Autonomous heat-cooling and power supply system based on renewable energy devices (trigeneration system)

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Abstract. The article presents the results of research on the possibilities of providing heat-cooling and electricity supply systems to autonomous consumers located far from centralized energy supply in the southern regions of Uzbekistan (Bukhara and Kashkadarya) based on renewable energy sources. In these regions, the average daily relative solar energy is 4.5 kWh/m^2/day, the average wind speed is 5.5...8.5 m/s, the relative energy is 300...580 W/m^2, and the underground low-potential temperature at a depth of 3...5 m, on average, is +10...+12^{o}C. Analyzes of scientific research conducted on the development and reliability of trigeneration systems in the world are presented, and the possibilities of using these systems in our region are based. A combined solar-wind power plant, which is adapted to the climatic conditions of the southern regions of Uzbekistan, works efficiently in weak wind currents and high temperature regimes, and a complex energy system consisting of geothermal heat pumps that produce continuous heat and cold energy in different temperature regimes is offered. The proposed complex power plant allows for continuous and reliable energy supply to autonomous consumers located far from the centralized energy supply.

1 Introduction

The use of renewable energy sources and heat pumps occupies one of the leading positions in the world in ensuring energy security, saving traditional fuel-energy resources, increasing energy continuity and reliability. "Given that it is planned to reduce greenhouse gases and emissions by at least 40%, increase the share of renewable energy sources by 32%, and energy efficiency by 32.5% in the period from 2021 to 2030" [1], which increases energy continuity and reliability requires the development and implementation of trigeneration systems based on renewable energy sources. In this regard, the use of complex energy devices adapted to the climatic conditions of the regions is considered important.

It is becoming important to develop a continuous heat-cooling and electricity supply system for autonomous consumers located far from centralized energy supply in the world with the help of renewable energy sources devices, in particular solar, wind and heat

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pumps. Scientific studies are being carried out on the comprehensive use of geothermal (underground low-temperature heat source) energy sources to ensure the continuity and reliability of energy supply to autonomous consumers, to increase the efficiency of operation of renewable energy source devices in changing climate conditions, and to stabilize the operation of heat pumps. Particular attention is paid to the use of wind power in variable and weak wind currents, as well as increasing efficiency coefficients of wind energy devices, ensuring the production of electricity with nominal capacity of solar photovoltaic batteries in high temperature regimes. Figure 1 shows the analysis of indicators of the use of renewable energy sources in the world. China takes the leading place with a capacity of 1160 GW [2].

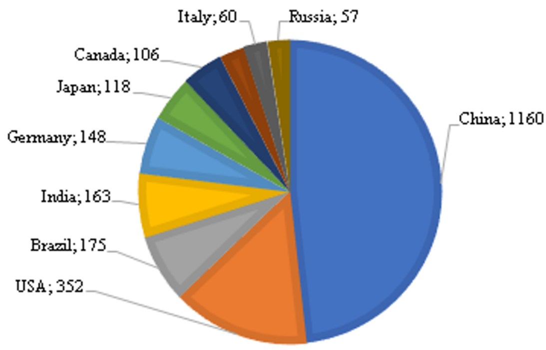


Fig. 1. Indicators of the use of renewable energy sources in the world (2022).

In the energy policy of European countries, it is planned to install a total of 45 million units of heat pumps in the residential sector by 2030. Heat pumps are one of the most important segments of the European electricity demand, and the demand of the segment was 77 TWh in 2022, and by 2050 this figure is planned to increase to 611 TWh [3].

Practical implementation of renewable energy sources in social and housing and communal services and economic sectors in Uzbekistan, ensuring compensation of energy deficit in the regions of the republic by increasing energy efficiency, comprehensive organization of work in this regard, and introduction of favorable conditions and incentive mechanisms for investors work is underway. In particular, renewable energy sources with a total capacity of 4,300 MW in 2023, including 2,100 MW of large solar and wind power plants, 1,200 MW of social sector facilities, buildings and structures of economic entities, and solar panels installed in apartments, 550 MW — launch of small photoelectric power plants built by entrepreneurs, as a result of which, by installing renewable energy sources, switching consumers to alternative energy and introducing energy-efficient technologies, in 2023 additional 5 billion kilowatt-hours of electricity production and 4.8 billion cubic meters natural gas economy is planned [4].

2 Materials and methods

Uninterrupted energy supply to autonomous consumers located far from the centralized energy supply in the southern regions of Uzbekistan (Bukhara and Kashkadarya) is becoming important in the development of their social and economic spheres. Based on the potential of renewable energy sources of these regions, special attention is paid to the introduction of complex energy devices and their effective use. The development of complex systems based on renewable energy sources adapted to the climatic conditions of our region has not been studied enough. We present the analysis of the scientific research conducted on the development of the heat-cooling and electricity supply system for autonomous consumers. A trigeneration system based on a combined solar photovoltaic battery, solar collector, and geothermal heat pump was proposed by Sangmu Bae et al. (Figure 2). Based on the feasibility of implementing this system. As a result of the energy analysis, Seoul, Ulsan, and Toronto have energy self-sufficiency rates of 62%, 65.1%, 57.7%, and 60.2%, respectively. In addition, the results of the technical economic analysis of the proposed system compared to the traditional energy supply system showed that the payback period of the tri-generation system in South Korea was estimated to be 13 years and 10 years in Canada [5].

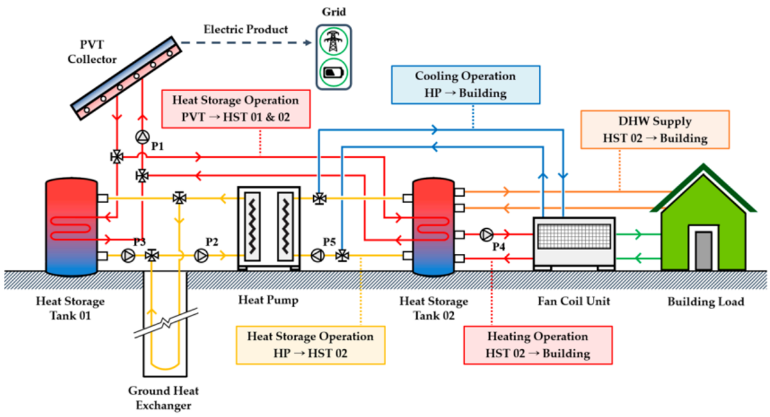


Fig. 2. A trigeneration system scheme proposed by Sangmu Bae.

In the scientific works conducted by Shao Zhuo and others, the experimental research results of the integrated trigeneration system of solar photovoltaic battery, solar collector and heat pump in the summer months are presented. The mathematical model of each component of the system is developed according to the distributed and integrated parameter models. Experimental studies on the operation of the trigeneration system were carried out in terms of simultaneous heating, cooling and power supply possibilities. According to the results of the research, the proposed system has the ability to provide cooling, hot water and electricity to buildings with high efficiency and long-term stable working conditions. The use of this system, developed on the basis of renewable energy devices, made it possible to save energy and resources (Figure 3) [6].

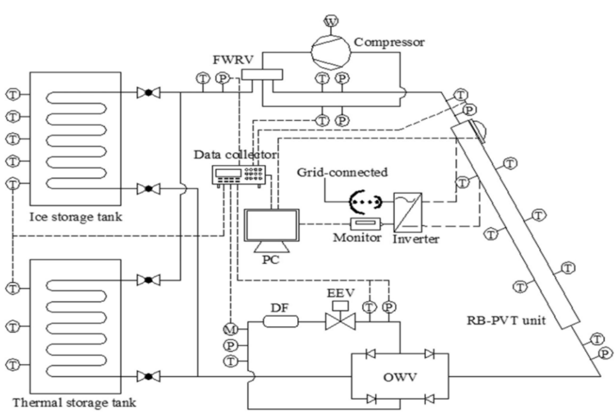


Fig. 3. Scheme of the trigeneration system proposed by Shao Zhuo.

The invention is known in the field of complex energy devices with a stable power supply system for autonomous consumers using renewable energy sources [7]. This power plant is composed of wind power plant, solar power plant, biogas plant and micro hydropower plant, gas generator, storage batteries, inverter and switchboard, and can provide consumers with electricity and heat energy. The main disadvantage of the energy device is the low possibility of simultaneous use of existing renewable energy devices (depending on the potential of energy sources) and complexity. In addition, this energy device has a number of constructive, technological and operational shortcomings.

In the field of combined energy devices [8], the invention is known, which is a solar photovoltaic battery and a solar collector installed perpendicular to the flow of solar energy, a horizontal axis wind energy device, produced electric energy storage batteries, an electric motor, a screw compressor, a two-circuit heat pump, known to the ground It consists of horizontally placed heat-carrying pipes, a heat accumulator, air conditioners capable of cooling water. The disadvantage of this combined power plant is that it can provide reliable electricity when using wind energy in variable wind speeds and weak wind currents, and solar photovoltaic cells in high temperature regimes.

Technically, the proposed complex energy device [9] is known as an invention, which is a compressor-type heat pump, a low-temperature heat-carrying heat exchanger in the external circuit of the heat pump, a hot water and heat-carrying heat exchanger in the high-temperature heating circuit, a tank for hot water supply, consisting of a solar collector, heat flow system control unit, thermal energy accumulator, pipes, water pumps for heating and hot water systems, electric accumulators, adapter, multilayer film thermocouples, solar photovoltaic batteries and wind energy devices. Such devices are based on the effective use of natural underground (soil) low-temperature sources for autonomous heating and hot water supply in residential buildings, industrial buildings and domestic utilities. A wind turbine and solar photoelectric batteries were used to supply the heat pump with electricity. The disadvantage of this complex energy device is that autonomous consumers can only use thermal energy, which has led to a decrease in the efficiency of the overall energy system.

In the southern regions of Uzbekistan, scientific research work was carried out on the possibilities of using solar and wind energy, the development and implementation of renewable energy source devices adapted to the climatic conditions of these regions [10-12]. However, the development of a heat-cooling and power supply system based on a complex energy device adapted to the climatic conditions of our region for autonomous consumers has not been sufficiently studied. Therefore, there is a need to develop a trigeneration system based on renewable energy sources.

The purpose of the study – through highly efficient combined solar-wind power plants adapted to changing climate conditions (wind speed 3...12 m/c, outdoor temperature -20...+50 ^{o}C, solar radiation 50...1000 W/m^2) development and justification of the parameters of an energy-efficient complex energy device with the possibility of obtaining heat-cold energy from continuous electricity and low potential temperature of the ground (at 3...5 m, +10...+12 ^{o}C) using a heat pump device.

3 Results and Discussion

Figure 4 shows the daily comparative energy indicators obtained from solar photovoltaic batteries in Bukhara and Kashkadarya regions. It was determined that the average daily solar energy is 4.5 kWh/m^2/day [13]. This, in turn, means that the possibilities of using solar energy in the regions are high.

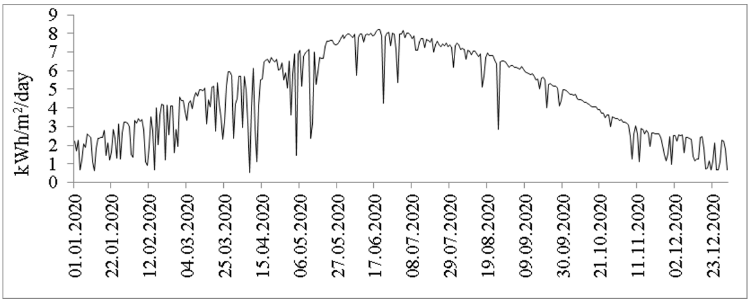


Fig. 4. Daily comparative energy indicators obtained from solar photovoltaic batteries in Bukhara and Kashkadarya regions.

Figure 5 shows the map of wind energy resource potential of Uzbekistan. These data are obtained from the Global Wind Atlas geographic information system and provide indicators of average wind speed and specific wind current energy at 100 m height. It was found that the average wind speed is 5.5...8.5 m/s, and the specific power is 300...580 W/m^2 [14].

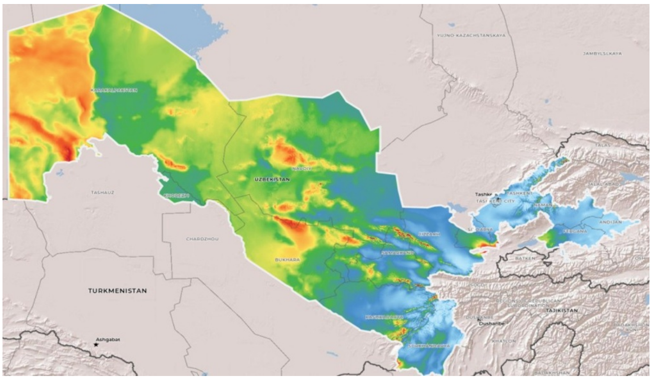
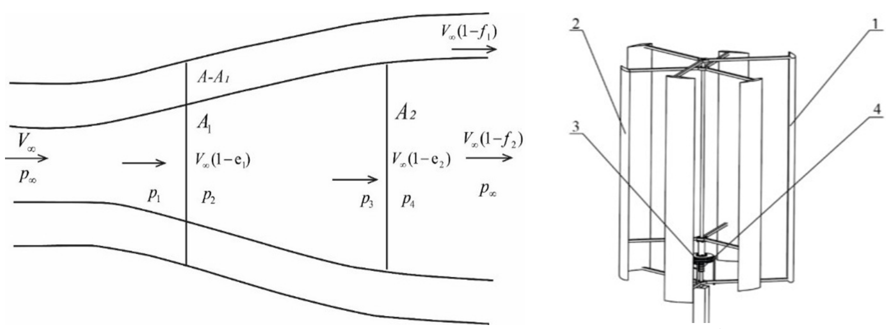


Fig. 5. Map of wind energy use in Uzbekistan.

Wind power plant. Today's traditional wind energy devices have a maximum wind energy utilization coefficient of C_p=16/27, and theoretically, the efficiency of wind energy devices does not exceed this indicator. We derive the maximum value of the wind energy utilization coefficient of the proposed two-wheeled, i.e. external and internal counter-rotating wind turbine based on the diagram in Figure 6.



a b

Fig. 6. Scheme for determining the wind energy power coefficient (C_p) of a two-wheel wind turbine (a), external view of a two-rotor wind power plant. 1-external wind wheel blades, 2-internal wind wheel blades, 3-electric generator, 4-brush collector.

Assuming that the cross-sectional surface of the outer wind wheel of the wind energy device is A, and the cross-sectional surface of the inner wind wheel is A1, we derive the following mathematical expression from the law of conservation of air flow mass [15]:

$$m_1 = m_2, \quad \rho \cdot V_\infty \cdot (1 - e_1) \cdot A_1 = \rho \cdot V_\infty \cdot (1 - e_2) \cdot A_2 \tag{1}$$

In which: e_1 and e_2 coefficients of variation of the wind flow speed in the internal flow pipe; ρ — air flow density; V_∞ — wind speed.

Analysis of flow through the outer annulus of the anterior disc (A-A1) is typical. Bernoulli's equations are:

$$\rho \cdot V_\infty^2 \cdot f_1 \cdot \left(1 - \frac{f_1}{2}\right) = P_1 - P_2 \tag{2}$$

In which: f_1 — coefficient of variation of wind speed in the outer flow pipe.

Based on the difference in side pressures, we derive the following expression:

$$f_1 = 2 \cdot e_1 \tag{3}$$

Bernoulli's equations in an internal flow pipe are as follows:

$$\begin{cases} P_2 + \frac{1}{2} \cdot \rho \cdot V_\infty^2 \cdot (1 - e_1)^2 = P_\infty + \frac{1}{2} \cdot \rho \cdot V_\infty^2 \cdot (1 - f_1)^2 = P_3 + \frac{1}{2} \cdot \rho \cdot V_\infty^2 \cdot (1 - e_2)^2 \\ P_\infty + \frac{1}{2} \cdot \rho \cdot V_\infty^2 \cdot (1 - f_2)^2 = P_4 + \frac{1}{2} \cdot \rho \cdot V_\infty^2 \cdot (1 - e_2)^2 \end{cases} \tag{4}$$

By simplifying the expression (4), we derive the following mathematical expression:

$$\frac{1}{2} \cdot \rho \cdot V_\infty^2 \cdot (f_1 - f_2) \cdot (f_1 + f_2 - 2) = P_3 - P_4 \tag{5}$$

A linear impulse is defined as follows:

$$(P_1 - P_2) \cdot A_1 + (P_3 - P_4) \cdot A = \rho \cdot A_1 \cdot V_\infty \cdot (1 - e_1) \cdot V_\infty \cdot f_2 \tag{6}$$

Using expressions (4), (6) and (3), we simplify the equations:

$$A_1 \cdot (1 - e_1) \cdot (f_2 - f_1) \cdot A = \frac{-(f_2 - f_1)}{2} \cdot (f_1 + f_2 - 2) \cdot A \tag{7}$$

$f_1 = f_2$ based on equality (7) we simplify the expression as follows:

$$A_1 \cdot (1 - e_1) = (1 - \frac{f_1 + f_2}{2}) \cdot A \tag{8}$$

Using expression (1), we derive the following equation:

$$2e_2 = f_1 + f_2 \tag{9}$$

The coefficient of use of wind energy is determined by the following mathematical expression:

$$C_P = \frac{(P_1 - P_2) \cdot A \cdot V_\infty \cdot (1 - e_1) + (P_3 - P_4) \cdot A \cdot V_\infty \cdot (1 - e_1)}{\frac{1}{2} \cdot \rho \cdot A \cdot V_\infty^3} \quad (10)$$

(3), (4), (5) and (10) using expressions, we derive the following simplified mathematical equation:

$$\begin{aligned} C_P &= 4e_1 \cdot (1 - e_1)^2 + (f_1 - f_2) \cdot (2e_2 - 2) \cdot (1 - e_2) \\ &= 4 \cdot [e_1 \cdot (1 - e_1)^2 + (1 - e_2)^2 \cdot \quad (e_2 - 2e_1) \end{aligned} \quad (11)$$

e_1 and e_2 The maximum value of C_P for all possible values of :

$$\begin{cases} \frac{1}{4} \cdot \frac{dC_P}{de_1} = (1 - e_1) \cdot (1 - 3e_2) - 2 \cdot (1 - e_2)^2 = 0 \\ \frac{1}{4} \cdot \frac{dC_P}{de_2} = (1 - e_2) \cdot (1 - 3e_2 + 4e_1) = 0 \end{cases} \quad (12)$$

In this $e_1 = 1/5$ and $e_2 = 3/5$ will be equal.

(12) we derive the maximum numerical value of C_P by putting the values determined by the expressions into the expression (11).

$$\begin{aligned} C_P &= 4 \cdot [e_1 \cdot (1 - e_1)^2 + (1 - e_2)^2 \cdot \ (e_2 - 2e_1) \\ &= 4 \cdot [0.2 \cdot (1 - 0.2)^2 + (1 - 0.6)^2 \cdot \ (0.6 - 2 \cdot 0.2) = 16/25 \end{aligned} \quad (13)$$

Today's traditional wind energy devices have a maximum wind energy utilization coefficient of C_P=16/27, and theoretically, the efficiency of wind energy devices does not exceed this indicator. It was found that the efficiency of the proposed two-wheel wind turbine can be increased by 8% compared to conventional wind turbines (Figure 7).

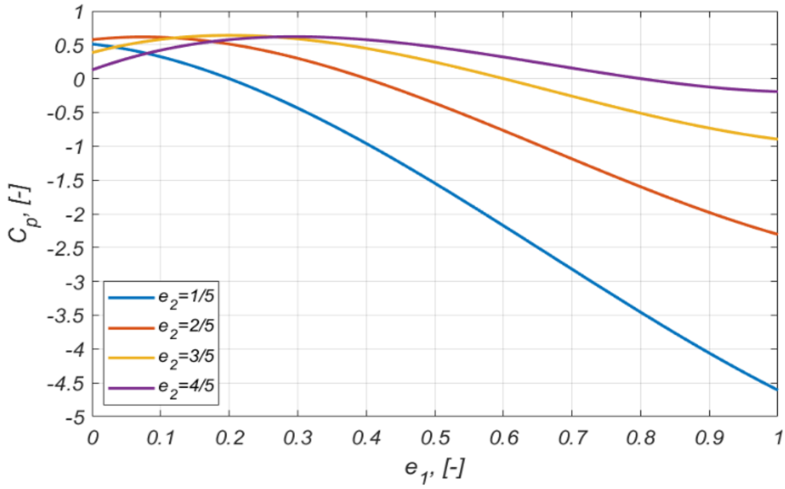


Fig. 7. Curves for determining the maximum value of the wind energy utilization coefficient of the two-wheel wind energy device.

The electricity generated by wind power plants is defined by the following mathematical expression:

$$E = \frac{\rho \cdot S \cdot V_{\infty}^{3}}{2} \cdot C_P \cdot \eta_{gen} \cdot t \qquad (14)$$

In this: ρ – air flow density, kg/m^3; S – cross-sectional surface of the wind turbine, m^2; V – average wind speed, m/s; C_P – power coefficient of wind turbine; η_{gen} – useful efficiency of the electric generator, t – annual operating time of the wind power plant.

Solar photovoltaic battery. The reliable operation of solar photovoltaic batterys mainly depends on the solar radiation and the external temperature, and the solar modules operate in the nominal mode when the solar radiation is 1000 W/m^2 and the temperature is 25 ^{o}C. We give theoretical calculations of the efficiency of operation of solar photoelectric batteries at different temperature regimes. The dependence of the power of solar photovoltaic batteries on the external temperature is determined by the following mathematical expression [16]:

$$P = P_{sts} + P_{T-coeff} \cdot (T_c - T_{NOCT}) \qquad (15)$$

n this: P_{sts} – nominal power of the solar photovoltaic battery, W; $P_{T-coeff}$ – specific power factor as a function of temperature is 0.004/ ^{o}C (500 Вт, -2 W/^{o}C); T_c – outside temperature ^{o}C; T_{NOCT} – nominal temperature in the solar module, 25 ^{o}C.

The dependence of the efficiency of solar photoelectric batteries on the external temperature is determined by the following mathematical expression [17]:

$$\eta = \eta_P \cdot (1 - \beta \cdot (T_c - T_{NOCT})) \qquad (16)$$

In this: η_P – useful efficiency of the solar module in the nominal mode (1000 W/m^2, 25 ^{o}C); β- temperature coefficient of dependence on power change, 0.004/^{o}C.

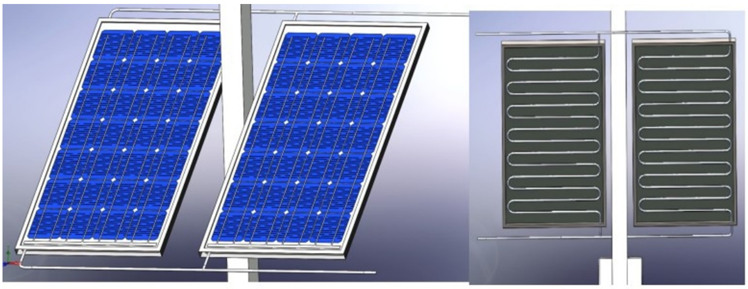
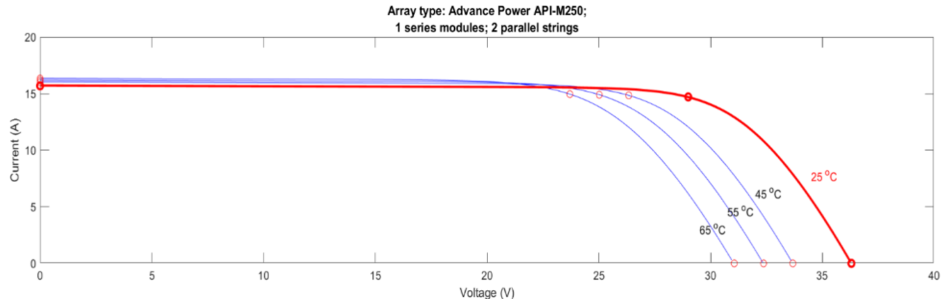


Fig. 8. Process plant.

Figure 9 shows the temperature-dependent energy parameters of the solar photoelectric battery. It shows the change in the amount of power produced by a solar photoelectric battery at temperatures of 25...65 ^{o}C when the solar radiation is 1000 W/m^2. If the external temperature exceeds the standard indicator, the solar module temperature can be maintained at 25 ^{o}C, the efficiency of the device can be increased up to 5%.

Geothermal heat pump. Ground water, river and lake water and soil can be used as a low-potential heat source for heat pumps. In industry, waste heat is used as a low-potential heat source. In agriculture, heat pumps can be widely used to create the required microclimate in livestock buildings, farms, greenhouses (teplitsa) and cooling chambers of fruit and vegetable warehouses. A heat pump with a compressor produces up to 2.5...5 kW of heat for the consumption of 1 kW of electricity. The temperature range of the heat pump in the heat supply system is around 35...55 ^{o}C. As a result of the use of heat pumps, it is possible to save up to 70% of energy resources.



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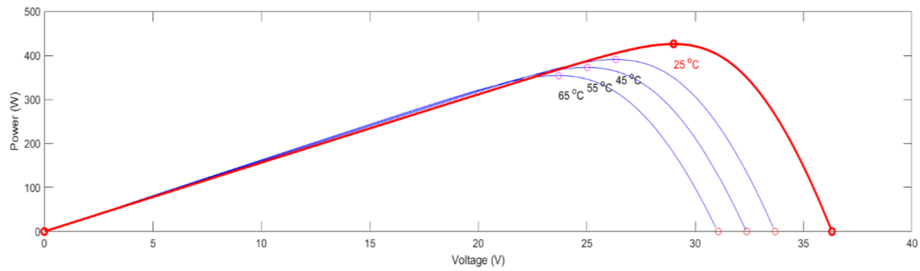


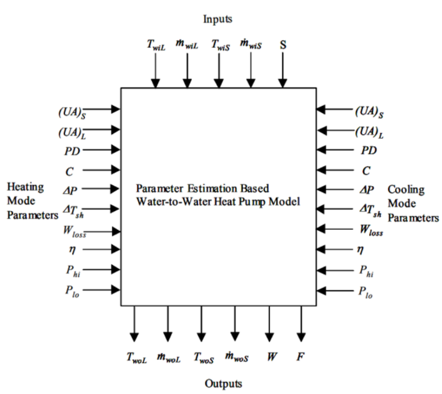
b

Fig. 9. Curves of change of energy parameters of solar photoelectric battery as a function of temperature: a- volt-ampere characteristic of a solar photovoltaic battery, b- power dependence characteristic of solar photovoltaic battery voltage.

When modeling a heat pump (water-water), the following parameters should be given:

- Source side inlet water temperature, flow rate and heat transfer (in cooling mode) or heat release (in heating mode).
- Load side inlet water temperature, flow rate and cooling capacity (cooling mode) or heat capacity (heating mode).
- Compressor power consumption.

Figure 10 shows the heat pump (water-water) heat and cold mode block diagram model (a), (water-air) heat and cold mode block diagram model (b) [18].



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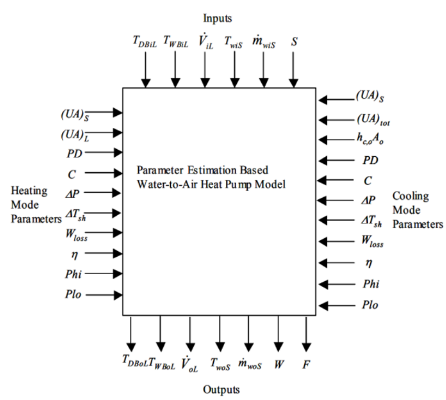

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Fig. 10. Heat pump (water-water) heat and cold mode block diagram model (a), (water-air) heat and cold mode block diagram model (b).

We determine the efficiency of the evaporator and condenser using the following formula [19]:

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$$\begin{cases} \varepsilon_L = 1 - \exp\left(-\frac{(UA)_L}{C_{pw} \cdot m_{wL}}\right) \\ \varepsilon_S = 1 - \exp\left(-\frac{(UA)_S}{C_{pw} \cdot m_{wS}}\right) \end{cases} \tag{17}$$

In this: ε_L − thermal efficiency of the evaporator, $(UA)_L$ − heat transfer coefficient of the evaporator, ε_S − thermal efficiency of the condenser, $(UA)_S$ − heat transfer coefficient of the condenser, m_{wL} − specific mass of water in the evaporator, kg/s, m_{wS} − specific mass of water in the condenser, kg/s C_{pw} − specific heat capacity of water, J/kgK.

The cooling temperature of the evaporator and condenser is determined by the following formula [20]:

$$\begin{gathered} T_e = T_{wL} - \frac{Q_L}{\varepsilon_L \cdot C_{pw} \cdot m_{wL}} \\ T_c = T_{wS} - \frac{Q_L}{\varepsilon_L \cdot C_{pw} \cdot m_{wS}} \end{gathered} \tag{18}$$

In this: T_e − evaporator temperature ^oC, T_{wL} − water temperature entering the evaporator ^0C, T_c − condenser temperature ^oC, T_{wS} − water temperature entering the condenser ^oC.

Heat pump efficiency is determined by the following mathematical expressions [21]:

Heat mode:

$$COP_h = \frac{|Q_h|}{W} = \frac{T_h}{T_h - T_c} \tag{19}$$

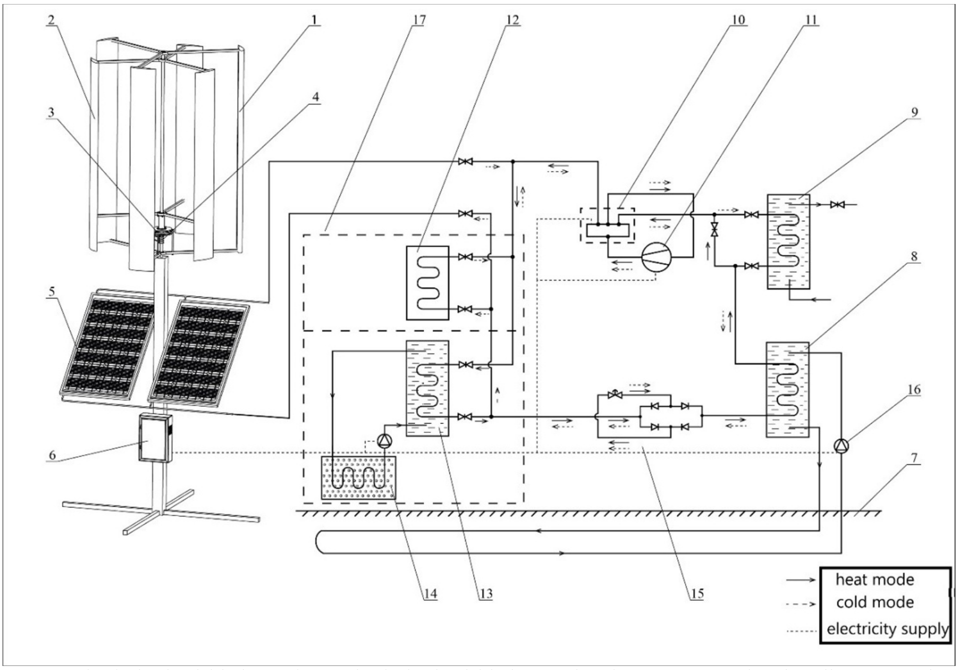
Cool mode:

$$COP_c = \frac{|Q_c|}{W} = \frac{T_c}{T_h - T_c} \tag{20}$$

In this: Q_h − heat energy kW, Q_c − cooling energy kW, T_h − obtained heat temperature ^oC, T_c − obtained freezing temperature ^oC.

Figure 11 shows the scheme of the proposed trigeneration system. An improved two-rotor vertical axis wind energy device and a solar photovoltaic battery with a cooling system were used in the power supply system of autonomous consumers, and a geothermal heat pump was used in the heat and cold energy supply system.

The principle of operation of the proposed trigeneration system is as follows: the temperature in the evaporator (in heat mode) 8 is always maintained at 10...12 ^0C using the circulating water pump 16 from the low-potential energy of ground 7, we control the heat and cold modes through the four-pipe valve 10, in the heat mode the compressor 11 increases the temperature to 55 ^oC and transfers it to the condenser 13, where the warm floor with a phase transition (paraffin) heat accumulator is supplied by a circulating water pump 14. Accordingly, autonomous consumers are provided with continuous heat during the winter season. In the summer months, when supplying the autonomous consumers 17 with cold energy 12 and cooling the solar photovoltaic batteries 5, we set the four-pipe valve 10 to the cold mode. In this case, the temperature is constantly maintained in the range of 0...5 ^oC. In addition, it is possible to receive hot water 9 with a temperature of 30...45 ^oC in the cold mode of the system. We use a compressor 11, a four-pipe valve 10 supply system, circulating water pumps 16 and a combined solar-wind power plant to supply electricity to autonomous consumers.



1-external wind wheel blades, 2-internal wind wheel blades, 3-electric generator, 4-brush collector, 5-solar photovoltaic battery, 6-control system and batteries, 7-geothermal energy source, 8-condenser (in cooling mode) or evaporator (in heat mode), 9-hot water tank, 10- reversing valve, 11-compressor, 12-cooler, 13-condenser (heat mode), 14-warm floor (paraffin), 15-throttle valve, 16- circulation pumps, 17- autonomous consumer

Fig. 11. Scheme of the proposed trigeneration system.

Table 1. The technical indicators of trigeneration system devices.

Power of the wind power plant	**2 kW**
Dimensions of the wind energy device:	
Outer rotor:	
height	3 m
diameter	2 m
Inner rotor:	
height	2.8 m
diameter	1.8 m
The maximum value of the coefficient of use of wind energy (for the case when the rotors rotate opposite to each other)	0.45
Power of solar photovoltaic batteries	2x500 W
"GWHP" geothermal heat pump heat capacity	5.4 kW
Cooling capacity of the heat pump	4.5 kW
Consumption power of the heat pump	1.24 kW
COP	4.35/3.62

There is a possibility of uninterrupted and reliable energy supply due to the use of autonomous consumers located far from the centralized energy supply from the proposed complex power plant.

4 Conclusion

- The average wind speed of the southern regions of Uzbekistan at a height of 100 m is 5.5...8.5 m/s, the specific power is 300...580 W/m^2, the daily specific energy obtained from photovoltaic batteries is 4.5 kWh/m^2 /day was determined to be.
- A combined solar-wind energy device that works efficiently at wind speeds of 3...9 m/c and high temperature regimes (30...55 ^{o}C) was proposed. As a result, it was proved that it is possible to provide uninterrupted electricity to autonomous consumers located far from the centralized energy supply.
- A methodology for increasing the power coefficient of a two-rotor vertical axis wind turbine composed of NACA 63-415 wind blades was proposed, as a result, it was determined that the coefficient of wind energy use could be increased by 8%. It was estimated that it is possible to increase the efficiency of solar photovoltaic batteries by 0.8-3.2% by using a cooling system in high temperature regimes.
- An energy-efficient trigeneration system was developed to provide heat-cooling and electricity supply to autonomous consumers located far from the centralized energy supply in the southern regions of Uzbekistan. As a result, it was determined that there is an opportunity to increase the continuity and reliability of energy supply.

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