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The Problem of the Energy Efficiency and Renewability in Applying Heat Pumps, Referring to the European Union Directive

1. Introduction

In nature there is an unlimited amount of heat energy accumulated. In many cases this energy cannot be directly used in houses or industry due to the low temperature character of the source. The exploitation of this energy is possible if heat pumps are applied. Heating with this method makes a perspective of relatively inexpensive and environmentally friendly heating, which prompts to higher investment costs compared to other installations.

Starting the economic assessment of the heat pump one should bear in mind that electric energy applied for the pumps is the most expensive, because it is the most refined energy.

The profitability depends on mean energy efficiency of the exploitation of the equipment for the whole year.

Investment costs are differentiated and depend on the kind of the applied renewable heat source (air, water, ground and wastewater) and the way of making it available. Compared to conventional installations using coal dust, coal, oil or gas, these costs are higher, but exploitation costs are usually lower.

The heat pump is a device which is quite environmentally friendly. During its work it does not require connection with a chimney or ventilation ducts. Heat pumps are more and more used in everyday life, but it is still the matter of controversy if their effect allows them to be counted among renewable energy. This results from the fact that a significant part of the obtained heat arises as a result of the applied electric energy, which is obtained by burning a certain amount of conventional sources (in Poland mainly coal).

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2. Energy Efficiency of Heat Pumps According to the EU Directive

Implementing the thermodynamic Linde's circulation, the heat pump takes electric energy from the network to compress of the working factor which was earlier transformed into a gas phase, taking energy from the renewable source (ground, water, air). Energy provided from the renewable source (a so-called low--temperature source) is usually much higher than the consumed electric energy, thus the pump produces about 3.5 times more energy than took from the power network. The coefficient of performance (COP) for pump as the ratio of the produced heat energy (Q_{usable}) to electric driving energy (L) s not however a constant parameter and its mean annual value changes depending on the conditions of exploitation and the kind of the applied renewable energy source, usually ranging from 2.5 to 4.0.

Taking into account the efficiency of converting the chemical energy of coal into electric energy, which in Poland is about 0.33 – it should be three times more primary energy (chemical energy of coal) to produce electric driving energy taken by the pump.

Thus if we consider in the energy calculations of the electric energy producer, and the coefficient of efficiency of the pump will be COP < 3.0 – energy efficiency of the pump becomes problematic; the amount of the used primary energy gets close to value of energy obtained from the pump. That means that burning the coal alone we would obtain similar value of heat energy.

Thus the discussed directive in the context of qualifying energy from heat pumps among the renewable energy states: "Only heat pumps with an output that significantly exceeds the primary energy needed to drive it should be taken into account".

It is not a precise definition, because it only means that COP should be bigger than 3.0. These results from a simple scheme of energy flow in the pump, as follows:

$$3L \rightarrow L \rightarrow \mathrm{COP} \rightarrow Q_{usable} = \mathrm{COP} \cdot L \tag{1}$$

where:

- L – driving energy provided from the energy network,
- $3L$ – primary energy (chemical e.g. coal) requires to make driving energy L (in Polish conditions at the efficiency of conversion 0.33),
- COP – coefficient of performance for the heat pump (in the directive marked as SPF), treated as seasonal – mean annual coefficient, depending on climatic conditions (higher values are obtained in warm regions, because of the lower requirements for heating temperature,
- $Q_{usable} = \mathrm{COP} \cdot L$ – energy obtained from the heat pump.

In Polish situation the postulated in the directive condition of the efficiency the work of the pumps would mean:

$$3L < Q_{usable} = \mathrm{COP} \cdot L, \text{ from taht } \mathrm{COP} > 3 \quad (2)$$

At such COP the pump produces more energy than consumes in the form of primary energy (here: chemical energy of coal).

In the subsequent note the condition appears that not all the energy efficient pumps will be taken into account while calculations of the amount of the produced renewable energy, but only those fulfilling the condition:

$$\mathrm{COP} > 1.15 \cdot 1/\eta \quad (3)$$

where η – the efficiency of the conversion of primary energy into electric energy in a given country (in Poland 0.33, but e.g. in Germany, where the wind energy is developed – 0.37).

This means that only the pumps of COP > 3.45 should be in Poland treated as belonging to the resources of renewable energy. This automatically eliminates the pumps of air-water type (COP: 2.5–2.7). This situation will change with the assumed growth of the value η by gradual introduction of renewable energy sources.

Re-writing the above condition in the form: COP > 1.15 · 3, and multiplying the inequality by L we obtain:

$$L \cdot \mathrm{COP} > 1.15 \cdot 3L \quad (4)$$

Thus:

$$Q_{usable} > 1.15 \cdot 3L.$$

This means that the effect of the work of compression heat pumps will be counted as the management of renewable energy only if energy obtained from the pumps (Q_{usable}) is at least 15% higher than the used primary energy ($3L$).

Thus it should be emphasized that the mentioned directive in the present shape does not include the issues referring to absorption heat pumps, which use the heat energy of gas. If one accepts the criteria of efficiency and renewability presented in the directive for compression heat pumps, these pumps would be treated as producing renewable energy if COP > 1.27 (taking the efficiency of gas-fired boiler of about 0.9 and the mentioned above 15 per cent surplus obtained heat energy over the chemical energy of gas). The low value of COP results from thermodynamic characteristic of absorption pump, but high coefficient of the conversion of the chemical energy of gas into heat energy (in expression (3) $\eta = 0.9$ should be taken as efficiency of the gas-fired boiler) allows getting a positive energy effect.

The value of the produced renewable energy in heat pumps Q_{odn} (in directive marked as E_{RES}), required for the summary assessment of the produced energy from renewable sources can by calculated according to the formula contained in the directive and resulting from:

$$Q_{odn} = Q_{usable} - L = Q_{usable} - Q_{usable} / \text{COP} = Q_{usable}\,(1 - 1/\text{COP}) \tag{5}$$

where:

- $Q_{usable} = Q_{odn} + L$ – the value of produced heat energy (according to the carried out measurements),
- COP – mean annual (seasonal – SPF) coefficient of performance (estimated for a given climatic zone, character of the low-temperature source and applications as well as the construction of the heat pump).

3. Alternative Approach: the Assessment of the Efficiency and the Degree of Energy Renewability for Heat Pumps

Taking 15% surplus of energy obtained compared to the primary energy as the condition to qualify heat pumps as the instruments of high energy efficiency and using renewable energy is an arbitrary procedure with no physical justification.

In energy analyses, to assess the energy efficiency of heat pumps, more rational approach is applied. It is assumed that the work of pumps is energy efficient when the collected primary energy is smaller than in the accepted, comparative heating system at the production of the same amount of energy [2]. Due to similar costs of exploitation and the level of emission, as a comparative system and at the same time alternative system for heat pumps, usually heating system based on natural gas is accepted. Then the comparison is not between primary energy and the obtained energy, but between the primary energy used in both comparable systems at the production of the same energy value [4].

For example, if the heat pump produces heat energy of the value $L \cdot \text{COP}$ using primary energy of the value $3L$, in the gas system with a standard boiler of efficiency 0.87, the required amount of primary energy (e.g. chemical energy of gas) will be $(L \cdot \text{COP})/0.87$.

Thus, assuming that the heat pump shows energy effect if:

$$(L \cdot \text{COP})/0.87 > 3L \tag{6}$$

we obtain the following condition of efficiency in case of gas heating:

$$\text{COP} > 2.6.$$

This is the lower value than accepted in directive, but the above condition refers to relative energy efficiency of pumps compared to the gas system of a defined energy efficiency.

Defined in such a way energy effect, if other efficiencies of comparative boilers are assumed, will be obtained for other values of COP (e.g. for condensing boilers of efficiency 1.0, it would be required that COP > 3.0).

As far as the theses of the directive mention the conditions of qualifying heat pumps as "producers" of renewable energy – they do not refer to the important parameter of the work of heat pumps, such as the degree of energy renewability. The assessment of the degree of energy renewability for compression heat pumps can be obtained by determining the percentage of the contribution of renewable energy in the relation to the total energy taken from the natural environment (e.g. total chemical energy of coal and geothermal energy).

For example, in Poland at the efficiency of the conversion of primary energy into electric energy 0.33 – the degree of energy renewability can be defined as:

$$\Lambda = [Q_{odn} \,/\, (Q_{odn} + 3L)] \cdot 100\% \tag{7}$$

After simple transformations, considering that:

$$Q_{odn} = Q_{usable} - L = \text{COP} \cdot L - L,$$

we obtain:

$$\Lambda = [(\text{COP} - 1)\ /\text{COP} + 2)] \cdot 100\% \tag{8}$$

Thus the degree of energy renewability for heat pumps will only depend on the mean annual value of COP. For example, for COP = 4.0 value Λ = 50% which means that the contribution of renewable and conventional energy is the same, and above the value of COP = 4.0, the participation of renewable energy will be higher than the used conventional primary energy.

4. The Influence of the Compression of Heat Pumps on the Emission of Substances to the Air

From the point of view of a local user, heat pumps are emission-free, but in the scale of the country the situation is different.

This is because using heat pumps is connected with the application of electric driving energy, which in Poland is mainly produced from coal.

Comparing the energy production from a heat pump of the value COP · *L* to a standard coal boiler of efficiency 0.8 – to obtain the same amount of energy, it would be necessary to apply coal fuel of the energy value COP · *L* / 0.8. The emission of pollutants to the air from the heat pump will be smaller than from the coal boiler when the pump uses less chemical energy of coal than the coal boiler, thus if the following condition is fulfilled:

$$3\mathrm{L} < \mathrm{COP} \cdot L/0.8$$

i.e.:

$$\mathrm{COP} > 2.4 \tag{9}$$

Actually, the boilers of the electric power station show higher emission of pollutants to the air (e.g. about 13% in case of CO_2) than home boilers at burning the same amount of primary fuel. Thus the value of COP under condition (9) should be higher (above 2.7 in the aspect of CO_2 emission).

For smaller COP value (e.g. pumps of air-water type) compression pumps emit more pollutants than coal boilers.

Comparing the emission of pollutants to the air from heat pumps to the emission from gas-fired boilers one should look at the value of emission for a specific kind of pollution.

For example, in the aspect of CO_2 emission, it is accepted that at producing the unit of heat in standard gas-fired boilers, the emission of CO_2 is about 0.6 emission from coal boilers [3]. According chapter 3, if to produce a definite value of energy, the heat pump uses primary energy of the value 3*L* (chemical energy of coal), then the standard gas boiler uses energy (*L* · COP)/0.87 (chemical energy of gas). Assuming that the emission of CO_2 by the gas-fired boiler is 0.6 of the from coal combustion, the heat pump will emit smaller amount of CO_2 if the following condition is fulfilled:

$$3L \,/\, [0.6\ (L \cdot \mathrm{COP})/0.87] < 1 \tag{10}$$

i.e.:

$$COP > 4.35.$$

Obtaining a such mean annual value of COP in Polish climatic conditions is difficult, thus despite the fact that in the scale of a local user, the heat pump seems to be emission-free, looking at the scale of the whole country, natural gas is usually cleaner source.

5. The Economics of the Application of Heat Pumps

Looking at this question – only the assessment of exploitation costs of heat pumps was taken into account, neglecting investment costs – always higher compared to conventional heating systems. The costs of the exploitation of heat pumps are always higher than the costs of exploitation in systems based on coal and coal dust, and at the same time, much lower than in systems using heating oil or electric energy.

Only the costs of systems based on natural gas show comparable values, thus analyzing economic profitability of using heat pumps e.g. by an individual user, as an alternative system, usually gas system is accepted.

Heat pumps, producing energy of the value $Q_{usable} = COP \cdot L$ take energy from the energy supply network, the value of which is L. Producing the same value of energy in the gas-fired boiler of the efficiency η^g, requires the use of chemical energy of gas of the value $(COP \cdot L) / \eta^g$. Marking the price of electric energy as K^e and the price of energy from gas as $K^{g,}$ the cost of produced energy in the heat pump is: $L \cdot K^e$, while in gas installation $(COP \cdot L) \cdot K^g / \eta^g$.

Thus the heat pump is more economical than gas heating when:

$$L \cdot K^e / (COP \cdot L \cdot K^g / \eta^g) < 1 \qquad (11)$$

i.e. when:

$$COP > (K^e/K^g)\ \eta^g \qquad (12)$$

Condition (12) implies that the profitability of applying heat pumps, compared to gas not only affects the value of COP, but also the relation between the price of electric and "gas" energy and the efficiency of the gas-fired boiler. For example, nowadays (according to 2010 data) the prices of electric and "gas" energy in Poland are about K^e = 0.55 PLN/KWh and K^g = 0.2 PLN/KWh and for the efficiency gas-fired boiler η^g =0.87, the heat pump will be more economical than gas heating if COP > 2.4.

For example, for COP = 3.0, after substituting the value on the left side of the expression (11) we will conclude that the exploitation costs of heat pumps will make about 80% of the costs of gas heating.

In case of the access to two-schedule calculation of electric energy (night and day schedule), the economic efficiency of heat pumps grows significantly (decrease of K^e), making the costs close to the costs of coal heating.

6. Conclusions

The discussed EU directive, despite the fact that its details require improvements, for the first time introduced the legal requirement for the devices using heat pumps to be energetically efficient. Also the criterion that, if fulfilled, the effect of the action of compression heat pumps allows counting this to renewable energy resources that can be taken into account at the assessment of the participation of renewable energy in the total production of gross energy.

Also the issues of renewability, emission and economics of the work of heat pumps are discussed. They have an orientation character, because they do not take into account many factors connected with the work of real heating systems based on heat pumps (factors like the uptake of electric energy by circulation pumps and control-measurement instruments or changeable prices of electric energy and gas, depending on the parameters of the customer).

A general conclusion resulting from the presented speculations is that aspects referring to renewability, emission as well as economics of the application of heat pumps are strictly connected with high mean annual value of the COP (SPF) and national coefficient of the efficiency of primary energy conversion η, according to the formula (3).

Heat pumps, during the heating season, show different values of COP, depending on the weather conditions. The highest values occur in spring and autumn, the lowest in winter. This results from thermodynamic characteristic of heat pumps showing that the COP value grows with lowering the temperature at output from a pump and reaches high values at higher temperatures of the low--temperature source (e.g. in case of thermal waters). As far as the temperature of the low-temperature source is for a given installation usually established, lowering output temperatures from the pump significantly increases the value of COP. Low temperature heating requires, however, the application of good insulation in the heated objects, or floor heating and/or wall heating, where for heating temperatures about 35°C are sufficient.

Despite the fact that the advantages resulting from the application of heat pumps depends on many factors, and usually on high the value COP (SPF) and η, their basic advantages compared to a standard reference, i.e. gas are the following: safe exploitation (lack of local emission and blast threat), independence from the prices and supply of gas (only electric energy is required), low costs of exploitation (in particular at two-schedule system), and first of all they make a heating alternative in the areas where there is no gas network.

References

[1] *Dyrektywa Parlamentu Europejskiego i Rady 2009/28/WE z dnia 23 kwietnia 2009 r. w sprawie promowania energii ze źródeł odnawialnych zmieniająca i w następstwie uchylająca dyrektywy 2001/77/WE oraz 2003/30/WE*.

[2] Kubski P.: *Uwarunkowania efektywności energetycznej stosowania pomp grzejnych zawarte w dyrektywie w sprawie promocji odnawialnych źródeł energii*. II Ogólnopolski Kongres Geotermalny, Bukowina Tatrzańska 23–25 września 2009.

[3] Pająk L.: *Wybrane zagadnienia dotyczące pozyskania ciepła z pierwotnych nośników biomasy*. Ciepłownictwo, Ogrzewnictwo, Wentylacja, nr 3, 2007, pp. 28–31.

[4] *Rozporządzenie Ministra Infrastruktury z dnia 6 listopada 2008 r. w sprawie metodologii obliczania charakterystyki energetycznej budynku i lokalu mieszkalnego lub części budynku stanowiącej samodzielną całość techniczno-użytkową oraz sposobu sporządzania i wzorów świadectw ich charakterystyki energetycznej*. Dz. U. z 2008 r. Nr 201, poz. 1240.