

Simulation model for assessing the efficiency of a combined power installation based on a geothermal heat pump and a vacuum solar collector

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Abstract. The article is devoted to the use of renewable energy sources and the assessment of the feasibility of their use in the climatic conditions of the Western Urals. A simulation model that calculates the efficiency of a combined power installations (CPI) was (RES) developed. The CPI consists of the geothermal heat pump (GHP) and the vacuum solar collector (VCS) and is based on the research model. This model allows solving a wide range of problems in the field of energy and resource efficiency, and can be applied to other objects using RES. Based on the research recommendations for optimizing the management and the application of CPI were given. The optimization system will give a positive effect in the energy and resource consumption of low-rise residential buildings projects.

1. Introduction

Despite the wide practice of using renewable energy sources (RES), there is practically no information on the effectiveness of the use of geothermal heat pumps (GHP) and vacuum solar collectors (VCS) in the regions of Russia with a cold climate, including in the conditions of the Western Urals. To solve the problem of objective efficiency assessment of heat supply systems through a combination of heat pump equipment and VCS is considered to be possible due to the development of information technologies, energy monitoring and energy modeling tools. The complex use of RES and the combination of various complementary, i.e. mutually complementary sources on the basis of an integrated simulation assessment of their potential leads to a significant increase in the efficiency of not only individual power installation, but also power systems of different scale. At the same time, the definition of effective modifications for involving RES in the energy balance is a complex problem that has not yet been resolved. At the moment, there are no reliable models for the effectiveness assessing of combined power installations (CPI) based on RES, taking into account the random processes of energy consumption caused by environmental factors. To create such a model is proved to be actual [1, 2].



2. Research on the development of a simulation model on the basis of laboratory research module with HTN and VCS

A project for the creation of power efficient stand-alone research module with a building dispatching system was developed and implemented at Perm National Research Polytechnic University jointly with the Ministry of Industry of the Perm Region [3]. The main source of heat supply of the module is GTN Buderus Logatherm WPS 22, consuming up to 9 kW of electric energy and issuing up to 20 kW of thermal energy. To increase the hydraulic stability of the system and to make the operation of the pump more stable, the battery-tank PS 300 is installed. This heat pump works in conjunction with the VSC, forming CPI for the thermal management of the building, Figure 1.

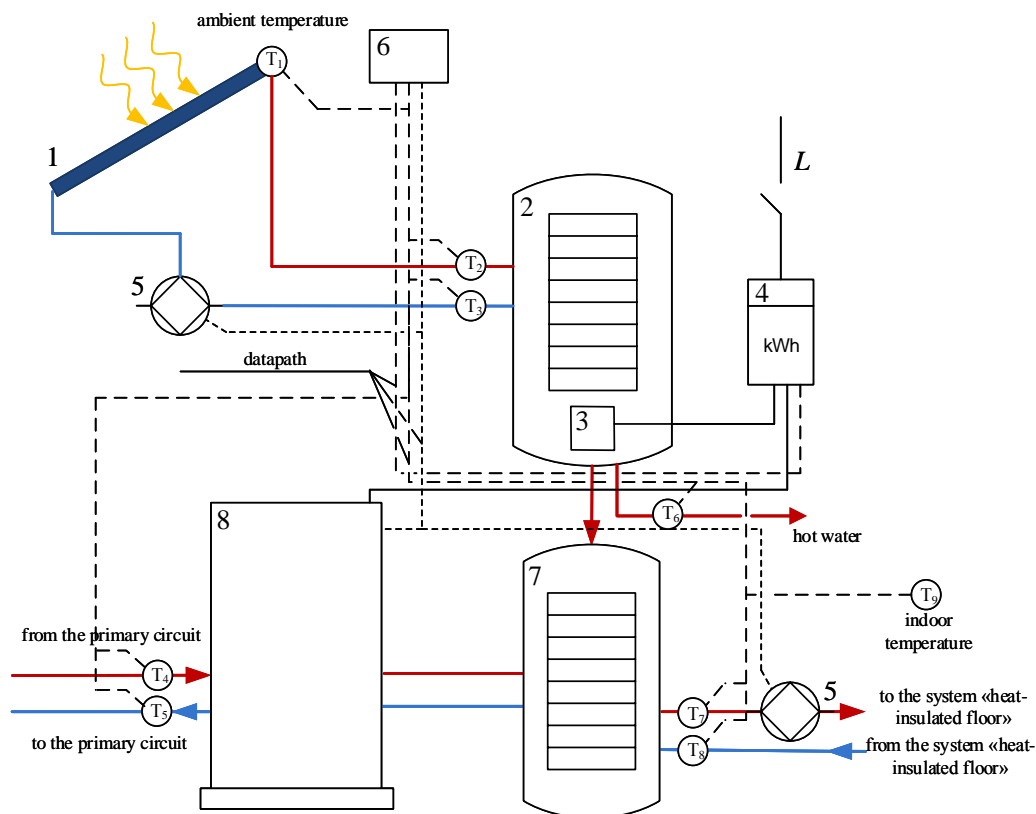


Figure 1. CPI scheme: 1 – VSC; 2 – boiler; 3 – thermoelectric heater; 4 – electric energy meter; 5 – pump; 6 – controller; 7 – heat exchanger tank; 8 – heat pump

Control over the operation of the CPI is carried out with the help of multifunction controllers and sensors of the dispatch and automation system that allows continuous monitoring and control of various parameters for assessing the effectiveness of this installation:

- climatic parameters of the environment (temperature, velocity of air, insolation level – T_1);
- flow and temperature of the heat-transfer agent along the circuits of the wells and the «heat-insulated floor» ($T_2 - T_8$);
- heat and power resources consumption;
- microclimate control in each placement (T_9).

3. Mathematical model for the evaluation the efficiency of CPI

The model for evaluating the efficiency of power installations based on integral criteria is most appropriate. Such criteria integrate energy balances estimations, degree of efficiency, unit cost

of the produced energy, costs of electric energy per unit of thermal, capital expenditures. Despite the versatility of integrated criteria, their applicability for evaluating the effectiveness of CPI on the basis of GTN and VSC in the climatic conditions of the Western Urals is low. This is mainly due to the climatic features of the region during the heating season, sharp changes in the ambient temperature in the autumn and spring, which are of a random nature. In addition, in the framework of the integral criteria under consideration, the excessive thermal power is accumulated, which is not entirely correct when providing a constantly maintained indoor temperature [4, 5]. In this regard, the following calculated indicators are proposed for the study of the efficiency of the CPI with the GTN and VSC within the heating season $I = 1..N$ based on the simulation model:

- energy provision with thermal power, generated by a heat pump Q_i^{gl} , exceeding the heat load on the premises Q_i^p :

$$E_1 = \frac{1}{N} \sum_{i=1}^N F_i; F_i = \begin{cases} 1 & Q_i^{gl} \geq Q_i^p \\ 0 & Q_i^{gl} < Q_i^p \end{cases}, \quad (1)$$

- energy provision with thermal power, generated by VSC Q_i^{g2} , exceeding the heat load on the premises:

$$E_2 = \frac{1}{N} \sum_{i=1}^N F_i; F_i = \begin{cases} 1 & Q_i^{g2} \geq Q_i^p \\ 0 & Q_i^{g2} < Q_i^p \end{cases}, \quad (2)$$

- energy provision with thermal power, generated by CPI, exceeding the heat load on the premises:

$$E_3 = \frac{1}{N} \sum_{i=1}^N F_i; F_i = \begin{cases} 1 & Q_i^{gl} + Q_i^{g2} \geq Q_i^p \\ 0 & Q_i^{gl} + Q_i^{g2} < Q_i^p \end{cases}, \quad (3)$$

- absolute indicator characterizing the increase in the energy provision indicator using CPI compared to the energy provision achieved by using a heat pump:

$$E_4 = E_3 - E_1. \quad (4)$$

To determine Q_i^p it is necessary to use the following:

$$Q_i^p = V \cdot \Delta T_i \cdot \frac{K}{860}, \quad (5)$$

where V – volume of the heated placement of the research module, 600 m^3 ; ΔT_i – difference between indoor temperature and ambient temperature ($^{\circ}\text{C}$) in the i -th time; K – coefficient of thermal loss of the building, taken as 1 (range 1.0–1.9 corresponds to the average thermal insulation: standard construction, double brickwork, small number of windows, standard roof); the value 860 is used to convert to kWh.

The thermal power of the geothermal heat pump is chosen from the relation: $Q_i^{gl} \geq Q_i^{p-av}$, where Q_i^{p-av} – average value of the thermal losses of the in the i -th time.

Then the expression for calculating the thermal power of the pump is the following: $Q_i^{gl} = Q_i^{gr} + Q_i^{el}$, where $Q_i^{gr} = L \cdot K_i^{gr}$ – thermal ground energy in the i -th time; L – wells length required to collect the required heat output; K_i^{gr} – value of the specific heat output of the ground

in the investigated area is within 30..45 W/m; Q_i^{el} – electric power of the heat pump in the i -th time, amounts to $\frac{1}{4}$ of Q_i^{gl} .

Taking into account sufficient conditions $Q_i^{\text{gl}} = Q_i^{\text{p-av}}$, we obtain an expression for calculating the total length of a wells' group:

$$L = \frac{3}{4} \frac{Q^{\text{p-av}}}{K_{gr_min}} \quad (6)$$

The expression for calculating the thermal power produced by the VSC:

$$Q_i^{\text{g2}} = \eta_0 S^{\text{g2}} E_i \quad (7)$$

where E_i – insolation in the i -th time, W/m²; S^{g2} – VSC square, m²; η_0 – coefficient of the installation efficiency in normal conditions, for VSC with heat pipes it is experimentally calculated and is 64,9 % [6].

The insolation, as the distribution function of the intensity of the sun's rays can be written as follows: $E_i = A_i \cdot CI \cdot \sin \alpha$, where CI , (W/m²) – solar constant; A_i – coefficient reflecting the percentage of the solar radiation passage as a function of cloudiness which varies from 1 for a clear day to 0.6 for an overcast day; α – angle of sunlight incidence (from 0° to 90°).

The larger the angle of sunlight incidence, the more energy is transferred to the earth's surface. In the north, with each degree of latitude, the degree of midday sun height over the horizon decreases. Knowing the geographical coordinates of Perm: 56.285° E and 58.017° N (in decimal degrees), we obtain the values of the midday sun height: in the spring – 32°; In the summer – 55.5°; In the autumn – 32°; In winter – 8.5°. The collector is fixed on the southern wall of the building at an angle of 45°. This tilt angle is optimal for medium latitudes, first, to absorb maximum solar radiation, and secondly to reduce the amount of snow accumulating on the reservoir itself [7].

4. Experimental study of the CPI operation of the research module using simulation methods

According to SP 131.13330.2012 “Construction climatology”, the climate of Perm is moderate continental, there are 250 sunny days per year in the territory of the region, and only 29 sunny days are completely clear (in Perm 145 sunny days), the average January temperature is -12,8 °C. The average temperature in July is +18.6 °C.

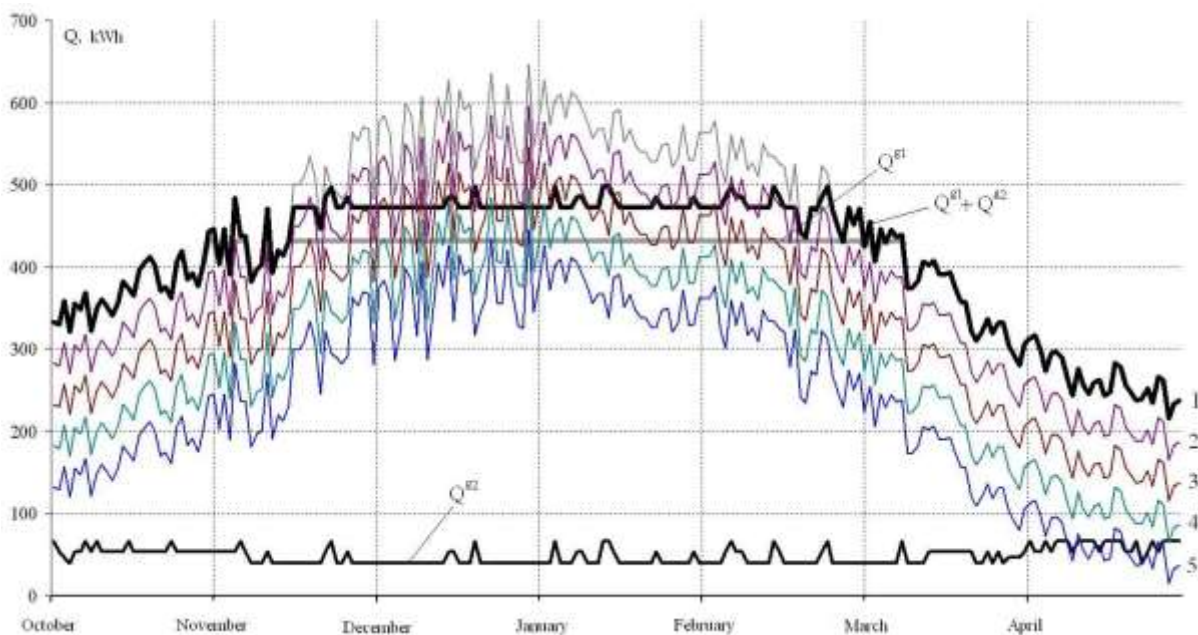
For each of the months, the duration of the light day is determined, during which the earth's surface in Perm gets direct solar radiation required for the solar collector. In the case of cloudy and overcast days, diffuse (weakened) solar radiation comes to the surface. The values of diffuse radiation were obtained by multiplying the value of direct solar radiation by the coefficient of a cloudy day per hour when there was a weak cloud cover, and for an overcast day – by multiplying by the cloudy day coefficient for each of the hours when there was high cloudiness. In the calculations, the correction coefficient k_1 of a cloudy day and k_2 a overcast day for each of the months are adopted. For taking into account the change in the angle of sunlight incidence, the coefficients possess large values in the autumn/spring period and smaller in the winter. The solar constant C_I varies with time, as the distance between the Earth and the Sun changes throughout the year (annual variation of 6.9 % – from 1.412 kW/m² in early January to 1.321 kW/m² in early July), solar activity is also changing. Also, the duration of a light day T (hour) is taken into account [8].

The statistical estimation of N_0 – the number of solar days, N_1 – the number of fair days with some clouds, N_2 – the number of overcast days and total solar energy by months for Perm was carried out for the heating period 2016–2017, Table 1.

Table 1. Climatic parameters of the region for the heating season 2016–2017

Month	$C_b, \text{W/m}^2$	$T_{av}, ^\circ\text{C}$	N_0	N_1	N_2	T, hour
October	1367	1.20	4	4	23	10.3
November	1382	-3.70	2	5	23	7.8
December	1397	-10.70	1	2	28	6.5
January	1412	-14.55	3	5	23	7.4
February	1397	-11.05	3	4	21	9.5
plan for March (forecast)	1382	-6.30	1	3	27	12
plan for April (forecast)	1367	3.25	4	7	19	14.5

Taking into account the statistics of the ambient temperature, the thermal losses of the building K and the added random variation of the parameters depending on the type of construction and the placement insulation required to maintain the operating temperatures, the amount of necessary heat energy for the period from October, 2016 to April, 2017, Figure 2. The figure shows the volumes of heat losses of the building at temperatures held indoors: 1 – 21 °C; 2 – 18 °C; 2 – 15 °C; 2 – 12 °C; 2 – 9 °C.

**Figure 2.** Visualization of the simulation results of the heat and power balance of the research module with full heating of 100 % of the building area

The power of the heat pump is determined based on the average thermal loss of the building $Q^{p_{av}} = 18 \text{ kW}$. To create a comfortable microclimate in the building within heating period of 212 days, it is necessary to following volume of heat energy:

$$\sum_{i=1}^{229} Q_i^p = 212 \cdot Q^{p_{av}} \cdot 24 (\text{ч}) = 91584 \text{ kWh.}$$

Taking into account the heat pump's consumption of electric power, which is approximately $\frac{1}{4}$ of the heat output, Buderus model of 20 kW was chosen. The consumed electric power is 5 kW, therefore the required value of heat power of 15 kW can be provided by a geothermal source – a set of wells with the total length according to the expression (6) of at least $L = 500 \text{ m}$. Figure 2 shows the graphs of the heat energy generated by the heat pump Q^{g1} .

From October to mid November and from March to the end of April, the heat energy Q^{g1} completely covers the building's losses while maintaining a comfortable temperature of 21 °C. However, within 3.5 months of this energy is not enough, for example: during December, the heat pump can provide only 9 °C indoors.

The power of the VSC Q^{g2} is determined according to the expression (7). With an installation area of 10 m², we obtain an average power $Q^{g2} = 1.86$ kW. Consequently, this collector produces about 44.77 kWh of heat per day, see Figure 2. According to the meter, the volume of the consumable coolant (V_c , l), which is heated by the collector during the day, was determined. To increase the temperature of 1 l of coolant by 1 degree approximately 1.16 W of power is required. Then, we find that the heat energy produced by VSC will be sufficient to heat 1 m³ of the heat-transfer agent of the system «heat-insulated floor» up to 38 °C [9].

Figure 2 clearly shows the periods when the heat power of the CPI exceeds the thermal load of the building, and when not.

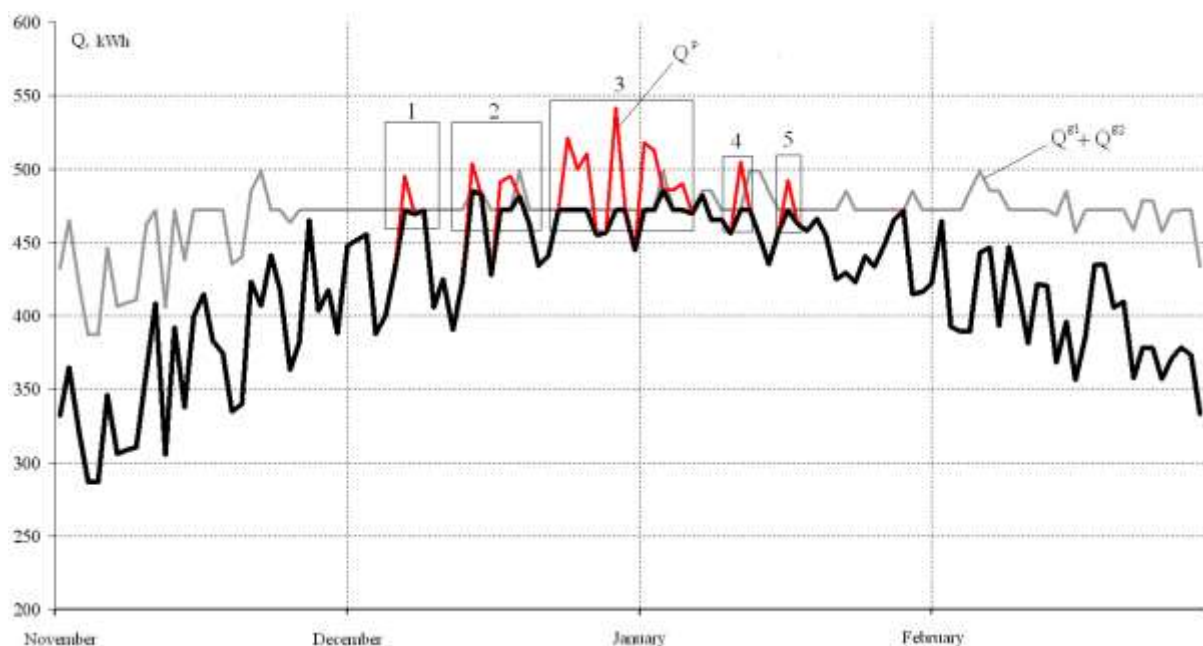


Figure 3. Visualization of the simulation results of the heat and power balance of the research module for heating 50 % of the building area to a temperature of 21 °C

In order to reduce the number of days in which energy supply is inadequate, it is proposed to lower the temperature in the unattended building premises, the total area of which reaches 50 % of the total area. As a result of the simulation of the building's heat losses with a retained temperature within 50 % of the room at 21 °C and 50 % at 9 °C, the heat and energy balance was obtained, see Figure 3. The figure shows that reducing the area where a comfortable temperature is required leads to a significant increase in energy supply [10]. The most critical time is observed in the period from the second half of December to the middle of January. Intervals 1 to 5 are observed where the building's losses exceed the heat power of the CPI. In this case, the additional heating of the heat-transfer agent must be carried out by means of an electric heater.

Taking into account the expressions (1)–(4), an estimation of the CPI efficiency was made, see Figure 4. The diagram shows the variation of indicators E_1 – E_4 depending on the required temperature in the building (model situations 1–7) and the results of simulation of the generated heat capacities and building losses for the heating period 2016–2017, which consists of 212 days. Model situation 1 corresponds to maintaining the indoor temperature equal to 9 °C; Situation 2 – temperature equal to 12 °C; Situation 3 – temperature equal to 15 °C; Situation 4 – temperature equal to 18 °C; Situation

5 – temperature equal to 21 °C; Situation 6 – a 50 % area temperature is 21 °C and another 50 % area temperature is °C; Situation 7 is a 50 % area temperature is 18 °C and another 50 % area temperature of 9 °C.

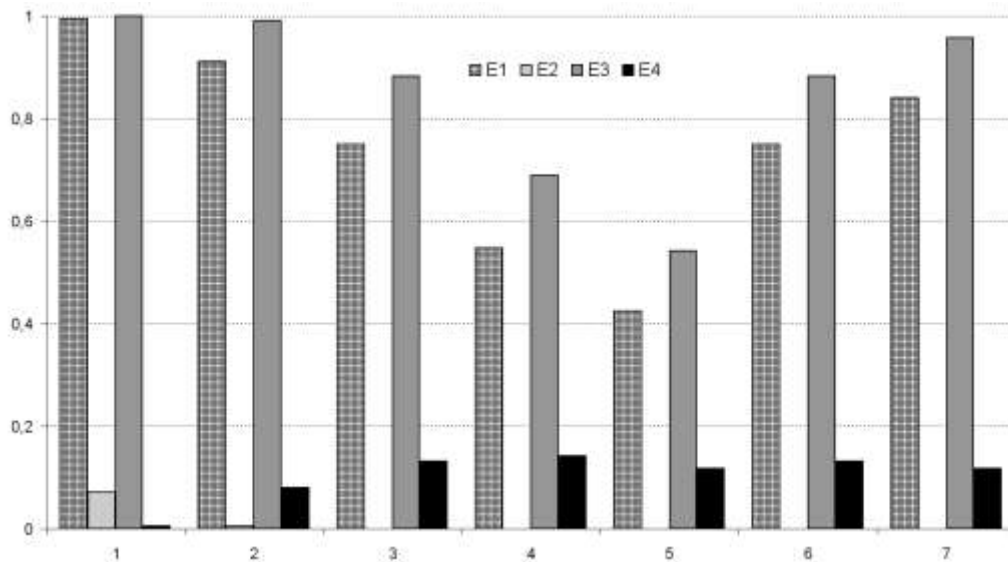


Figure 4. Visualization of calculation results of CPI efficiency indicators

Despite the low efficiency of independent use of VSC – E₂, it provides a good efficiency gain in the structure of the CPI – E₄, reaching 16 %.

5. Conclusion

The developed simulation model allows solving a wide range of problems in the field of energy and resource efficiency, and also can be applied to other objects using RES.

Based on the simulation results, the following recommendations can be made:

- to reduce the amount of heat losses in the building under study, it is necessary to reduce the glazing area of the object and to apply the more efficient insulation;
- the dispatch and automation systems for the existing building allows efficient distribution of heat energy in residential and business premises, while reducing the need for heat power, and therefore in the electrical energy required for the heat pump;
- the model permits to optimize the control of the CPI.

The calculations show that the application of GHP and the VSC in the climatic conditions of the Western Urals is technically and economically feasible. GHP allows reducing the energy consumption of a residential building and can be used as an alternative to traditional sources of heat supply, including gas boilers, in areas where there is no centralized heat and gas supply system. In conditions of the middle and central Russia, solar water heating systems can be effectively used by various consumers for household purposes for 6–8 months a year (March/April – September/October).

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