

Case Report

A Case Study and Scientific Nexus of a Hybrid Solar and Wind Power Plant with a Heat Pump for Emission Decarbonization

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Abstract: During the operation of any source of electrical energy, thermal energy is also generated. The heating of generator parts is accompanied by the loss of the efficiency of the entire system as a whole and eventually leads to failure. In order to remove the heat load from generators based on renewable energy, such as wind turbines and solar panels, it is possible to use heat pumps based on various refrigerants. This article presents a comparative analysis of methods for evaluating the efficiency of the technological process, using the example of increasing the efficiency of the heat pump based on the heat produced by renewable energy installations. An example of improving the efficiency of a laboratory stand is used. Exergetic calculation, fluid selection, an analysis of external sources and emission reduction were performed. This thermal energy transmission system uses a solar panel as an additional low-potential source of heat. Options for increasing the energy efficiency of the installation are considered. An assessment of the reduction in emissions when using an equivalent diesel power plant was carried out using the developed mathematical model.

Keywords: selection of refrigerant; combined generation; heat pump; renewable energy; solar energy; wind energy



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1. Introduction

The basis for creating highly efficient thermal engineering solutions is the analysis of the designed system in terms of the degree of its thermodynamic perfection. The analysis of the technological system contributes to the disclosure of the energy potential of the equipment by identifying and covering areas of extreme thermal stress. The measure of the effectiveness of the method used is the change in the degree of thermodynamic efficiency of the system [1]. As methods of increasing the efficiency of the system, the method of selecting a refrigerating agent and the method of analyzing external energy sources were chosen. The result of the application of analytical methods for evaluating the efficiency of the system is to obtain an optimal characteristic of the efficiency of the system for the transfer of thermal energy, compiled on the basis of exergetic analysis [2], and the formulation of thermodynamic requirements for the investigated installation.

The modernization of existing and projected systems is carried out on the basis of exergetic analysis. This analysis, being based on the simultaneous use of the first and second laws of thermodynamics, is the theoretical basis of the energy saving process. Exergetic analysis is used to evaluate ways to improve the efficiency of energy carriers, conversion processes and the rational use of energy. The task of the analysis is to determine the optimal path of exergy brought into the analyzed system in such a way that it is minimal and implemented with the maximum possible exergetic efficiency, which is the general criterion of efficiency. The thermodynamic requirements formulated on this basis are the basis for improving the technological scheme. This analysis makes it possible to

modernize individual inefficient components of the experimental stand and therefore more advanced installations.

The selection of the refrigerant with the necessary thermophysical parameters is carried out using the method of the selection of the working fluid (refrigerating agent). The thermophysical parameters for the refrigerant used in the laboratory stand are as follows:

- Boiling point of the liquid;
- Steam condensation temperature;
- Degree of toxicity;
- Heat of vaporization;
- Specific heat capacity.

The task of the working fluid selection method is to identify a refrigerant with a high value of the amount of useful work. This value has the maximum effect on the efficiency and efficiency of the equipment.

Studying the properties of refrigerants is an important task. Work on the selection of optimal refrigerant parameters was carried out by many modern authors. The authors of works [3,4] are devoted to the consideration of an alternative to the harmful refrigerant R22; a comparative analysis of R290, R134 and R600 was also carried out. However, due attention has not been paid to the use of these refrigerants in renewable energy systems. The authors of [5] pay attention to the consideration of systems with the combined refrigerant liquefaction of hydrogen, which can be adapted for use in renewable energy but, nevertheless, is not directly related to it.

To identify external energy sources that may affect the efficiency of the system, the method of environmental analysis was used. The amount of usefully used energy in the installation increases with the introduction of a well-chosen energy source. In the stand, the external factor is the generation of electricity by a solar panel. When the panel is heated by sunlight, thermal energy is also generated. The method allows you to determine the amount of heat generated by the solar panel, increasing the amount of usefully used energy released for the operation of the compressor. This method allows you to increase the efficiency of the technological process and reduce the emissions of CO₂, CO and NO into the atmosphere [6,7].

Heat pumps are technologies that do not generate polluting emissions with negative potential to the environment, other than those emitted by the production of electric energy. If the electricity consumed by the heat pump compressor comes from environmentally friendly sources such as solar or wind, the positive effect of this equipment on greenhouse gas reduction can be quantified [8].

The purpose of this article is to compare analytical methods for assessing the efficiency and reduction in process emissions using the example of a heat pump using renewable energy sources as an additional low-grade heat source.

2. Materials and Methods

The analysis of methods for evaluating the efficiency of the technological process, using the example of increasing the efficiency of the installation, was carried out on an experimental stand designed to study the process of heat extraction from the rear surface of the solar panel. The main task of the stand is to use the solar panel as a source of two resources at the same time: heat and electricity.

The components of the stand are as follows:

- Solar panel (Figure 1). The power is 50 watts. The panel dimensions are 670 × 540 × 28 mm. The design is thermally insulated, providing a tight fit of the panel to the evaporator, to which the panel gives heat through the interface.
- Coolant. It enters the compressor from the evaporator through tubes with a cross-section of 5 mm with a power of no more than 200 Watts.
- The capacitor. After the compressor, the coolant passes through a coil condenser. The length of the capacitor is 10 m. It is placed in a heat-insulated tank with a volume of

10 L. The material for the manufacture of the condenser is stainless steel. The flow of the coolant in the condenser is from the top to the bottom.

- Tank. Made of stainless steel. For the possibility of descaling, it has a removable lid. In addition, there is a filler neck in the upper part of the side wall, a drain tap on the lower part and a tubular water level indicator.
- Temperature control valve. The coolant enters the valve after the condenser. The thermal cylinder of the valve is located at the outlet of the evaporator.
- Sensors for measuring the pressure and temperature of the coolant. Located at the inlet and outlet of the capacitor.

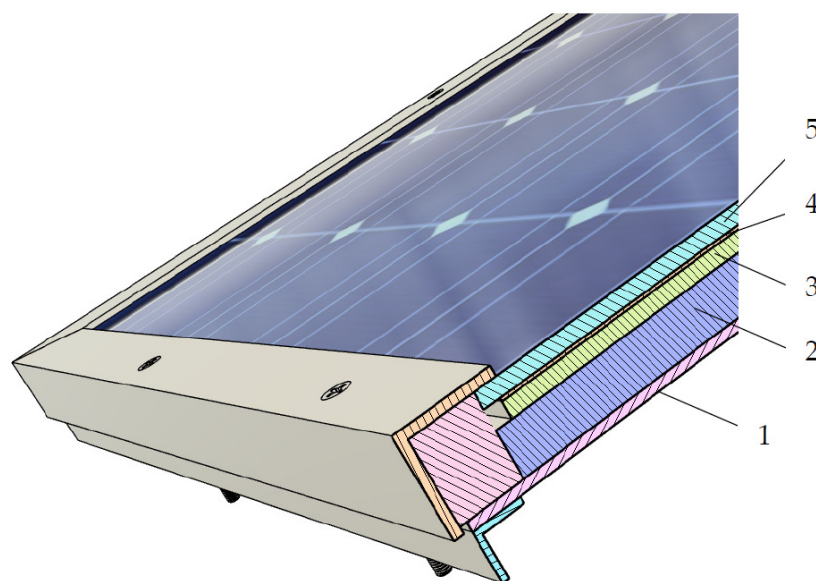


Figure 1. Layers of thermophotovoltaic converter. 1—metal substrate, 2—heat insulator, 3—heat exchanger, 4—heat-conducting paste, 5—solar panel.

Figure 2 shows the layout of the experimental stand.

The experimental stand operates on the principle of a heat pump. This principle consists in taking thermal energy from the environment and converting it into useful energy.

The following methods were applied to the experimental stand of the heat pump:

- Selection of the working fluid;
- Analysis of the external environment.

The effectiveness of the methods was evaluated on the basis of exergetic analysis. In the process of analyzing the results of the methodology, the location, dimensions and sources of thermodynamic inefficiency in the energy conversion system were determined.

The method of the selection of the working fluid allows you to estimate the values of the efficiency when using various refrigerants. This method makes it possible to modernize the system by selecting freon with optimal thermophysical parameters. The optimal working fluid for the heat recovery system must have stable thermodynamic characteristics and a safe impact on human life and the environment. The following indicators should be absent in the working fluid: toxicity and flammability. The presence of these indicators in the liquid is possible only with small leaks. In the process of selecting the working fluid, it is necessary to take into account the level of thermal stability of the fluid. The selection process is not a generalized approach and is rather adapted for a specific application. The method of the selection of the working fluid consists in the thermodynamic calculation in the p-h diagram of the experimental system of the steam compression heat pump.

The method of environmental analysis allows you to evaluate possible sources of alternative energy that can increase the energy efficiency of the system. This method consists in analyzing the potential energy released by the external environment. The

modernization of the stand, when choosing this method, is to increase the energy efficiency of the solar panel. Modernization takes place due to the transfer of electrical energy from the accumulation to the own needs of the installation. After the improvement in the solar panel, the costs of electricity released for the operation of compressors are reduced. The efficiency of the experimental stand increases by 4–5%.

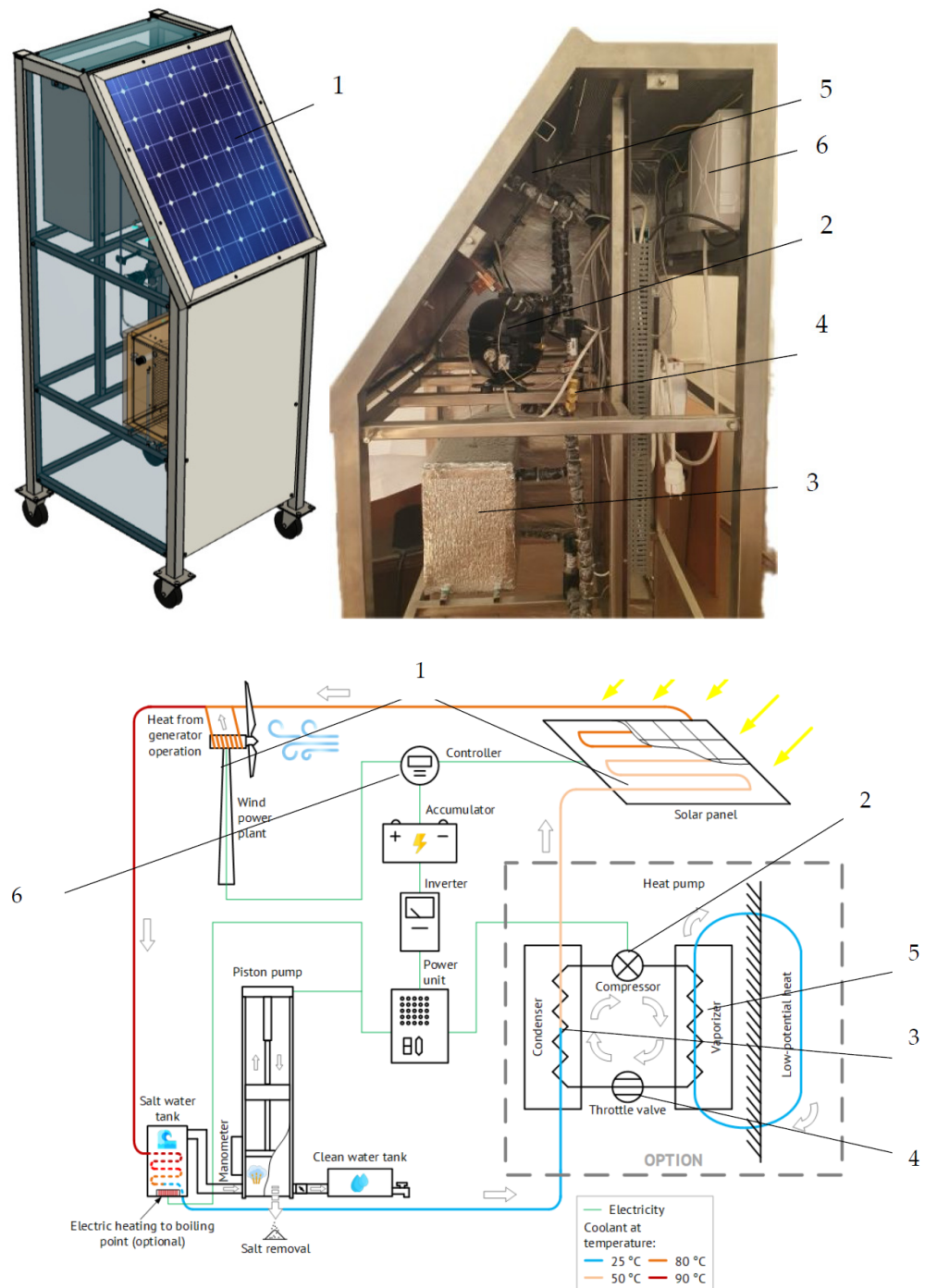


Figure 2. Layout of experimental stand (3D model and photo from side) working on heat taken from wind and solar power plants and its 3D model of heat pump part. 1—wind and solar power plants, 2—compressor, 3—condenser, 4—throttle valve, 5—vaporizer, 6—controller.

In the condenser, heat is transferred from the hotter freon to the water. Based on the outlet water temperature $t_{h-p2} = 50\text{ }^{\circ}\text{C}$ and the temperature difference $\Delta t_c = 5\text{--}10\text{ }^{\circ}\text{C}$, the freon condensation temperature is determined:

$$t_c = t_{h-p2} - \Delta t_c = 60\text{ }^{\circ}\text{C} \quad (2)$$

Based on the condensation temperature t_c , point 3 is located on the right boundary of the curve, for which the enthalpy $h_3 = 260\text{ kJ/kg}$ and the condensation pressure $p_c = 0.52\text{ MPa}$ are determined.

At the intersection of the line of constant entropy S_1 passing through point 1 and the isobar line p_c passing through point 3, point 2a will be determined, which corresponds to the end of adiabatic compression. The diagram determines the enthalpy $h_{2a} = 490\text{ kJ/kg}$ at point 2a.

The adiabatic efficiency of the compressor η_a is equal to the following:

$$\eta_a = \frac{(h_{2a} - h_1)}{h_2 - h_1} \quad (3)$$

$$h_2 = \frac{h_1 + (h_{2a} - h_1)}{\eta_a} \quad (4)$$

The adiabatic efficiency of a compressor can be calculated using the following expression:

$$\eta_a = \frac{0.98 \cdot (273 + t_0)}{273 + t_c} = 0.86 \quad (5)$$

where t_0 —outside air temperature equal to $20\text{ }^{\circ}\text{C}$.

$$h_2 = \frac{h_1 + (h_{2a} - h_1)}{\eta_a} = 495\text{ kJ/kg} \quad (6)$$

based on the enthalpy value h_2 and pressure p_c , point 2 is determined. Based on the enthalpy value $h_3 = h_4$ and pressure p_e , point 4 is determined.

The specific heat loads in the heat pump units are calculated:

$$q_e = h_1 - h_4 = 200\text{ kJ/kg} \quad (7)$$

$$q_c = h_2 - h_3 = 235\text{ kJ/kg} \quad (8)$$

$$l_{cmp} = h_2 - h_1 = 35\text{ kJ/kg} \quad (9)$$

The correctness of the calculation is determined by checking the heat balance:

$$q_e + l_{cmp} = q_c = 235\text{ kJ/kg} \quad (10)$$

The specific energy consumed by the electric motor W is as follows:

$$W = \frac{l_{cmp}}{\eta_{e.m.} \cdot \eta_e} = 36\text{ kJ/kg} \quad (11)$$

The energy efficiency indicators of the heat pump are determined, such as the heat conversion coefficient:

$$\mu = \frac{q_c}{l_{cmp}} = 6.7 \quad (12)$$

and the electricity conversion ratio:

$$\mu_e = \eta_{e.m.} \cdot \eta_e \cdot \mu = 5.75 \quad (13)$$

The compressor pressure ratio is as follows:

$$\varepsilon = \frac{p_c}{p_e} = 2.6 \quad (14)$$

Next, an exergetic calculation of the circuit is performed. The exergy e_{l-p} given off by the low-potential coolant in the evaporator is as follows:

$$e_{l-p} = \tau_{l-p} \cdot q_e \quad (15)$$

where τ_{l-p} is the exergy temperature of the low-potential coolant (the exergy temperature value should be from 0 to 1):

$$\tau_{l-p} = \frac{T_{av.l-p} - (t_0 + 273)}{T_{av.l-p}} \quad (16)$$

where $T_{av.l-p}$ is the average logarithmic temperature of the cold coolant:

$$T_{av.l-p} = \frac{\tau_{l-p1} - \tau_{l-p2}}{\ln \frac{\tau_{l-p1} + 273}{\tau_{l-p2} + 273}} = 322.58 \text{ K} \quad (17)$$

After substituting all values, the exergy value e_{l-p} (16) was obtained, equal to 18.2.

The exergy e_{h-p} obtained by the high-potential coolant in the condenser is as follows:

$$e_{h-p} = \tau_{h-p} \cdot q_c \quad (18)$$

With the substitution of the corresponding values of the variables for the high-potential coolant ($T_{av.h-p}$, τ_{h-p}) into Equations (17) and (18), the value e_{h-p} was obtained, equal to 11.28.

The exergy of the electricity consumed by the electric motor is as follows:

$$e_{el.} = W = 27 \quad (19)$$

The exergy efficiency $\eta_{ex.}$ of a heat pump is determined by the total exergy of the input e_{in} and output e_{out} flows:

$$\eta_{ex.} = \frac{e_{out}}{e_{in}} = \frac{e_{h-p}}{e_{l-p} + e_{el.}} = 0.181 \quad (20)$$

$$\eta = \eta_{ex.} \cdot 100\% = 18.1\% \quad (21)$$

2.2. Liquid Selection Method

The calculation of the exergy efficiency of the installation when using the refrigerant selection method was carried out in the sequence given below.

Salt water is used as a high-potential coolant in a heat accumulator. A low-grade heat source is a heated solar panel. Heat is taken from the solar panel for the purpose of cooling it [13].

In the evaporator, heat from the low-potential coolant is transferred to freon, the temperature of which should be lower. Based on the panel surface temperature $t_{l-p2} = 30^\circ\text{C}$ and the temperature difference $\Delta t_e = 3\text{--}5^\circ\text{C}$, the freon evaporation temperature is determined as follows:

$$t_e = t_{l-p2} - \Delta t_e = 25^\circ\text{C} \quad (22)$$

Based on the evaporation temperature t_e , on the right boundary of the p-h curve of the freon diagram, there is point 1, for which the enthalpy $h_1 = 405 \text{ kJ/kg}$ and the evaporation pressure $p_e = 0.6 \text{ MPa}$ are determined. Freon R134a is selected.

In the condenser, heat is transferred from the hotter freon to the water. Based on the water temperature at the outlet $t_{h-p2} = 50\text{ }^{\circ}\text{C}$ and the temperature difference $\Delta t_c = 5\text{--}10\text{ }^{\circ}\text{C}$, the freon condensation temperature is determined:

$$t_c = t_{h-p2} - \Delta t_c = 60\text{ }^{\circ}\text{C} \quad (23)$$

Based on the condensation temperature t_c on the right boundary curve (or according to the tables of the thermodynamic properties of the refrigerant in the state of saturation), point 3 is located, for which the enthalpy $h_3 = 285\text{ kJ/kg}$ and the condensation pressure $p_c = 1.8\text{ MPa}$ are determined [14].

At the intersection of the line of constant entropy S_1 passing through point 1 and the isobar line p_k passing through point 3, point 2a will be determined, which corresponds to the end of adiabatic compression. The diagram determines the enthalpy $h_{2a} = 430\text{ kJ/kg}$ at point 2a.

Next, the enthalpy h_2 value is to be found as follows:

$$h_2 = \frac{h_1 + (h_{2a} - h_1)}{\eta_a} \quad (24)$$

where the adiabatic efficiency of the compressor η_a is equal to the following:

$$\eta_a = \frac{0.98 \cdot (273 + t_0)}{273 + t_c} = 0.86 \quad (25)$$

Based on the obtained enthalpy value $h_2 = 434\text{ kJ/kg}$ and pressure p_c , point 2 is determined. Since the enthalpy $h_3 = h_4$ and the pressure p_e are known, point 4 is determined.

The specific heat loads in heat pump units are as follows:

$$q_e = h_1 - h_4 = 120\text{ kJ/kg} \quad (26)$$

$$q_c = h_2 - h_3 = 149\text{ kJ/kg} \quad (27)$$

$$l_{cmp} = h_2 - h_1 = 29\text{ kJ/kg} \quad (28)$$

The thermal balance check is conducted as follows:

$$q_e + l_{cmp} = q_c = 149\text{ kJ/kg} \quad (29)$$

The specific energy consumed by the electric motor W is as follows:

$$W = \frac{l_{cmp}}{\eta_{e.m} \cdot \eta_{ex}} = 34\text{ kJ/kg} \quad (30)$$

The energy efficiency indicators of the heat pump are determined. The heat conversion coefficient is as follows:

$$\mu = \frac{q_c}{l_{cmp}} = 5.1 \quad (31)$$

and the electricity conversion ratio is as follows:

$$\mu_e = \eta_{e.m} \cdot \eta_{ex} \cdot \mu = 4.4 \quad (32)$$

The compressor pressure ratio is as follows:

$$\varepsilon = \frac{p_c}{p_e} = 2.6 \quad (33)$$

Next, an exergetic calculation of the circuit is performed as in the previous case. The exergy e_{l-p} given off by the low-potential coolant in the evaporator is as follows:

$$e_{l-p} = \tau_{l-p} \cdot q_e = 10.92 \quad (34)$$

The exergy e_{h-p} obtained by the high-potential coolant in the condenser is as follows:

$$e_{h-p} = \tau_{h-p} \cdot q_c = 11.28 \quad (35)$$

The exergy of the electricity consumed by the electric motor is as follows:

$$e_{el.} = W = 36 \quad (36)$$

The exergy efficiency $\eta_{ex.}$ of a heat pump is determined by the total exergy of the input e_{in} and output e_{out} flows:

$$\eta_{ex.} = \frac{e_{out}}{e_{in}} = \frac{e_{h-p}}{e_{l-p} + e_{el.}} = 0.24 \quad (37)$$

$$\eta = \eta_{ex.} \cdot 100\% = 24\% \quad (38)$$

2.3. Method of Analysis of External Sources

The calculation of exergy efficiency using the external source analysis method was carried out in the sequence shown below.

The external energy source in this case is solar energy. The solar panel was used to split solar energy into thermal and electrical energy, then storing both types of energy in batteries. If the system is considered as a closed system, then the exergy efficiency of the system will increase significantly after redirecting electrical energy to power the compressor [15].

With a solar panel area of $S = 0.3618 \text{ m}^2$, average energy flux density $W = 170.8 \text{ kW} \cdot \text{h}/\text{m}^2$ and efficiency $\eta = 14.6\%$, the generated power has a value of $N = 8.96 \text{ kW}$.

The amount of electricity from external sources can be determined by the following formula:

$$W = \frac{l_{cmp}}{\eta_{e.m.} \cdot \eta_{ex.}} - N = 18.4 \text{ kWh}/\text{m}^2 \quad (39)$$

The exergy efficiency η_{ex} of a heat pump is as follows:

$$\eta_{ex.} = \frac{e_{out}}{e_{in}} = \frac{e_{h-p}}{e_{l-p} + e_{el.}} = 0.234 \quad (40)$$

$$\eta = \eta_{ex.} \cdot 100\% = 23.4\% \quad (41)$$

3. Results and Discussion

In the experimental stand, two methods for assessing the efficiency of the technological process were used. The highest efficiency was 24%; it was obtained using the refrigerant selection method. However, the use of the R134a refrigerant is impractical due to its high cost [16,17].

The plant achieves the highest exergy efficiency of 23.4% when upgraded according to the external energy source analysis method. A solar panel was used as an additional energy source.

The main installation parameters for all studied cases are summarized in Table 1 and cycle parameters in Table 2.

Table 1. Studied case parameters.

Heat Pump Parameters	Case 1	Case 2	Optimized
Freon	R134a	R21	
Solar panel temperature, t_{l-p2}	30 °C	30 °C	30 °C
Evaporator temperature difference, Δt_e	5 °C	5 °C	5 °C
Refrigerant evaporation temperature, t_e	25	25	25
Heat accumulator temperature, t_{h-p2}	50	50	50
Temperature difference in the condenser, Δt_c	10	10	10
Freon condensation temperature, t_c	60	60	60
Adiabatic compressor efficiency, η_a	0.86	0.86	0.86
Specific heat load in evaporator, q_e	120 kJ/kg	200 kJ/kg	120 kJ/kg
Specific thermal load in condenser, q_c	149 kJ/kg	234.5 kJ/kg	149 kJ/kg
Specific work of compression, l_{cmp}	29 kJ/kg	34.5 kJ/kg	29 kJ/kg
Specific energy consumed by the electric motor, W	33.9 kJ/kg	40.7 kJ/kg	24.95 kJ/kg
Heat conversion coefficient, μ	5.13	6.7	5.13
Electricity conversion ratio, μ_e	4.39	5.77	4.39
Compressor pressure ratio, ε	3.0	2.6	3.0
Exergy temperature of the low-potential coolant, τ_{l-p}	0.091	0.091	0.091
Exergy temperature of the high-potential coolant, τ_{h-p}	0.048	0.048	0.048
Exergy given off by the low-potential coolant in the evaporator, e_{l-p}	11.0 kJ/kg	18.34 kJ/kg	11.0 kJ/kg
Exergy obtained by the high-potential coolant in the condenser, e_{h-p}	7.14 kJ/kg	11.25 kJ/kg	7.14 kJ/kg
Exergy of electricity consumed by an electric motor, e_{el}	33.9 kJ/kg	40.7 kJ/kg	24.95 kJ/kg
Exergy efficiency, η_{ex}	15.9%	19.0%	19.8%

Table 2. Calculated cycle parameters.

Parameter	Point 1: Evaporation	Point 2: Condensation	Point 2a: Adiabatic Compression	Point 3: Condensation	Point 4: Evaporation
Temperature, t	25 °C			60 °C	
Pressure, p	0.6 MPa		1.8 MPa	1.8 MPa	
Enthalpy	405 kJ/kg	434 kJ/kg	430 kJ/kg	285 kJ/kg	285 kJ/kg
Temperature, t	25 °C			60 °C	
Pressure, p	0.2 MPa		0.52 MPa	0.52 MPa	
Enthalpy	460 kJ/kg		490 kJ/kg	260 kJ/kg	
Temperature, t	25 °C			60 °C	
Pressure, p	0.6 MPa			1.8 MPa	
Enthalpy	405 kJ/kg		430 kJ/kg	285 kJ/kg	285 kJ/kg

The optimization of the technological process of the experimental stand, using heat from a renewable source, was carried out through the use of analytical methods.

Exergy analysis helped determine the amount of useful work generated by the heat pump. The main energy costs for compressor operation were calculated. Exergy calculation indicates the cause of energy losses in the system. The cause of energy losses in the experimental heat pump installation was the irrational use of condenser heat.

To assess the energy efficiency of the system, the selection of the working fluid was carried out in the stand. Using this method, the working fluid with the best thermophysical parameters for the experimental setup was determined. This working fluid is freon R134a. The exergy efficiency value using the method of analyzing external sources decreased by 0.6% compared to using the method of selecting the working fluid [18].

A calculation was made showing how much the energy efficiency of the heat pump will increase after the appropriate use of solar panel energy for its own needs. Accumulating solar energy was irrational from the point of view of a closed system, due to the fact that electrical energy was not directed to the energy needs of the system. After calculations, it was determined that it was necessary to direct the electrical energy generated through the solar panel to the compressor. This technical solution increased the energy efficiency

of the system by 5.3%. To clearly demonstrate the reduction in emissions on the scale of a solar/wind power plant, we calculated a similar station operating on diesel fuel [19]. For this purpose, a mathematical model was created, Figure 4.

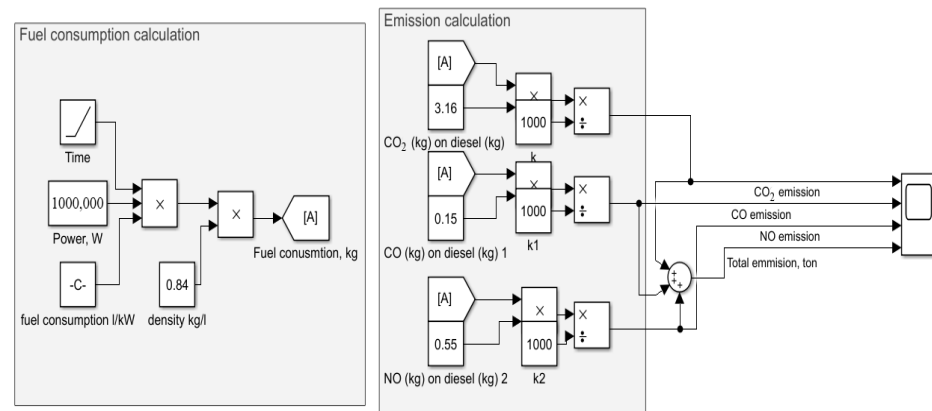


Figure 4. Mathematical model for emissions estimating.

The model consists of two main blocks; the first one calculates fuel consumption depending on the power and type of installation, and the second one calculates the main greenhouse gases.

For two configurations, graphs of changes in emission levels were calculated; the performance improvement calculated in this work ensures a reduction in emissions by 2 tons per day, Figure 5.

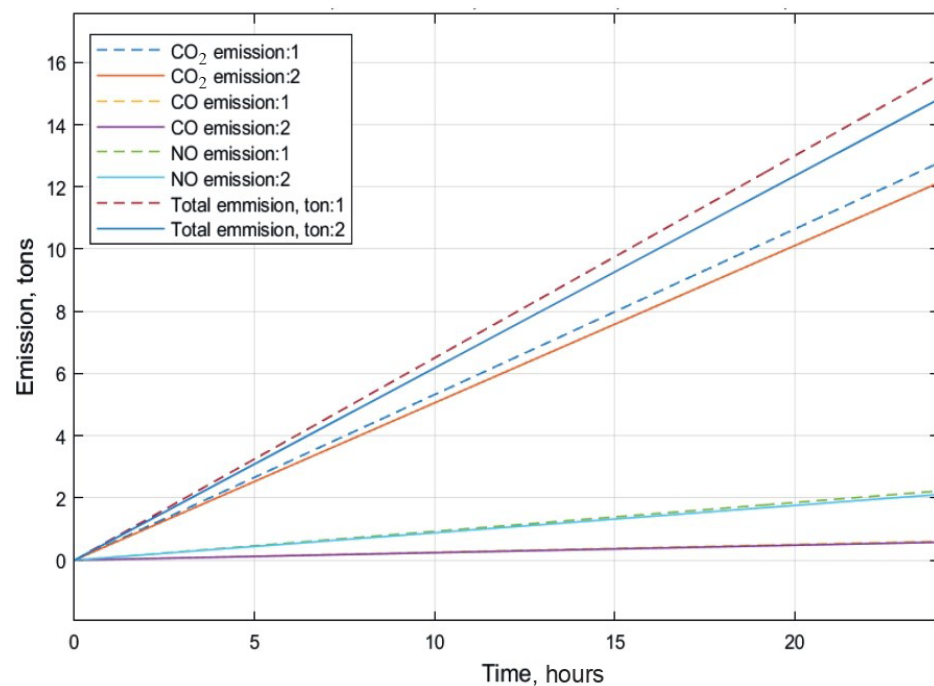


Figure 5. Graph of emissions of different types (tons) versus time (hours).

The methods presented above for optimizing the technical process of energy generation can be used in refrigeration units and heat pumps and also be useful for ecological situation improvement.

4. Conclusions

This article describes two methods for analyzing the operating cycle of a heat pump experimental stand with the possibility of using low-grade heat from solar panels and wind power generators. Examples are given of calculating the exergy efficiency of the system when commissioning new technical solutions. The technically competent and most effective method is the method of analyzing environmental sources. After introducing this method into the system, energy efficiency increased by 5.3%. This result was achieved by correcting the identified problem in the direction of electrical energy. The energy was redirected to the compressor. Due to this, energy losses decreased, and the value of exergy efficiency increased. By introducing the redirection of energy to the compressor, it is also possible to reduce emissions into the atmosphere. With the 24 h operation of a diesel generator equivalent in power, the reduction is equal to 1 ton for the main greenhouse gases, which is a percentage of 6.25%.

The scientific significance of this work lies in the results obtained and will be useful in the design of heat pumps based on renewable energy sources to reduce greenhouse gas emissions into the atmosphere.

In future studies, it is planned to expand the range of freons studied, as well as improve the automation of the system to reduce energy consumption.

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