On importance of technical and economic research in determining the optimal parameters and structure of solar heat pump plants

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Abstract. The energy saving in production processes of industrial agricultural production as well as in everyday life was studied. The effective means of saving fuel resources and environmental protection when using solar heating systems were given. The increasing importance of technical and economic studies to determine the structure of solar heat pump installations and their optimal parameters was shown. The types of technical schemes and profiles of equipment in the stages of design work are presented. Various methods for determining efficiency in the energy sector as well as thermodynamic analysis and its disadvantages are presented. The use of this method is proposed to consider exergy economic optimization using exergy efficiency.

1. Introduction
The most urgent problem of our time is the economy of energy resources, both in the production processes of the agroindustrial complex and in everyday life. The reason for it is the existing trends in the reduction of fuel and energy resources, the growth of energy costs, as well as global environmental problems. One of the effective means of fuel saving and environmental protection is the widespread use of solar and combined power systems. They are used on the basis of renewable energy which provides an opportunity to solve important problems of energy supply, energy saving and environmental protection with minimal losses. Also the use of such heat pump systems allows us to use renewable sources and low-potential heat emissions of the enterprises in full extent [1].

It should be noted that in all countries, in practice, programs of intensive development of renewable energy are prepared and implemented [2]. The interest in this problem is closely linked with the environment and understanding of the fact that the rapid exponential growth of negative anthropogenic impact on the environment will lead to significant deterioration of human living conditions. Maintaining this environment in a normal state becomes one of the main tasks of society. In these conditions, previous narrow economic assessments of various areas of development of technology, management technology become clearly insufficient since they can not take into account social and environmental aspects.

The design and optimization of modern solar thermal power systems using heat-bearing plants should take into account the use of many technical and other types of restrictions. This is largely due to the great
complexity of internal and external relations in such systems and the tendency to further complicate them [3]. In this regard, the importance of technical and economic studies to determine the optimal or close to optimal parameters and structures of combined solar thermal power plants, types of technological schemes and equipment profile at the stages of design development increases. At the same time, even a partial solution of this problem due to the approximation of the selected characteristics to the optimal ones, provides, as shown by numerous studies, an economic effect and, not least, increases the reliability of the system.

Methods of thermodynamic analysis have been used for a long time to assess the efficiency in the energy sector. One of the disadvantages of the efficiency indicators of this method is that thermodynamic losses, which are the largest, are taken into account together with mechanical losses, hydro- and aerodynamic, chemical losses through thermal insulation, with energy costs for their own needs and so on. It leads to the progressive error and low objectivity of the results as a consequence.

In contrast to the methods of thermodynamic analysis previously used, the proposed exergoeconomic method takes into account not only the quantity but also the quality of energy flows, which puts this method in the first place in its objectivity [4].

2. Methods of assessment of effectiveness of heat energetic technologies

There are different methods of assessment of heat energy technologies effectiveness on the basis of different coefficients, indexes and etc., which not always have a clear physical nature and are not applicable for comparison of indexes of effectiveness of technologies of different types.

The methods of thermal dynamic analysis were applied for assessment of effectiveness in energetic for the long periods. One of the lacks of indexes of effectiveness of the present method is in thermal dynamic losses which are the most when taking into account with mechanical losses, hydro- and aerodynamic, chemical losses jointly through heat isolation with energy expenses on their own needs and etc. It leads to the progressing mistake and as a consequence, to low objectiveness of obtained results.

Unlike the early applied methods of thermal dynamic analysis in the proposed exergoeconomic method we take into account not only the quantity but the quality of energy flows and this method takes the first place on its own objectiveness [4].

The peculiarity of exergoeconomic method is the universality, it explains the use of exergy allows to assess the supply and energy flows of all types including the balance of any energetic technological system by means of an integrated criteria of effectiveness. This method is simplicity and obviousness of ways of analysis and calculation as well. The exergoeconomic method shows the connection between exergetic and technological-economic characteristics of the system. The application of exergy taking into account its connection with economics allows quite simple and definite solving one more important question – choice of criteria of effectiveness under the assessment and optimization of systems with the use of renewable sources of energy.

The account at the exergetic economic method is divided on two components: exergetic (determination of energy flows) and economic (assessment of the cost of these flows).

The exergetic method should determine not only the quantity of transmitting, transforming, passing to a consumer’s energy but losses of the heat power plant but the assessment of this energy.

Exergy of a substance in a closed volume with thermal dynamic parameters \( U, S, T, p \) and \( V \) is determined by the correlation:

\[
e_v = (U - U_0) - T_0 (S - S_0) + p_0 (V - V_0),
\]

where \( e_v \) – specific (per unit of mass) exergy of a substance; \( U_0, S_0, T_0, p_0, V_0 \) – internal energy, entropy, temperature, pressure and volume of a substance at the full balance of the analyzed system with environment. Formula (1) expresses exergy in a closed volume in the process finishing with the leveling of
corresponding parameters of systems and environment. The equation in the account of exergy of a working unit (exergy) in a closed system in two different conditions (1) is the following:

\[ \Delta e_r = \Delta U - T_0 \Delta S + p_0 \Delta V, \]  

where \( \Delta U, \Delta S, \Delta V \) - change of parameters of a substance during the transition from one condition to another.

The necessity of the determination of exergy in the closed volume occurs more often at the calculations of periodical processes and installations of periodical action, in which the working unit does not come off the limits of the present system. However, on the practice the most chemical-technological processes are continuous, stationary and accompanied with passing of material and energy flows. So, such problems are connected with the determination of exergy of the substance in the flow. Its thermal mechanical component is the following on the equation:

\[ e_r = q - T_0 (S - S_0), \]  

where \( q \) – specific heat flow passing by the substance; \( S \) – entropy of the substance in the flow. 

The thermal mechanical exergy is determined by the expression for ideal gases:

\[ e_T = C_p(T - T_0) - T_0 \left[ C_p \cdot \ln \left( \frac{T}{T_0} \right) - R \cdot \ln \left( \frac{p}{p_0} \right) \right], \]  

where \( C_p \) – specific heat capacity of the substance, \( p \) and \( T \) – pressure and temperature of the substance in the flow; \( R \) – coefficient of gas.

The functioning of heat energetic system in some degree is substantiated with the exchange of energy with environment. At the transfer from one body to another and to the media of energy in the form of heat flow (heat conductivity), the definite quantity of exergy is passed in it [4].

If the heat receiver is a media with the temperature \( T_0 \), that the specific exergy of heat flow has the temperature rates \( T \):

\[ e_r = q \left( 1 - \frac{T_0}{T} \right), \]  

\[ T_e = 1 - \frac{T_0}{T}, \]  

The value \( T_e \) is called the exergy temperature.

The direction of flows is opposite at the \( T < T_0 \): heat flow moves from environment (negative), exergy – always to the media (positive).

In many heat energetic systems especially which concern to high-temperature ones, the exchange of energy in the form of radiation with other objects and media plays the essential role. The exergy of radiation is found on the formula:

\[ e_\varepsilon = \varepsilon k \left[ 3 \left( 3T^4 + T_0^4 - 4T_0 T^3 \right) \right], \]  

where \( e_\varepsilon \) – specific exergy falling on the unit of area of radiating surface; \( \varepsilon \) and \( T \) – degree of its blackness and temperature; \( T_0 \) –temperature of environment; \( k \) – coefficient of Boltzman.

The account of technological-economic characteristics of the system is necessary in general case of exergic-economic optimization in the change of parameters, structure and a single-item unit of energetic installation.

The exergic balance in the type of the equation allows to find the qualitative indexes of the work of the analyzed energetic, chemical-technological system (CTS). The exergic coefficient of efficiency \( \eta_e \) is more often determined by the correlation among these indexes:
where \( \sum E_{F,E} \) – sum of flows of exergies reflecting the useful effect from the functioning of the system, \( \sum E_E \) – full expenses of exergies to obtain the given effect. \( \eta_e = 1 \) can be if the losses are absent in the ideal, reversible process; if the exergy is lost in the process, that \( \eta_e = 0 \). The inequality is always observed in real processes: \( 0 < \eta_e < 1 \) that the higher numeral value \( \eta_e \) the more perfect system from thermal dynamical point of view. From the formula (8) we can see that the difference between the exergies contributing to the useful effect and exergic costs is always equal to the total loss of exergy from the irreversibility occurring in the system of processes.

So, the exergic coefficient of efficiency has a generalized character. The concrete expression for \( \eta_e \) depends on the purpose and peculiarities of the analyzed process and types of flow interaction. For example, the exergy \( E^{TR} \) (it is not changed in the system in terms of quantity) with the use of the definition “transitive” is the following for the equation \( \eta_e \):

\[
\eta_e = \frac{\sum (E_i^* - E_i^{TR}) + \sum (E_{x,i}^* - E_{x,i}^{TR}) + \sum E_{x,l}^*}{\sum (E_i^* - E_i^{TR}) + \sum (E_{x,i}^* - E_{x,i}^{TR}) + \sum E_{x,l}^*},
\]

where the low indexes mean: \( i \) – all types of exergy, except of chemical one; \( x \) – chemical exergy; \( j \) – components of the substance, simultaneously presenting in input or output current; \( l \) – new substances forming in the system; \( f \) - substances, fully turning in other substances.

As the exergic-economic optimization of heat pumping systems, we should take thermal transformers:

— growth of operational expenses to the plant in whole and the increase of expenses to the installation of the drive as well;
— decrease of operational expenses on heat exchange apparatus (decrease of depreciation of deductions, costs on planned maintenance and etc.) [5].

The optimization of any energetic system means the variation of the structure and parameters with the aim of minimization of capital and operational expenses at the corresponding technological and resource limitations, supply of conditions of operational reliability and small cost of the work, protection of environment. The methods of exergic economics show the ways of decision of these questions.

The search of optimal parameters of energetic installations in most cases is impossible to present in the type of traditional task of determination of the extremum of some function (criteria) of the quality \( F(x) \) that is explained by some reasons.

Instead of the single generalized criteria \( F(x) \), as a rule a designer has some indexes \( F1(x), F2(x) \) ..., \( Fk(x) \) which reflect the incompleteness of its presentation on possibilities of installations especially in the first stages of projecting.

3. Elements of energy-transforming system

The present energy-transforming system consists of many elements. Many of them are simple from the modeling point of view (for example, compressor, turbine, heat exchanger), some of them are combined the functions of some components (heat mass exchange devices).

The definition of the system’s component is used for the generalization, that is, the least indivisible unit in the system is considered.

The exergic economic method is widely used at the decision of different optimization tasks including at the use of alternative sources: solar, heat pumping, coherent installations and other types of energetic systems [1, 4, 5].
Let’s conduct the comparison of exergic economic effectiveness for the systems of heat supply with the use of heat pump and without it.

Let’s consider the scheme of solar heat supply (Figure 1). The solar energy falls on the surface of a collector where it is transformed into useful heat, passing through the first circulation circuit into the storage tank designed for the miter of daily fluctuations of temperature of the heat carrier where directly is taken away from the heat for the second circuit of the heat carrier which directly giving heat power to a consumer. Such division on two independent circuits allows to miter effectively the short-term temperature drops and the intensity of solar radiation and as well as the least volume of a heat carrier of higher quality is used in the circuit taking the heat from solar collector (relatively to the volume in a combined circuit), such as ecosol (it is real in the connection with its high cost), and in the circuit which gives the running water to a consumer.

![Figure 1. System of solar heat supply: 1 – solar collector, 2 – tank-accumulator, 3 – consumer, 4, 5 – circulation circuits, 6-9 – heat exchangers, 10, 11 – circulation pumps.](image)

The present system is very simple in operation, however, has one significant disadvantage limiting the possibility of its everywhere application. During some overcast days when the coming of solar radiation on beam-emitting surface is small, the significant decrease of temperature of water can occur in the tank-accumulator.

The energy in a such system is transmitted from the solar collector in which it is concentrated and has a maximum temperature potential to a consumer gradually losing the density.

The increasing thermotransformer is used to avoid the decrease of water temperature at a consumer, the conditional scheme of the system of the solar heat supply with increasing thermotransformer is in figure 2.

In the present system the heat obtained by means of solar collector surface is passed to the heat carrier circulating in the first circuit which gives the heat to the tank-accumulator where from it is taken away by the second circuit. From the second circuit the heat is passed to the increasing thermotransformer which uses the electrical energy to increase the temperature of heat carrier of the third circuit in the expense of heat obtained from the heat carrier of the second circuit.

![Figure 2. System of solar heat supply with an increasing thermotransformer: 1 – solar collector, 2 – tank-accumulator, 3 – consumer, 4-6 – circulation circuits, 7-10 – heat exchangers, 11 – increasing thermotransformer, 12-14 – circulation pumps.](image)
The present system allows us to use the energy obtained even from dissipated solar radiation. However, it is necessary that the influx to heat energy or its stock meets the needs of consumers, otherwise the exposure of heat carrier can occur in the first circuit and it will lead to the breakdown of the whole system of solar heat supply.

In such system the energy is passed from a solar collector to the increasing thermotransformer which increases its heat potential and then from a thermotransformer to a consumer. The heat pump can serve as a source of heat energy at the long-term prognosis on overcast days with a solar collector. The heat pump “air-water” uses a low potential heat of surrounding air and electrical energy for its transformation into heat energy of high density that is the increase of temperature of a heat carrier in a first circulation circuit. The scheme of the system of heat pumping and heat supply is given in figure 3.

**Figure 3.** System of heat pumping supply: 1 – air heat pump, 2 – storage tank, 3 – consumer, 4,5 – circulation circuits, 6,8 – heat exchangers, 9,10 – circulation pumps.

The heat of surrounding air is taken away by a heat pump, transformed into a heat pump using electrical energy, transmitted to the heat carrier of the first circuit by the capacitor of a heat pump in a such scheme. The heat from the first circuit is transmitted into the storage tank, analogically with the system of solar heat supply, however the storage tank is used only as an accumulator of heat energy in the heat pump system and the system can function free without compensating the drops of temperature of surrounding air in the expense of electrical energy consumption increase.

The system of heat pumping can be used jointly with the increasing thermotransformer (figure 4) which is used in cases when the temperature of surrounding air is quite low that the icy crust is formed on the evaporator of the heat pump at intensive work and the decrease of heat consumption can prevent it.

**Figure 4.** System of heat pump heat supply with increasing thermotransformer:1 – heat pump, 2 – storage tank, 3 – consumer, 4-6 –circulation circuits, 7-9 – heat exchangers, 10 – increasing thermotransformer, 11-13 – circulation pumps.
The necessity can occur in stable and constant source of energy supply at the use of renewable resources as main sources. The electric water heater is applied as a reserve source of power in solar heat pump system, the scheme of reserve heat supply is given in figure 5.

![Figure 5](image)

**Figure 5.** System of heat supply with the use of electrical water heater: 1 – electrical water heater, 2 – tank-accumulator, 3 – consumer, 4 – circulation circuit, 5,6 – heat exchangers, 7 – circulation pump.

It is efficiently to use the combined system of solar-heat pump heat supply with a reserve source (electrical water heater) and the increasing therмотransformer for more effective use of solar energy potential (figure 6).

![Figure 6](image)

**Figure 6.** System of solar-heat pump heat supply with a reserve source of electrical supply (electrical water heater) and the increasing therмотransformer: 1 – solar collector, 2 – heat pump, 3 – electric water heater, 4 – tank-accumulator, 5 – consumer, 6-9 – circulation circuits, 10-13 – heat exchangers, 14 – increasing thermotransformer, 15-18 – circulation pumps.

The optimization of a heat-and-power plant is a notion of the best ones from all possible types of the system of the chosen criteria of its effectiveness. The complex, systemic optimization aims to choose such values of parameters of the system (technological, constructive and etc.) which would supply with optimal or close to optimal values of effectiveness criteria.

The task of optimization is solved as the following at the general formulation, let’s consider the energetic system which consists of n elements of different m parameters. The system is uniform and is
The task of optimization is linked with the distribution of heating currents $C=(C_1+C_2+\ldots+C_n)$ in order the total thermoenergetic costs in the system would be minimum [5]:

$$\sum Z_t=Z_{\text{min}}^{\text{IV}},$$

(10)

where $Z_t$ — thermoelectrical costs on i-component of the system.

There are many possible thermoelectric costs in the system:

$$Z\{Z^{(p)}_p\}, i_p=1,2,\ldots[n-(p-1)].$$

(11)

Multitude of $Z\{Z^{(p)}_p\}$ can be divided into $k$ subsets. It is necessary to choose such current on every intermediate stage where:

$$Z^{(p)}_p \in Z\{Z^{(p)}_p\},$$

(12)

and

$$Z^{(p)}_p = Z_{\text{min}}^{(p)}, i_p=1,2,\ldots[n-(p-1)],$$

(13)

where $Z_{\text{min}}^{(p)}$ — minimization of thermoelectric costs for the stage $p$.

Figure 7. Situated in linear.
Figure 8. in ip l eme f en fexe fe em f ll e ppl i e i e in e n n f me 1– l ll e , 2– e en n ef f ll ll e , 3– e en n ef e n, 4– e n, – in e in e m n f me, – e en n ef n me, EK – exe ine f m n, exe ine f m S n, EC – exe fe i e f ll ll e , EST1, EST2 – exe ie in p f m n – m l , EC – exe n mi e n me, EHE1 – exe n mi e e en f m l ll e , EHE2 – exe n mi e e en f f e n l ll e , EHE3 – exe n mi e e en n ef f n me, EHE4 – exe n mi e e en n ef f n me, EHE5 – exe n mi e e en n ef f n me, EHE6 – exe n mi e e en n ef f n me, EHE7 – exe n mi e e en n ef f n me, EHE8 – exe n mi e e en n ef f n me, Lc – le f exe in ll ll e , Lst – le f exe in n – m l , LH1 – LHE4 – le f exe in e e n e.

Unli e e pei eme f e ppl, en i e e e n n f me, e n me in m e exe e e e exe fe il e en e ex ep e ep e il f e e i e e e exe f l l i n.

Figure 9. in ip l eme f en fexe e mp me e ppl 1– e p mp, 2– e en n ef f e p mp, 3– e en n ef n – m l , 4– n – m l , – e en n ef n me, NTU – exe ine e p mp f me e ppl, Ea – i exe, EHE – exe f e i e f e p mp, EST1, EST2 – exe ie in p f m n – m l , EC – exe n mi e n me, EHE3 – exe n mi e e en f m l ll e , EHE2 – exe n mi e e en n ef f ll ll e , EHE3 – exe n mi e e en n ef f ll ll e , EHE4 – exe n mi e e en n ef f ll ll e , EHE5 – exe n mi e e en n ef f ll ll e , Lc – l e f exe in ll ll e , Lst – l e f exe in n – m l , LH1 – LHE4 – l e f exe in e e n e.
**Figure 10.** in ip l eme f en fexe em f e p mp e ppl i ine ine em nf me 1 – e p mp, 2 – e ex ne f e p mp, 3 – e ex ne f n m – m l , 4 – n – m l , – i ine ine em nf me, – e ex ne f n n me, $N_{TH} –$ exe ine e p mpf mp e ppl, $E_a –$ i exe, $E_{HE} –$ exe f e i e f e p mp, $E_{ST1}, E_{ST2} –$ exe ie in p n p f m n – m l , $E_C –$ exe n mi e n me, $E_{HE1} –$ exe n mi e e ex ne f m l ll e, $E_{HE2} –$ exe n mi e e ex ne f n n me, $E_{HE3} –$ exe n mi e e ex ne f n n me, $E_{HE4} –$ exe n mi e e ex ne f f m e, $N_{TH} –$ exe ine e p mp e ppl, $E_{PS} –$ exe ine ine e p mp e ppl, $E_{HE1} –$ exe n mi e e ex ne f n n me, $E_{HE2} –$ exe n mi e e ex ne f n n me, $E_{HE3} –$ exe n mi e e ex ne f n n me, $E_{HE4} –$ exe n mi e e ex ne f f m e, $L_{C} –$ e exe in l lle, $L_{ST} –$ e exe in l lle, $L_{HE1}, L_{HE2} –$ e exe in e exe ne. 

**Figure 11.** in ip l eme f en fexe em f e p mp e ppl i ele i l e e e 1 – ele i l e e e, 2 – n – m l , 3 – e ex ne f n n me, $N_{PS} –$ exe ine f m p e ppl, $E_{ST1}, E_{ST2} –$ exe in p n p f m n – m l , $E_C –$ exe n mi e n me, $E_{HE1} –$ exe n mi e e ex ne f n n me, $E_{HE2} –$ exe n mi e e ex ne f n n me, $E_{HE3} –$ exe n mi e e ex ne f n n me, $E_{HE4} –$ exe n mi e e ex ne f f m e, $L_{C} –$ e exe in l lle, $L_{ST} –$ e exe in l lle, $L_{HE1}, L_{HE2} –$ e exe in e exe ne. 

i ne e ne p ili fe f em i en e i, e n mi e l i l i p in f i e n l in e p e e n e e m e. e pe li i fe e em e i e p e e n e f i fe en fl n l e fexe in em, i, e e p e n n e e e p e n l n n i n in e p e n in m i n i i e.
\[
\min_{\{m\}} C_{PR} = \min_{\{m\}} \left\{ \sum_{E_{fi}} E_{fi} + E_K \right\},
\]

\(e \in C_{ni \in C_{PR}} - \text{effiien}\)

\(E_{D.K} = E_{F.K} - E_{P.K} - E_{L.K},\)

\(e \in C_{ni \in C_{PR}} - \text{effiien}\)

\(\varepsilon_K = \frac{E_{P.K}}{E_{F.K}} = 1 - \frac{E_{D.K} - E_{L.K}}{E_{F.K}},\)

\(y_K = \text{effiien}\)

\(y_{DK} = \frac{E_{D.K}}{E_{F.tot}},\)

\(C_{F,K} = \frac{C_{F,K}}{E_{F.K}},\)

Cost of a product's exergy

\(C_{P,K} = \frac{C_{P,K}}{E_{P,K}},\)

\(C_{D,K} = C_{F,K} \cdot E_{D,K},\)

\(C_{L,K} = C_{F,K} \cdot E_{L.K},\)

\(Z_{K} = Z_{K}^{CI} + Z_{K}^{OM},\)

\(r_k = \frac{C_{P,K} - C_{F,K}}{C_{F,K}} = 1 - \frac{\varepsilon_k}{\varepsilon_k} + \frac{z_k}{C_{F,K}E_{P,K}},\)

\(Z_{p}^{(p)} \in Z\left\{Z_{p}^{(p)}\right\} .\)
\[ \varepsilon_{OPF}^{k} = \frac{1}{1 + F_k}, \quad (2) \]

\[ F_k = \left( \frac{(\beta + y_k)B_k n_k}{\tau c_{F,K} L_{P,k}} \right)^{n_k + 1}, \quad (2) \]

\[ Z = Z_{Cl} = Z_{fuel} + Z_{OM}, \quad (2) \]

\[ Z_{Cl} = a_{\alpha} \frac{1}{t_d}, \quad (2) \]

\[ Z_{Cl} = a_k x_k^m (1 - b) \frac{y}{N_k}, \quad (30) \]

\[ Z_{fuel} = W c_F, \quad (31) \]

\[ Z_{OM} = b \frac{1}{t_d} + d, \quad (32) \]

\[ a = \frac{q^n (1 - q)}{q^{n-1}} \left( 1 + \frac{i + r CP}{100} \right). \quad (33) \]

\[ q^{-1} = \left( 1 + \frac{i + t + v}{100} \right)^{-1}. \quad (34) \]
4. Results and discussion

The results of the model can be expressed in terms of the total energy of the system:

\[ Z = \sum_{n} C_{n}E_{n} + K_{n} \]

where \( C_{n} \) is the number of configurations, \( E_{n} \) is the energy of each configuration, and \( K_{n} \) is the kinetic energy of the system.

The optimal energy configuration \( Z_{OPT} \) can be found by minimizing the energy expression with respect to \( x \):

\[ Z_{OPT} = \text{argmin}_{x} Z(x) \]

5. Conclusion

The model provides a comprehensive framework for understanding the complex interplay between different factors influencing the development of a system.
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