depth of discharge DOD $\leq 80\%$ $\Delta W_{B46} = 0.8 W_B \cdot \eta_C \cdot \eta_B$ and a maximum value $\Delta W_{B24} = 0.8 W_B / \eta_C \cdot \eta_B$. At the same time, we believe that to exclude consumption during the evening peak, the SoC value at time $t4$ is SoC4 $\rightarrow 100\%$.

The main clarification is that the k_{PV} and kE values are calculated based on the corresponding energy values for all days over 5 years, without averaging. Table 1 shows the indicators for June $(k_{EJ}, k_{\mathrm{PV}J})$ and for the year k_{EY}. The k_E values from [28] are given in parentheses for comparison.

Table 1. PVS indicators taking into account PV generation by day for 5 years

m	**June**				**Year**	
	$k_{\mathrm{PV}J}$, p.u.	**k_{EJ}, p.u.**	**ΔW, Wh**	**k^1_{EJ}, p.u.**	**k_{EY}, p.u.**	**k^1_{EY}, p.u.**
1	0.697	6.45(7.21)	2714	9.137	2.27	2.968
0.75	0.844	5.03(6.47)	1304	5.846	2.02	2.331
0.7	0.881	4.66(6.25)	1022	5.196	1.96	2.206
0.65	0.918	4.23(5.92)	740	4.541	1.9	2.08

The question of the feasibility of increasing k_{PV} is being considered since the efficiency of the system is ultimately determined by the value of k_E. On the other hand, there is a contradiction, since an increase in k_E for the autumn-winter-spring period is associated with an overestimation of the PV power and a decrease in k_{PV} in summer.

With full use of PV energy for consumption, we have

$$k^1_E = (W_L + (W_{\mathrm{PV}} - W_{\mathrm{PV}L}))/W_g, \tag{6}$$

Possible values of k^1_E with full use of PV energy for consumption for all days in the period under consideration (5 years) are given in Table 1. With $m = 0.7$ for June, we have an increase in k^1_{EJ} of almost 11.5%, over the year the increase in k1EY is 12.6%. In this case, the value of k^1_{EY} is close to the value k_{EY} at $m = 1$ (overstatement of power by $1/0.7 = 1.429$ times). Thus, due to the full use of PV energy for consumption, we have the same effect as when increasing the installed capacity of the PV and incomplete use of energy for consumption.

An increase in the degree of PV energy use implies an increase in LO consumption during daytime hours. For June, Table 1 shows the energy value $\Delta W = \eta C$ (mW$_{\mathrm{PV}R\mathrm{MAX}} - W_{\mathrm{PV}B}$), which must be consumed by the LO to fully utilize the PV energy per day with maximum generation ($W_{\mathrm{PV}R\mathrm{MAX}}$ – maximum generation of the PV). The increase in consumption (load) at $m = 0.7$ in the application considered is about 35%, and at $m = 1$ we have 93%. The $W_{\mathrm{PV}B}$ value at $m = 0.7$ approximately corresponds to the average monthly PV generation in summer. It is unrealistic to double the load. Increasing consumption makes sense only with high PV generation, otherwise, it will lead to a significant decrease in k_E. Ideally, the increase in consumption should be controlled and implemented by the PV generation.

4.2. Assessment of the possibility of increasing consumption when using an electric storage boiler (ESB) with power regulation

Let's consider the use of PVS for LO using an ESB with power control of the heating element. The power regulator can be made on a rectifier with a PWM DC converter.

We use the graph of the average load power $P_{LC}(t)$ by time intervals (Fig. 1), considered in [28] with a total daily consumption $W_L = 3140$ W and an installed PV power of 0.7 kW ($m = 0.7$). This graph $P_L(t)$ is conditional to the accepted value of $P_{\text{PV}R}$ and the peak load $P_{L\text{MAX}} = 200$ W. Let's recalculate to real figures with a 5-fold increase in power, then $P_{L\text{MAX}} = 1000$ W. We assume that this load includes a boiler with a volume of $V = 100$ l and a heater power of $P_T = 1$ kW. The main consumption of warm water occurs in the morning, at lunchtime and in the evening. We set the volume of water consumed over time. To simplify, we concentrate consumption into three-time intervals (three volumes).

The mathematical model of thermal processes in an ESB uses the first law of thermodynamics. With a relatively small size, the effect of stratification can be neglected [20]. Heat exchange within the room can also be neglected since modern ESB have good thermal insulation. In this case, the temperature of the water in the ESB is

$$\tau_{\text{in}} = \frac{1}{m}\int (Q_E \cdot S - c \cdot v_B(\tau_{\text{in}} - \tau_C))\mathrm{d}t + \tau_{\text{in}0}, \tag{7}$$

where: m is the mass of water in the ESB (corresponds to the volume in litres $m = V$), Q_E is the heat generated by the electric heater, S is heater control function (1 – on and 0 – off), c is heating capacity of water, v_B is mass consumption of water from the ESB in l/s, τ_C is the temperature of cold water that enters to the boiler ($\tau_C = 15°\text{C}$), $\tau_{\text{in}0}$ is the initial temperature value in the ESB.

According to the energy balance for the water mixer, we have

$$v_{\text{OUT}}\tau_{\text{OUT}} = v_B\tau_{\text{in}} + v_C\tau_C, \tag{8}$$

where: $v_{\text{OUT}} = (v_B + v_C)$ is the mass of water at the output of the mixer with a temperature τ_{OUT} (economy mode is taken with $v_{\text{OUT}} = 4$ l/s, $\tau_{\text{OUT}} = 37°\text{C}$), v_C is the mass of cold water from the water supply.

Then

$$v_B = \frac{v_{\text{OUT}}}{1 + \dfrac{\tau_{\text{in}} - \tau_{\text{OUT}}}{\tau_{\text{OUT}} - \tau_C}}. \tag{9}$$

Effective use of PVS capabilities requires fairly strict consumption planning (without compromising comfort). In this case, this concerns the average energy consumption over time intervals (load graph). The same should be attributed to the warm water consumption mode (τ_{OUT}). It can be simplified into 3 volumes: morning V_1, lunchtime V_2, evening V_3. Typically, greater consumption is in the morning and evening. Therefore, the values of V_1 and V_3 are decisive in determining the temperature regime. Possible relationships: $V_1 = V_3$, $V_1 > V_3$, $V_1 < V_3$. For the considered algorithm, with the same total consumption per day ($V_1 + V_2 + V_3$), the temperature balance with the same value of τ_{inMIN} is achieved at different values of $\tau_{\text{in}0}$ at the beginning of the day.

A fairly economical mode of warm water consumption has been taken: $V_1 = 57.6$ l, $V_2 = 36$ l, $V_3 = 57.6$ l. ($V_{B1} = 34.1$ l, $V_{B1} = 19.7$ l, $V_{B1} = 34.1$ l). In this case, the energy consumption to maintain $\tau_{\text{in}} = 60°\text{C}$ is, respectively, 1480 Wh, 920 Wh, and 1480 Wh (total $W^1_{TC} = 3\,880$ Wh). When recalculated to the accepted load schedule (reduced by 5 times) $W_{T1} = 296$ Wh, $W_{T2} = 184$ Wh, $W_{T3} = 296$ Wh (total $W_{TC} = 776$ Wh). The boiler model uses real power and energy values, which are recalculated when analyzing energy processes in the PVS.

Figure 1 shows a graph of the total power consumed by the load $P_{LC}(t)$ and a graph of power $P_{L1}(t)$ without taking into account boiler consumption. The boiler power graph $P_T(t)$ is based on consumption at three-time intervals. The load $P_{L1}(t)$ remained the same during the evening peak but decreased at other intervals. Let's consider the possibility of eliminating energy consumption by the boiler in the interval (t_4, t_5). This, by reducing the load of the W_{L45}, will limit the degree of battery discharge with the possibility of using its energy for consumption at night. The battery is discharged to 20% (DOD ≤ 80%), which is necessary to maximize the use of the battery's energy capacity the next day.

We proceed from the fact that in the interval (t_3, t_4) it is possible to heat water to a maximum temperature of 75°C due to the excess PV energy. This is enough to provide warm water in the evening. At the same time, under the average schedule of warm water consumption by intervals, a temperature schedule is drawn up: initial temperature in the morning τ_{in0}, expected temperature τ_{in1} at the end of use of the first volume V_1, after the second volume $V_2 \tau_{\text{in2}}$. It is advisable to use two threshold values for the water temperature in the boiler: the minimum τ_{inMIN} and the maximum τ_{inMAX} (usually 75°C). At a comfortable temperature $\tau_{\text{OUT}} = 37°\text{C}$, you can take $\tau_{\text{inMIN}} = 38°\text{C}$ with the boiler turned on for minimal heating.

The calculation shows that at $\tau_{\text{in0}} = 58 - 60°\text{C}$ after consuming volume V_1, the value of τ_{in1} without using heating is sufficient to use volume V_2 with τ_{in2}. Further, it is possible to concentrate all the heating (W_{TC}) due to the PV energy in the interval (t_3, t_4). In this case, we obtain a graph of $P_L(t)$ shown in Fig. 1 with a dotted line.

As a result, for the interval (t_2, t_4) we have an increase in W_{L24} by $W_{T3} = 296$ Wh. The PV energy used for the interval (t_4, t_5) for consumption by the LO load $(\eta_C \cdot W_{\text{PV}L45})$ can be determined under the $P_{\text{PV}}(t)$ schedule for a specific clear day in June with maximum generation. For the graph $P_C(t)$ we have $\eta_C \cdot W_{\text{PV}L45} = 390$ Wh, and for the graph $P_L(t)$ we have $\eta_C \cdot W_{\text{PV}L45} = 312$ Wh. Thus, for the $P_L(t)$ schedule, the increase in consumption during the daytime is $\Delta W = 218$ Wh. This value, of course, is less than the value of ΔW in Table 1 and is 21%. At the same time, it should be taken into account that when PV generation decreases, the energy balance is disturbed ($W_{TC} = \text{const} = 776$ Wh), which leads to the need to heat the water or switch to a mode that maintains the set water temperature. This can be done based on the PV generation forecast. The water heating mode is carried out by switching control to the boiler thermostat upon completion of the evening peak load.

Increasing the load in summer is possible by using an air conditioner. In cold times with high PV generation, the air conditioner can be used for heating. Let's evaluate the possibilities of total PV energy consumption when using an air conditioner in combination with an adjustable boiler. The performance of the air conditioner is determined by the thermal cooling/heating power. The consumed electrical power is determined by the energy consumption class, depends on some factors and is set by the manufacturer at an outside temperature of 35°C, and an indoor temperature of 27°C with doors and windows closed. Let's consider the use of an air conditioner with a maximum electrical power consumption of $P_{CR} = 1$ kW when recalculated to the accepted load schedule $P^1_{CR} = 200$ W. We accept that in hot weather the air conditioner can turn on after

11.00 and work until 20.00. We will take into account the change in energy consumption of the air conditioner by introducing the K coefficient, or $P_C^1 = P_{CR}^1$.

Limitations on the possible energy consumption of the air conditioner when the PV generation changes. We will determine the upper limit on the maximum value of K_{MAX} from the condition of a sufficient supply of $\text{SoC}_4 \to 100\%$, which is necessary to exclude (reduce) energy consumption from the grid during the evening peak. Then

$$W_{\text{PVMAX24}} \cdot \eta_C \cdot p = W_{L24} + W_T + K \cdot P_{CR}^1 (t_4 - t_2) + \Delta W_{B24}, \tag{10}$$

where $p = W_{\text{PV}}/W_{\text{PVMAX}}$, the value of W_{L24} is determined for the graph $P_{L1}(t)$.

Determination of K is carried out taking into account the temperature regime of the boiler. We accept $\tau_{\text{in0}} = 60°\text{C}$. In this case, the PV energy may not be enough to heat water in the daytime $W_T < W_{TC}$. Accordingly, night heating will be required to ensure the value $\tau_{\text{in0}} = 60°\text{C}$. If $W_T < 0.5W_{TC}$, then the water temperature will not be sufficient to use the volume V_3 and the value of τ_{in3} is less than the minimum permissible. Thus, additional heating is required during the daytime. The required value of additional energy W_{TA} can be determined from the measured value of W_{TA} at time t_4. Table 2 shows the values of $K(p)$, determined from the possibility of using only night heating for two values of air conditioner power.

Table 2. Dependence $K(p)$

Parameter	**Value**					
P_{CR}, kW	1			0.8		
p, p.u.	1	0.9	0.8	1	0.9	0.8
K_{MAX}, p.u.	1	0.7	0.4	1	0.875	0.5
K_{MIN}, p.u.	0.65	0.36	0.1	0.81	0.45	0.25

We determine the lower limit of K_{MIN} from the condition of excluding water overheating without limiting the degree of PV energy use. The energy balance with the equality $\tau_{\text{in0}} = \tau_{\text{in}f} = 60°\text{C}$ ($\tau_{\text{in}f}$ is the water temperature at the end of the day) is ensured by the condition $W_T \leq W_{TC}$. When $W_T = W_{TC}$, water is heated without additional consumption from the grid. If $W_T > W_{TC}$ we have incomplete use of PV energy since the water will heat up to the limiting value $\tau_{\text{inMAX}} = 75°\text{C}$ before moment t_4. This leads to the boiler turn-off and limits its ability to consume the excess PV generation. If you set value $\tau_{\text{in0}} < 60°\text{C}$, then have $\tau_{\text{in0}} < \tau_{\text{in}f}$, which will limit the ability to manage energy consumption the next day.

It is desirable to set the operating mode of the system with K_{MIN}. When the established limits are exceeded, the PV energy use indicators deteriorate. But the energy consumption of an air conditioner is determined to a greater extent by climatic conditions, and not by the generation of PV. Consequently, the possibilities for such applications are limited.

4.3. Implementation of PVS control

The structure of the system is shown in Fig. 2 in a single-line version. It is possible to use a grid-connected inverter (GI) with limited energy generation into the grid [28] or solutions discussed in [26]. In this case, to ensure energy balance, regulation of PV generation is used. In the case of using an air conditioner, it is possible to use an inverter with generation, since generation does not exceed 1–2%. When you pay for generation as consumed energy, this will have virtually no impact on your electricity bills. About inverter control, the DOD limiting function is used. In this case, when the battery is discharged to the limit value, the missing energy is consumed from the grid. The PV and battery are connected to the inverter input via DC-DC converters CPV and CSB. The heating element of the EK boiler is connected through the power regulator unit CPU. The thermostat, protection and boiler activation circuits are preserved. The CPU is a rectifier with a step-down pulse voltage converter on a transistor. Regulation is carried out using the PWM method.

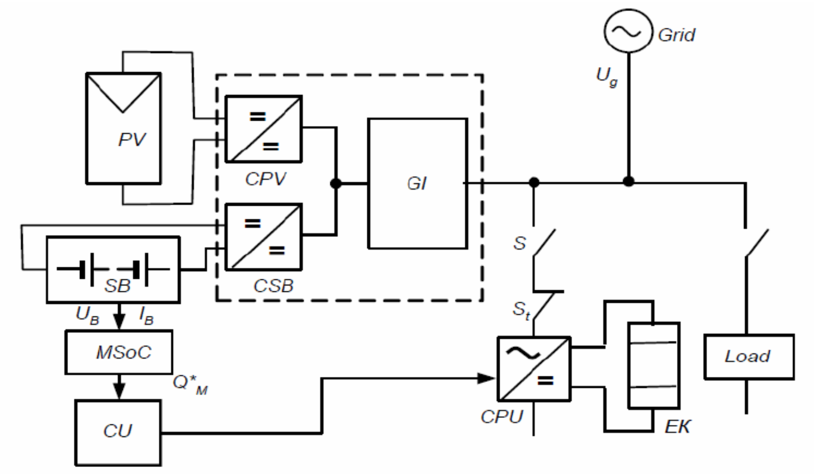


Fig. 2. System structure

The CU control unit implements power control functions under the measured battery SoC value (MSoC). The CU also performs the calculation of the given SoC schedule. Let us limit ourselves to considering the implementation of control when generating PV above the monthly average value in the summer when incomplete use of PV energy is possible.

To concentrate the energy consumption of the boiler, the formation of the battery SoC is carried out in the interval (t_3, t_{4+1}). When $p > 0.7$ for the accepted graph $P_{L1}(t)$ the value SoC_3 (or $Q^* = Q/Q$, $Q = Q_0 + \int I_B \mathrm{d}t$, I_B – battery current, Q – corresponds to battery capacity C) at time t_3 is quite large – $Q_3^* > 50 - 80\%$. At the same time, after reaching the value $Q^* = 88 - 92\%$, the battery is charged at a constant voltage, when the value of the charge current decreases and is limited by the charging characteristic [33]. Therefore, to reduce the rate of change $\Delta Q^*/\Delta t$, an exponential graph of change $Q_R^*(t)$ is taken

$$Q_R^* = Q_3^* + (Q_4^* - Q_3^*)(1 - e^{-\frac{t}{\tau}}), \tag{11}$$

where: $\tau = (t_4 - t_3)/3.5$ is the time constant, Q_3^* is the measured value, $Q_4^* \to 100\%$.

Correspondence of the $Q^*(t)$ graph to the given $Q_R^*(t)$ is possible by adjusting the boiler power according to the deviation $\Delta Q_t^* = (Q_R^* - Q_M^*)$ (Q_M^* – measured value). It is carried out with discrete time Δt. In this case, the $Q_R^*(t)$ graph has a stepped shape with a constant value over the interval Δt, the measurement is carried out at the beginning of the interval $(t_3, (t_3 + \Delta t), (t_3 + 2\Delta t), \ldots, t_4)$.

Boiler power $P_{Tt} = b \cdot \Delta Q_t^*$ with limitation $P_{Tt} \geq 0$. The value of b is determined for the maximum deviation $P_{TR} = b\Delta Q^*_{t\mathrm{MAX}}$ (P_{TR} – boiler heater power). The value $\Delta Q^*_{t\mathrm{MAX}}$ is determined for the initial section $Q_R^*(t)$. Taking into account the fact that the value of Q_3^* varies within wide limits depending on the PV generation, the value of b is given by the dependence $b = f(Q_3^*)$.

5. 24h simulation of energy processes

The simulation was carried out for the daily cycle of the system using the Matlab software. The structure of the model of energy processes in the electrical circuits of the system, including the battery, is made according to the principles presented in [32]. PV power, LO load and air conditioner power are specified by the corresponding dependencies $P_{\mathrm{PV}}(t)$ (according to archival data [29]), $P_{L1}(t)$ and $P_C(t)$. The structure has been added: a model of thermal processes in the boiler (7) and (9); Q^* measurement module; boiler power control module. Control discreteness $\Delta t = 0.5$ hour. The measurement error $Q^*(5\%)$ is taken into account. The boiler power setting from the control module is entered into the model of thermal processes in the boiler, which also implements the thermostat function (turn-off at $\tau_{\mathrm{in}} \geq 75°\mathrm{C}$). The resulting value is used in the energy process model.

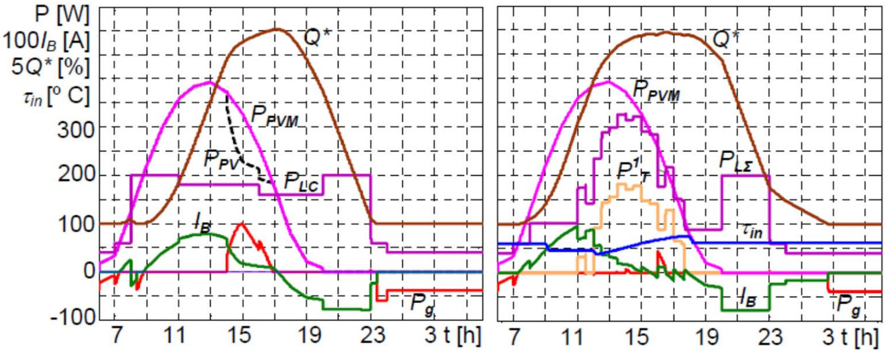
Table 3 shows the performance indicators of the PVS: W_T – energy consumed by the boiler; $W_{L\Sigma}$ is the total load consumption of the LO, W_g is the energy consumed from the grid; k_{E3}, k_{E2}, k_{E1} – the degree of reduction in electricity consumption costs at three, two, one payment tariff rates. The accepted tariff ratio is: for 3 tariffs – peak/half-peak/night = $1.5/1/0.4$, for 2 tariffs – day/night = $1/0.5$.

Table 3. Efficiency indicators of PVS without the use of air conditioning

Variant	**W_C, W**	**$W_{L\Sigma}$, W**	**W_g, W**	**k_{E3}, p.u**	**k_{E2}, p.u**	**k_{E1}, p.u**
Maximum generation of PV $W_{\mathrm{PV}R\mathrm{MAX}}$ ($p = 1$)						
v1	776	3140	980	34.4	23.96	13.25
v2	776	3149	780	295	264	277
PV generation is $0.85W_{\mathrm{PV}R\mathrm{MAX}}$ ($p = 0.85$)						
v1	776	3140	443.4	27.3	19.1	10.7
v2	776	3149	217.6	50.89	38.48	22.89
PV generation is $0.77W_{\mathrm{PV}R\mathrm{MAX}}$ ($p = 0.77$)						
v1	776	3140	177	21.84	15.91	9.136
v2	776	3149	15.4	37.12	27.9	16.36

Two variants for boiler controlling without using an air conditioner were considered: v1 – using the basic graph $P_{LC}(t)$ (Fig. 1) (taking into account consumption for heating water); v2 – using the $P_{L1}(t)$ graph (Fig. 1) and regulating the boiler power during operation. An analysis was performed for different schedules of warm water consumption with the same total volume. In this case, the indicators are practically the same, the differences relate to the initial value of the water temperature in the boiler. The results are given with the equality $V_1 = V_3$. Value $m = 0.7$ ($P_{\mathrm{PV}} = 0.7$ kW). The increase in the degree of PV energy use makes it possible to reduce energy consumption from the grid in particular for one tariff from 1.7 to 2 times.

At $p = 0.77$ or $W_{\mathrm{PV}} = 0.77 W_{\mathrm{PV}R\mathrm{MAX}}$ (Fig. 3), almost complete use of PV energy for consumption is achieved (W_g is 0.5% of the total consumption by the LO load).



(a) (b)

Fig. 3. Oscillograms of processes in the system at $p = 0.77$: (a) variant v1; (b) variant v2

Fig. 3 shows: load power P_L, power consumed from the grid P_g, power of the boiler P_T^1, PV power in MPPT mode $P_{\mathrm{PV}M}$ (initial data from the archive), PV power, which is used for consumptionP_{PV}, state of charge of the battery Q^*, battery current I_B, water temperature in the boiler τ_{in}: (a) variant v1; (b) variant v2.

Table 4 shows the PVS indicators for two variants with using an air conditioner (W_T and W_{TA} – accordingly, the energy consumed in the control process during the day and the energy for heating at night). The ratio of p and K was considered according to Table 2, as well as when going beyond the specified limits for $p = 0.8$ and $K = 0.53$ (in this case we have additional heating day and night).

For the upper limit of K_{MAX}, when using regulation, we have a slight decrease in k_{E1} from 2% to 5%. At the same time, we have an increase in k_{E3} (from 1.39 to 2.11 times) and k_{E2} (from 1.16 to 2 times). For the lower limit of K_{MIN}, we have an increase in k_{E1} by 1.466 and 1.558 times. The increase in k_{E3} and k_{E2} is due to a decrease in consumption during the evening peak, up to complete exclusion. In variant v2 we have almost complete PV energy consumption and W_g is no more than 0.56%.

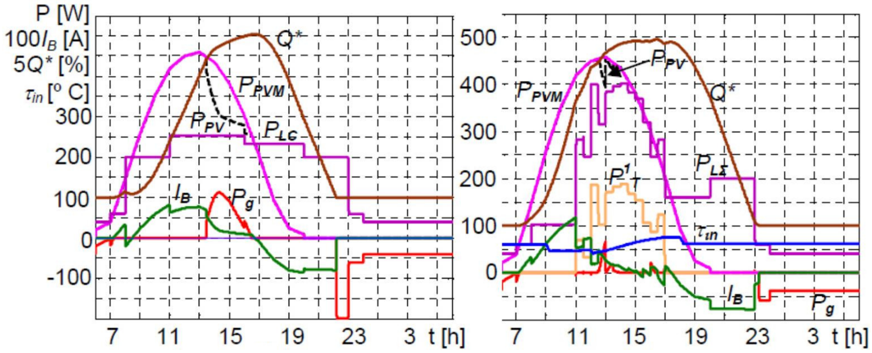
Table 4 also shows data for reducing W_{L35} consumption in the time interval from 11:00 to 18:00 by 20% ($P_{L1} = 0.8$) at $p = 1$ and $K = 1$. In this case, the value of K_{MIN} increased from 0.65 to 0.75.

Fig. 4 shows oscillograms at $p = 0.9$ at $K = 0.36$: (a) variant v1; (b) variant v2.

Fig. 5 shows oscillograms at $p = 0.8$ at $K = 0.53$ (variant v2), additional heating of the boiler during the day and evening is highlighted by a dotted line.

Table 4. Performance indicators of PVS with air conditioning

Variant	W_T, **W**	W_{TA}, **W**	$W_{L\Sigma}$, **W**	W_g, **W**	k_{E3}, **p.u**	k_{E2}, **p.u**	k_{E1}, **p.u**
$P = 1$ at $K = 0.65$							
v1	776	–	4310	244	9.157	8.329	6.474
v2	776	–	4319	19	18.31	14.48	9.489
$P = 1$ at $K = 1$							
v1	776	–	4940	0	5.08	5.49	4.76
v2	419	357	4586	1.8	7.06	6.44	4.667
$P = 0.9$ at $K = 0.7$							
v1	776	–	4480	0	5.71	5.869	4.947
v2	410	366	4472	3.67	9	7.139	4.8
$P = 0.9$ at $K = 0.36$							
v1	776	–	3788	214	13.62	10.56	7.413
v2	776	–	3797	19	28.77	21.08	11.55
$P = 0.8$ at $K = 0.53$							
v1	776	–	4094	0	4.671	4.903	4.22
v2	235	143 + 398	4102	13	6.857	5.793	4.07
$P = 1$ at $K = 1$ ($W_{L35} = 0.8$)							
v1	776	–	4696	90	6.066	6.24	5.25
v2	565	211	4557	15	7.89	7.22	5.37
$P = 1$ at $K = 0.75$ ($W_{L35} = 0.8$)							
v1	776	–	4246	325	8.676	7.95	6.23
v2	776	–	4318	50	16.4	13.09	8.9



(a) (b)

Fig. 4. Oscillograms of processes in the system at $p = 0.9$, $K = 0.36$: (a) variant v1; (b) variant v2

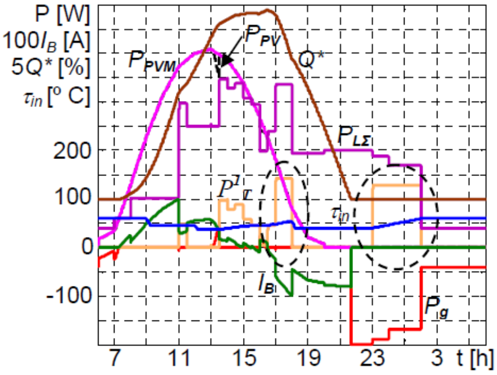


Fig. 5. Oscillograms of processes in the system at $p = 0.8$, $K = 0.53$

6. Discussion

A refined technique for PVS determining makes it possible to estimate the degree of decrease in energy consumption from the grid over a year with the full utilization of PV energy. A variant of PVS parameters calculation is considered with the exclusion of energy consumption from the grid during the daytime (8:00, 23:00) with an average monthly PV generation in the summer. In this case, with constant energy consumption of LO, increasing the degree of PV energy utilization to 20% is possible due to:

- regulation of the boiler power to redistribute the energy consumed, taking into account the schedule of warm water consumption and the possibility of heat accumulation in this case. The energy consumption of the boiler is concentrated during the hours of maximum PV generation with a decrease in LO consumption in the evening hours. It will allow to increase in the degree of PV energy consumption and use of the battery energy stored in the evening hours at night to reduce electricity consumption from the grid;
- regulation of the boiler power according to the deviation of the SoC graph according to the taken $\mathrm{SoC}_R(t)$. This ensures the regulation of energy consumption by the PV generation and the actual load of the LO. The temperature in the boiler is also maintained.

Full PV energy consumption is possible when using an additional seasonal load – an air conditioner init. The recommended boundary modes for changing the energy consumption of the air conditioner unit depending on the PV generation have been determined.

This study is a development of work [28], where the technique of determination of parameters of PVS with storage battery for SC of LO. At the same time, the incomplete use of PV energy at separate time intervals was not taken into account, and monthly indicators were determined as average values. As a result, the obtained indicators are somewhat overestimated. There are no expected indicators for the year.

The special feature of the present work is to increase the reliability of the assessment of the expected reduction in energy consumption from the grid with an increase in the degree of PV energy consumption. For this purpose, the technique for assessing indicators has been refined, taking into account PV energy, not used for consumption. An assessment of the expected degree of reduction in energy consumption from the grid with the full PV energy consumption for different PV powers was carried out. Two options for increasing consumption with an adjustable electric boiler were considered: a) within the accepted schedules of LO load power and warm water consumption; b) when using additional seasonal load – air conditioning unit. Regulating the energy consumption of the boiler based on the deviation of the SoC schedule of the battery links the degree of power increase to the actual PV generation. A 24-hour mathematical model of energy processes in the PVS is combined with a model of thermal processes in the boiler. To increase the reliability of the simulation, the SoC measurement error (5%) was taken into account.

There are certain restrictions regarding the use of the results of the work:

- energy management is considered at high PV generation, when there may be incomplete use of PV energy for consumption;
- a specific graph of the power consumed by the LO with a fixed graph of the volume of warm water consumption is considered;
- changes in the energy consumption of the air conditioner with different PV generation are considered within the recommended limits, regardless of real natural factors, which require additional study.

A further development of the work is the improvement of control by maintaining the required temperature conditions of the boiler and taking into account the weather forecast throughout the entire range of PV generation.

7. Conclusions

There is a refined technique for calculating the expected indicators of a hybrid PVS with a battery for self-consumption of LO using archival data on PV power generation for 5 years. For the specific application considered, the full self-consumption of the PV at values $m = (0.65 - 1)$ (m is the ratio of the PV power relative to 1 kW) allows for a reduction in electricity consumption in the summer months from 1.073 to 1.416 times, per year from 1.095 to 1.307 times. At value $m = 0.7$ and the accepted value of the battery energy capacity, this requires an increase in daytime consumption for summer days with a maximum PV generation of 35%. If PV generation decreases, increasing consumption is not advisable. As m increases, the required degree of increase in consumption also increases. It is advisable to control the consumption of LO taking into account the actual PV generation.

The possibility of partially increasing the degree of PV energy use for consumption is shown when using an adjustable electric storage boiler. At that, the LO total energy consumption remains constant. This is possible by redistributing the energy consumption of the boiler during hours of maximum PV generation and correspondingly reducing consumption in the evening hours. The degree of battery discharge decreases in the evening, and the stored energy is used for consumption during the evening peak and nighttime. In the case of using an air conditioner in combination with an adjustable boiler – it is possible to use the PV energy almost completely for consumption. The boundary modes for the maximum and minimum energy consumption of the air conditioner are determined depending on the PV generation.

The energy consumption of the boiler is controlled during the hours of maximum PV generation in the interval ($t_3 = 11:00$, $t_{4+1} = 17:00$) by the deviation of the SoC graph from the set value, taking into account the temperature regime. The control is discrete with the step 0.5 hours, and the set SoC value changes according to an exponential law. The power control channel gain is determined by the measured SoC value at the end of the morning peak.

The simulation results confirm the possibility of redistributing consumption when using an adjustable electric boiler. For the considered load variant and warm water consumption schedule at maximum PV generation and $m = 0.7$, the additional consumption is 20.4%. In this case, it is possible to reduce consumption from the grid, in particular from 1.7 to 2 times.

The use of an adjustable boiler in combination with an air conditioner unit ensures the possibility of almost complete use of PV energy for consumption (deviation up to 1%). The degree of reduction in the cost of electricity consumed from the grid depends on the ratio of PV generation and air conditioner energy consumption. For the recommended values of minimum energy consumption of an air conditioner, it is possible to reduce consumption from the grid in comparison with the boiler operating mode with a constant temperature of 1.466 and 1.558 times. For the recommended values of the maximum energy consumption of the air conditioner, there is an increase in consumption from the grid by 2–5%. At the same time, with two and three payment tariffs, electricity costs are reduced by reducing consumption during the evening peak, up to complete elimination.

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