Determining the cost-effectiveness of thermal energy production by air-to-water heat pumps

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Abstract. This paper provides a methodology for identifying the cost-effectiveness of thermal energy generation by air-to-water heat pumps. The results of a comparative estimate of the cost of energy received and the profitability of the method under consideration are presented.

1. Introduction

In solving the problem of energy conservation, one of the most promising methods to improve the energy efficiency of buildings is the use of thermal energy of the environment - atmosphere, sources of natural water, soil, having a comparatively low temperature potential. The thermal energy contained in these sources is extracted by heat pumps with increased temperature capacity for use in the building's heat-consuming systems - heating, hot water, ventilation.

The use of heat pumps as "miners" of energy from "gift" sources is an attractive idea in itself, but its implementation is associated with the high cost of heat extraction equipment, which calls into question the economic feasibility of this way of heating. On the other hand, the constant increase in energy prices with irritating consumers inexplicable speculative component of tariffs gives some positive emotional effect from the "independent" energy supply. Therefore, many consumers are willing to take one-off economic costs for the sake of gaining independence and relative freedom in
providing thermal energy "their object" from a "no man's" source: air, soil, reservoir.

At the same time, it is necessary to have a fairly objective idea of the price, which will cost the use of an alternative method of energy generation. Moreover, traditional heating and heat generation systems have spent technology (whole industry), use fossil fuels, as yet inexhaustible reserves, established infrastructure that ensures stable energy supply of guaranteed capacity and volume.

The transition from traditional sources of heating to alternative (renewable) should be accompanied by an objective understanding of the ratios of acquisitions and losses from such replacement, especially since the economic component in long-term operation object may prove to be a priority when deciding on the maintenance of engineering equipment and building systems.

2. Materials and methods

This paper considers the provisions of the methodology and the results of the evaluation of the effectiveness of heat pumps in the conditions of the changing temperature of the heat-containing environment - outdoor air. The methodology is based on the use of analytical expressions and statistical models of system parameters and related elements that determine a comprehensive assessment of the effectiveness of the heating method.

3. Results

The most affordable way to generate thermal energy is the air-to-water heat pump system, in which heat is extracted from the outside air and transferred to the heat-carrier heating system. The main operating feature of such a system is the dependence of the heat performance of the pump on the temperature of the outside air and the required temperature of the coolant. It therefore seems necessary to take this factor into account when choosing equipment and analysing the system. The main criterion for the effectiveness of the "heat source" is the cost of the thermal energy generated (RUB/MW/h):

$$C_{np} = \frac{C_K + C_3}{T_3} / W_{TH},$$

where is $C_K$ and $C_3$ - costs respectively for the heat pump and its installation (rub.) and operational, (rub./year);

$T_3$ - the period of operation of the system, the year;

$W_{TH}$ - the amount of thermal energy generated by the (pumped) system,
MW/year.

The cost of the heat pump system will be presented by dependence on its calculated (passport) thermal performance:

\[ C_K = K_{мон} * c_q * Q_{TH,0}, \]  

(2)

where is \( c_q \) - Value (unit value) related to the unit of the estimated thermal power of the pump, ruble/kW;

\( K_{мон} \) - factor that takes into account the cost of installing the system.

Accepted the proportional cost of the heat pump.

Operating costs are mainly related to the consumption of electricity for pumping the working environment by the pump compressor \( C_{эл,эС} \) and ongoing repairs (maintenance) \( C_{ТР эС} \):

\[ C_э = C_{эл,эС} + C_{ТР эС}. \]  

(3)

\[ C_{эл,эС} = N_{TH,0} \sum (N_{т,i} \tau_{т,i}) * c_{эл}, \]  

(4)

where is \( N_{TH,0} \) - installation capacity of the heat pump compressor, kW;

\( N_{т,i} \) и \( \tau_{т} \) -accordingly, the relative power consumption of the heat pump under current working conditions and the duration of the period of standing of these conditions, an hour;

\( c_{эл} \) - cost of electricity, ruble/kW*h.

The annual cost of ongoing repairs and maintenance is usually tied to the cost of the equipment [5] and is (3-8)% of \( C_K \). Then addition (3) will take the form:

\[ C_э = N_{TH,0} \sum (N_{т,i} \tau_{т,i}) * c_{эл} + k_{TP} * K_{мон} * c_q * Q_{TH,0}, \]  

(5)

where is \( k_{TP} \) - the rate of deductions for the current repair, year\(^{-1}\).

As the analysis of the prices of equipment presented on the market shows, the specific cost of heat pumps is inversely proportional to their estimated thermal performance. Figure 1 is dependent \( c_q \) from maximum (passport) thermal power for well-known heat pump brands (according to the Price-list of manufacturers and the retail chain at the end of 2019).

As can be seen from the chart, the price range fluctuates significantly, especially for devices with a capacity of up to 15 kW - the difference in price can reach 600%! Therefore, in order to implement different comparison options, it would be appropriate to introduce a distribution \( c_q \) (ruble/kW) 2 parametric model (6): for maximum price (argument) and minimum (argument) \( \mathcal{P} = -1 \).
\[ c_q = \exp(4.461 + 0.998P - 0.0571Q_{TH,0} - 0.0093Q_{TH,0}^2 \cdot P + 0.00051Q_{TH,0}^2) \times 10^3. \]  
(6)

**Picture 1.** Value dependency \( C_q, \) thd. rub./kW. from the estimated thermal power \( Q_{TH,0}, \) kW

Equation (4) adequately characterizes price distribution to 5\% accuracy (statistical convergence criteria: Fisher's calculation criterion for adequacy variance is 0.0022 at table value \( F_{\text{ad}} = 3.84 \) 0.95 per cent).

The cost factor for the installation of the heating system \( K_{\text{安装}} \) proportional to the power of the heat pump, being for air-water systems ranging from 1.8 to 1.3 and slightly decreases with growth \( Q_{TH,0} \). This dependency can be imagined as an equation (6):

\[ K_{\text{安装}} = 1.826 - 0.0087 \times Q_{TH,0}. \]  
(6)

The amount of heat energy pumped by the heat pump (MW)hour depends on its power \( Q_{TH,0} \), duration \( \tau_{TH} \), temperature of the heated environment \( t_w \) and outdoor air \( t_n \):

\[ W_{TH} = \sum (Q_{TH,0} \times k_n \times \Delta t_i), \]  
(7)

where is \( k_n \) - temperature factor taking into account the change in the heat
performance of the pump from the temperature $t_w \text{ и } t_n$;

$\Delta t$, - period during which the temperature of the outside air
 corresponds to a certain value, an hour.

The temperature of the heated environment is determined by the type of
heating system. For a water system with compact heating devices (radiator
s or convector) it is accepted at the level of 55 degrees Celsius, for heating
systems of the type "warm floor" - 35 degrees Celsius [6].

The heat conversion rate by the pump and the electricity consumed
depend on the design features and the type of refrigerant and is the working
characteristic of the pump. For pumps with inverter compressors, this
characteristic is graphically presented in Figure.2 [7].

These characteristics are universal and express a change in the parameter
relative to the estimated power of the heat pump. To solve the problem, it is
convenient to present them in the form of dependencies:

$$k_n = \frac{Q_n}{Q_{TH,0}} = \exp(0,0333 \times t_u - 0,0062 \times t_w - 0,1289)$$  \hspace{1cm} (8)

- for $t_w = 55^\circ $C: \hspace{1cm} $N_{TH,n} = \frac{N_n}{N_{TH,0}} = 0,899 + 0,0125 \times t_u$

\hspace{1cm} a) \hspace{6cm} b)

\hspace{1cm} Picture 2. Changing temperature $k_n$ (a) and the electricity
consumed $N_{TH,n}$ b) from working temperatures

- for $t_w = 35^\circ $C: \hspace{1cm} $N_{TH,n} = \frac{N_n}{N_{TH,0}} = 0,585 + 0,0036 \times t_u$  \hspace{1cm} (9)

where is $Q_n$ - current heat pump power at appropriate temperature values,
W;

$N_n$ - current electricity pump power consumption at appropriate
temperature values, kW;

The distribution of periods of standing of outdoor air temperatures is given in [8] for the characteristic points of climatic zones. Figure 3 shows graphs of the distribution of temperature standing periods for geographic points "moderate" (Moscow) and "moderately cold" (Ulan-Ude) climate in the working ranges of heat pump temperature (from 8 degrees Celsius to -25 degrees Celsius).

**Picture 3.** The duration of the temperature of the outdoor air

Installation power of heat pump compressors $N_{TH,0}$ proportional to nominal thermal power (Figure 4) and this dependence can be represented by formula (10).

$$N_{TH,0} = 0.0277 + 0.257*Q_{TP,0} - 0.00015*Q_{TH,0}^2.$$  (10)

Electricity tariff $c_{3t,r}$ not constant and increases in time. To take this factor into account, we will use the expression [9]:
Picture 4. Compliance with the installation electrical and thermal capacity of the pumps.

\[ c_{33,t} = c_{33,0} \times (1 + \bar{c}_w)^{(\tau - 1)} \]

where is \( c_{33,t} \) the current cost of electricity, rub/kW*h;
\( c_{33,0} \) - the cost of electricity at the time of the project, rub/kW*h;
\( \bar{c}_w \) - tariff increase in shares from the previous year;
\( \tau \) - period from the implementation of the project to the calculation of the calculations, the year. In this case, it is accepted equal \( T \).

Thus, equations (2-13) form a system that fully describes the specifics of the production of thermal energy by the pump in the conditions of changing economic and technical parameters.

4. Debate

The steady trend of rising energy tariffs contributes to the search for technical solutions that provide cheaper energy with ways of heating independent from network companies. On rice. 5 the results of the analysis of the impact of individual characteristics of the system on the cost of thermal energy produced by heat pumps (with a minimum price level) calculated on the proposed model (2-13) (at the level of electricity tariff of 1.1 rubles/kWh for Ulan-Ude and 5.47 rubles/kWh for Moscow and 2 percent annual increase in the cost of electricity). To estimate this indicator, the graphs show a line reflecting the tariff on thermal energy in the central heating systems as of 2019 for the relevant item.

The cost of obtaining air-water pumps depends significantly on its estimated capacity and the duration of operation of the equipment before it is replaced or overhauled. The high proportion of one-time costs in the cost of a system with a relatively small capacity (up to 15 kW) means that the cost of heat produced does not become less than the district tariff, even during the long period of operation of the system in temperate-cold climate. And only due to the high level of heat prices in the temperate climate, the cost of production of low-potential heat (\( t_w = 35^\circ C \)) the pump begins to compete with the traditional method at the (7-8-year)-year period of operation and further becoming a cost-effective and therefore more attractive way for the
consumer. The use of more powerful heat pumps (30-60 kW) looks quite optimistic.

Here, the share of capital expenditures in these drastically reduced, which affects the cost of the final product - $C_{np,Q}$. The cost of thermal energy generation becomes less costly after the (6-7) years of operation of the equipment, even at a relatively low tariff (moderately cold area) and almost

**Picture 5.** Change in the cost of thermal energy generated by heat pumps for the conditions of Ulan-Ude a) and Moscow b).
immediately (3-4) years) for items with high prices for Energy. At the same time, it should be kept in mind that the life of such equipment (similar to household refrigerators) can be 20-25 years and, accordingly, you can eventually get thermal energy at a price almost 2 times lower than the current tariff. Therefore, it makes sense to focus on the use of one more powerful heat pump for more objects than to supply each object with a low-power machine.

Of course, it should be borne in mind that these conclusions follow from the analysis of graphs (Figure 5) oriented to the minimum level of prices ($P = -1$ in the equation (6)). And as a rule, cheap equipment is less durable than expensive. Therefore, the cost and timing of achieving competitive-capable costs will be different. But using the proposed dependency can easily identify these metrics for a specific facility and operating conditions.

5. Conclusion
Analyzing the resulting expressions (2-13) to determine the cost of thermal energy production, it can be noted that the proposed methodology takes into account as fully as possible factors that contribute to obtaining objective baseline information for evaluation efficiency of air-to-water heat pumps for heat heating facilities. At the same time, the proposed approach applies to any thermal consumption capacity facility located in any climate zone. The proposed method, although it has an "estimated" purpose, allows you to predict the possible effects of the use of heat pumps and choose a satisfying way to provide the object with thermal energy.

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