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Simplified procedure for evaluating energy performance of heat pumps. Energy and economic analysis

Procedura simplificată de evaluare a performanței energetice a pompelor de căldură. Analiza energetica si economica

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Abstract: The use of heat pumps to solve energy issues in the field of thermal utilities in buildings is increasingly recommended and necessary.

Key-words: heat pump, correlation, energy issue

1. Introduction

The use of heat pumps to solve energy issues in the field of thermal utilities in buildings (space heating, preparation of hot water for consumption) is increasingly recommended in the current context in which we talk about nZEB buildings. In this sense, it was an important issue to choose the appropriate capacity of the heat pump in relation to the capacity of the customer served. In this sense, it was considered a space heating type consumer and an air-water type heat pump through which the consumer heating installation was supplied. The correlation between the energy capacities of the consumer and the heat pump is a rather complex problem that involves a number of operating parameters such as the size of the heating system, the temperature range for the heating period and others. In this paper we intend to present mainly the analysis procedure that leads to the identification of the optimal ratio between the energy capacities of the consumer and the heat pump.

2. Description of a new procedure, simplification of the evaluation of the energy performance of the heat pump serving a consumer

The procedure is based on the correlation that exists between the CARNOT refrigeration efficiency and the difference between the hot and cold medium temperatures to which thermal power is delivered and respectively from which thermal power is extracted.

$$\varepsilon_{VP}^{C} = \frac{T_{VP}}{T_{CD} - T_{VP}} = \frac{\theta_{VP} - \Delta t_{VP} + 273.15}{\theta_{CD} - \theta_{VP} + \Delta t_{CD} + \Delta t_{VP}} \qquad (1)$$

A graphical representation of the CARNOT refrigeration efficiency according to relation (1) can be found in fig.1 which follows:

For values of the average temperature differences at the evaporator and condenser of the heat pump of approx. 5 oC a fairly good correlation is obtained between the efficiency of εCVP and the temperature difference Δθ = θCD - θCD as can be seen from fig. 2.

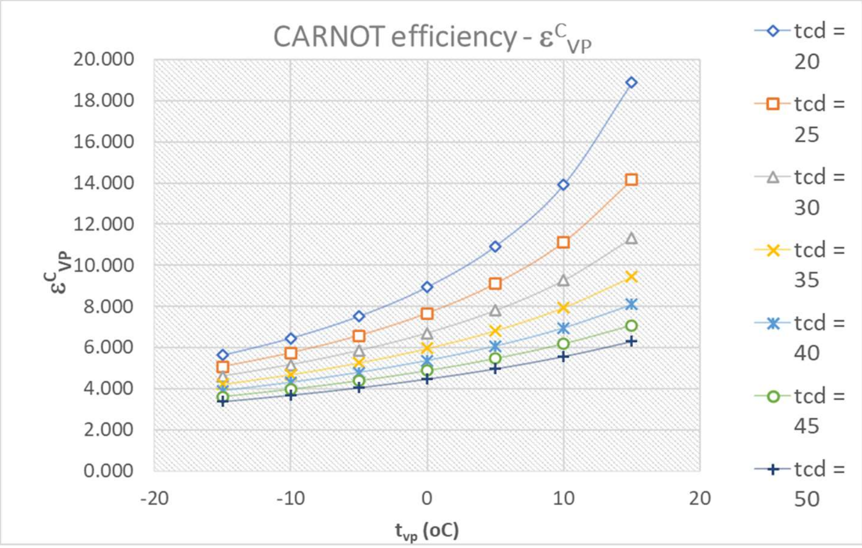

Fig.1

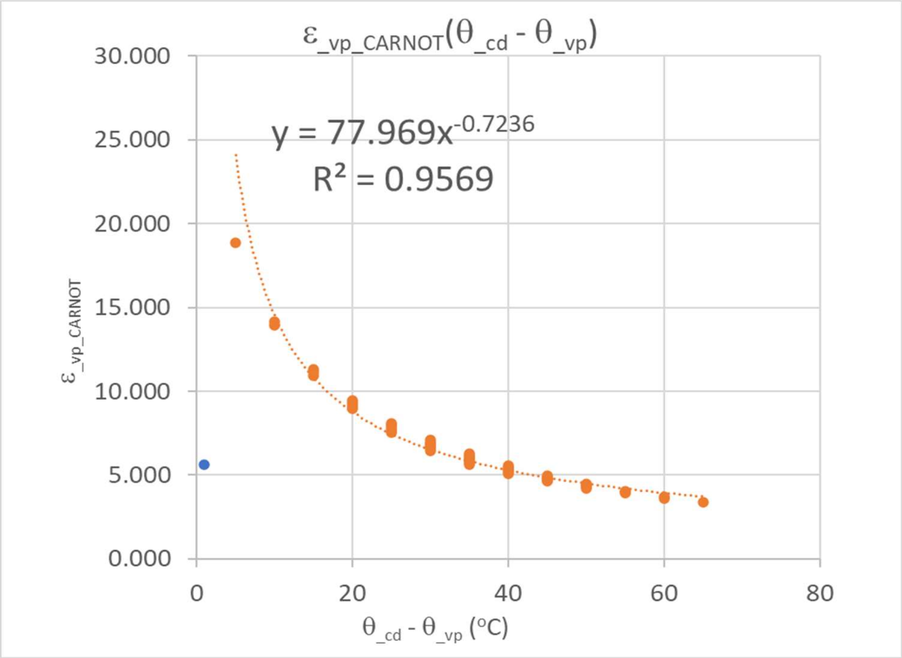

Fig. 2

Which means:

$$\varepsilon_{VP}^{C} = 77.969 \cdot \Delta\theta^{-0.7236} = \frac{77.969}{\Delta\theta^{0.7236}} \tag{2}$$

Considering the correlation between isentropic refrigeration efficiency and CARNOT refrigeration efficiency highlighted in several previous works [1], [2], [3].

$$\begin{aligned} \varepsilon_{VP}^{IZ} &= M \cdot \varepsilon_{VP}^{C} - N = 0.958 \cdot \varepsilon_{VP}^{C} - 1.5321 \\ \varepsilon_{VP}^{IZ} &= 0.958 \cdot \frac{77.969}{\Delta\theta^{0.7236}} - 1.5321 \end{aligned} \tag{3}$$

The result is the coefficient of performance of the heat pump, COP expression:

$$\begin{aligned} COP &= \left(1 + \varepsilon_{VP\_iz}^{*} \cdot \eta_{iz}\right) \cdot \eta_{EL} \\ COP &= \left[1 + \left(0.958 \cdot \frac{77.969}{\Delta\theta^{0.7235}} - 1.5321\right) \cdot \eta_{iz}\right] \cdot \eta_{EL} \end{aligned} \tag{4}$$

The effective evaluation of the COP presupposes the knowledge or the prior determination of the isentropic, η_{iz} and electrical η_{EL} yields.

On the other hand, in terms of electric power, we have the expression:

$$P_{EL} = \frac{P_{CD}}{COP} \tag{5}$$

If the heat pump is chosen so that Pcd = Pnec, and:

$$\begin{aligned} P_{nec} &= H \cdot \left(t_{i0} - t_{e}\right) \\ P_{CD} &= H \cdot \left(t_{i0} - t_{e}\right) \end{aligned} \tag{6}$$

On the other hand, according to the working procedure presented in detail in [4], the temperatures of the cold and hot media are established according to:

$$\begin{aligned} \theta_{VP} &= t_e \\ \theta_{CD} &= \frac{t_{m0} - t_{e0}}{t_{i0} - t_{e0}} \cdot t_{i0} - \frac{t_{m0} - t_{i0}}{t_{i0} - t_{e0}} \cdot t_e \\ t_{m0} &= \frac{1}{2} \cdot \left(t_{T0} + t_{R0}\right) \end{aligned} \tag{7}$$

Relation (7_2) considers the qualitative thermal regulation which presupposes adequate values of the temperatures of the thermal agent in the central heating installation of the consumer with external temperature.,

With notation:

$$a = \frac{t_{m0} - t_{i0}}{t_{i0} - t_{e0}} \tag{8}$$

Equations (7) are redraw as:

$$\begin{aligned}&\theta_{VP}=t_e\\&\theta_{CD}=(1+a)\cdot t_{i0}-a\cdot t_e\\&\Delta\theta=\theta_{CD}-\theta_{VP}=(1+a)\cdot(t_{i0}-t_e)\end{aligned}\tag{9}$$

Thus, there are relations between the electric power and the thermal power emitted at the capacitor:

$$\begin{aligned}&P_{EL}=\frac{P_{CD}}{COP}=\frac{P_{CD}}{\left[1+\left(0.958\cdot\frac{77.969}{\Delta\theta^{0.7236}}-1.5321\right)\cdot\eta_{iz}\right]\cdot\eta_{EL}}\\&P_{CD}=P_{EL}\cdot COP=\left[1+\left(0.958\cdot\frac{77.969}{\Delta\theta^{0.7236}}-1.5321\right)\cdot\eta_{iz}\right]\cdot\eta_{EL}\cdot P_{EL}\\&\Delta\theta=(1+a)\cdot(t_{i0}-t_e)\end{aligned}\tag{10}$$

If we consider the dependence of the thermal power necessary for the consumer and of the thermal power delivered by the condenser of the heat pump depending on the external temperature presented in the relations (11):

$$\begin{aligned}&P_{nec}=H\cdot(t_{i0}-t_e)\\&P_{CD}=P_{EL}\cdot COP=\left[1+\left(0.958\cdot\frac{77.969}{\Delta\theta^{0.7236}}-1.5321\right)\cdot\eta_{iz}\right]\cdot\eta_{EL}\cdot P_{EL}\\&\Delta\theta=(1+a)\cdot(t_{i0}-t_e)\end{aligned}\tag{11}$$

These can be represented graphically as seen in fig. 3.

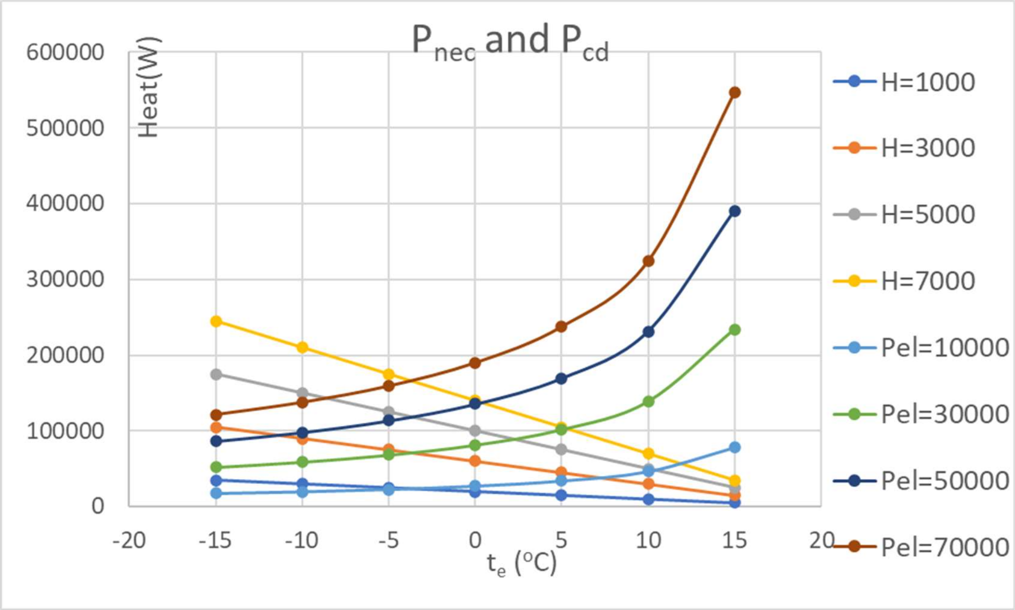

Fig. 3

Both from relations (11) and from fig.3 it is observed that each of the 2 families of curves depends on a parameter, Thus the necessary thermal power of the consumer depends on the thermal capacity of the heated building, H, and the thermal power delivered by the condenser heat pump depends on the electrical supply power of the heat pump compressor. In fig. 2 it is observed how the 2 families of curves intersect in points characterized on the abscissa of external equilibrium temperature. We consider that there is an optimal association between the curves of the 2 families. Each line in the required power beam $P_{nec} = P_{nec}(t_e, H)$ has its optimal pair curve in the $P_{cd} = P_{cd}(t_e, Pel)$ beam. This curve, the optimal pair, will result from an energetic and economic analysis.

For this analysis, a value was chosen for the heat transfer capacity of the consumer, H = 5000 W / K, which corresponds approximately to a 10-storey household. Next, we looked for in the bundle of power curves delivered by the heat pump those curves that intersect the line corresponding to the consumer power for H = 5000 W / K at the points of external equilibrium temperature, t_{eE} = -15, -10, -5, 0 , +5 and +10℃. In addition, it will be considered that these values of external temperature are representative (averages) on domains of 5℃ and on the whole cold period of the year they have durations as it results from tabel 1.

Tabel 1

t_{eE} (oC)	Δte (oC)	Nz (zile)
-15	-17.5 …-12.5	2
-10	-12.5 …-7.5	11
-5	-7.5 …-2.5	32
0	-2.5 …+2.5	60
5	+2.5 …+7.5	53
10	+7.5 …+12.5	24

What needs to be done is to find the electrical power parameter from the corresponding expression of the thermal power delivered by the heat pump in case its vapor becomes equal to the required thermal power of the consumer for the external equilibrium temperatures t_{eE} = -15, -10, -5, 0, +5 and +10 oC. Solving is simple using relationships (11). The values presented in table 2 are obtained.

Tabel 2

t_{eE} (oC)	Pcd (W)	Pel (W)
-15	175000	97763.49
-10	150000	74065.66
-5	125000	53430.48
0	100000	35906.64
5	75000	21573.15
10	50000	10568.14

Fig. 4 shows an example variant for an intersection between the 2 types of curves mentioned. The intersection point indicates the equality between the necessary power of the consumer and the thermal power delivered by the heat pump, having the abscissa teE. The 3 zones are distinguished: Z1, Z2 and Z3. Zone Z1 corresponds to the thermal power delivered to the power plant consumer, zone Z2 corresponds to the thermal power delivered by the heat pump and zone Z3 corresponds to the thermal power delivered by the heat pump in the conditions of decreasing the electric power used by the car compressor. As can be seen, the mentioned areas are areas of thermal power whose values depend on the outside temperature. Thus for te <teE the heat pump will work with the electric power corresponding to the temperature teE and with a COP corresponding to the respective outdoor temperature, te, and for te> teE the heat pump will work with Pcd = Pnec and with a COP corresponding to the respective outdoor temperature, te. Fig. 5 also shows a qualitative diagram of the thermal and electrical powers in case the equilibrium outdoor temperature is teE = -5 oC. It is observed that in the area of outside temperatures, te, lower than the outside equilibrium temperature, teE, the electric power will be kept constant at the maximum value.

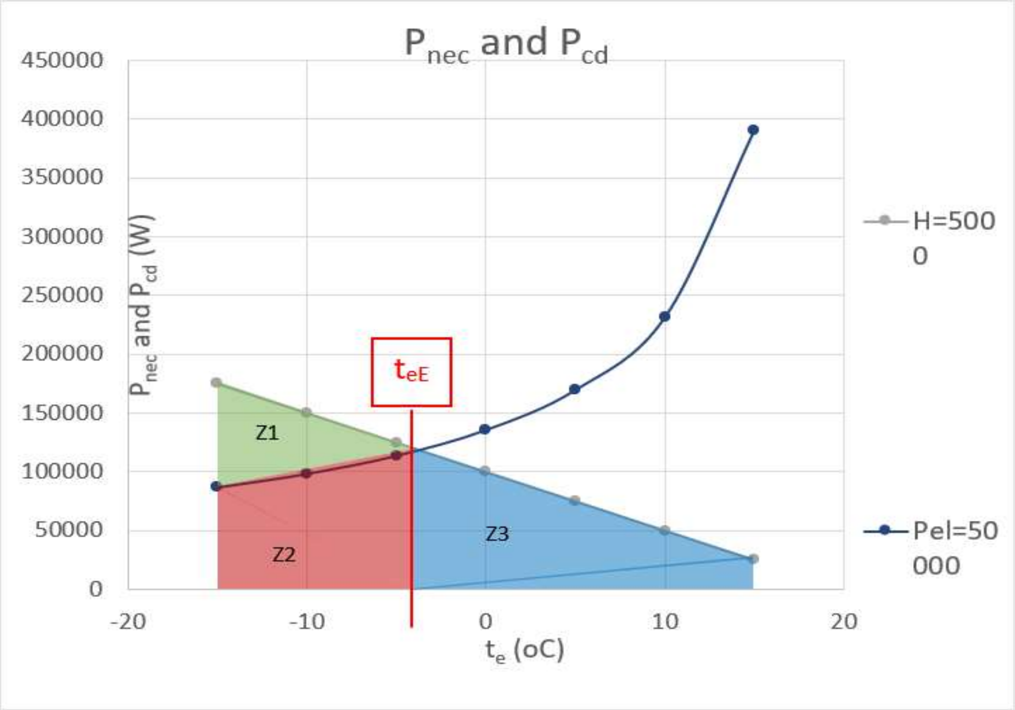

Fig.4

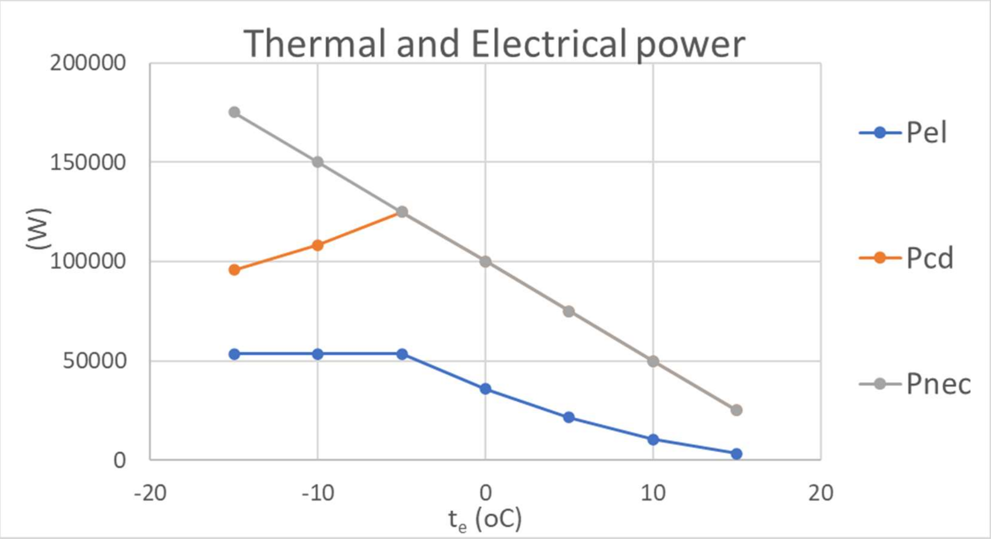

Fig.5

3. Energy considerations

We have a more concrete image in fig.6 which corresponds to a temperature $t_{eE} = 0$ ℃. An image like the one in fig.6 is the one presented in fig.7 which now refers to the thermal energies corresponding to these areas. There is a decrease in the share of energy supplied by the boiler while the share of heat supplied by the heat pump has increased. This is due to the frequency of outdoor temperatures that are higher in the range te = -5… 0 ℃ than in the range t_e = -15… -10 ℃. Figures 8 and 9 show the diagrams of the electric and thermal powers at the vaporizer and respectively the diagrams of the electrical and thermal energies at the vaporizer.

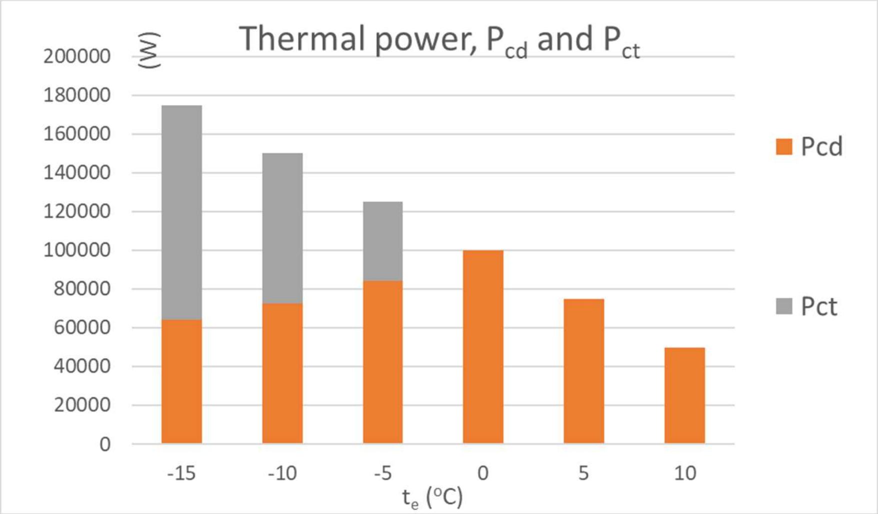

Fig.6

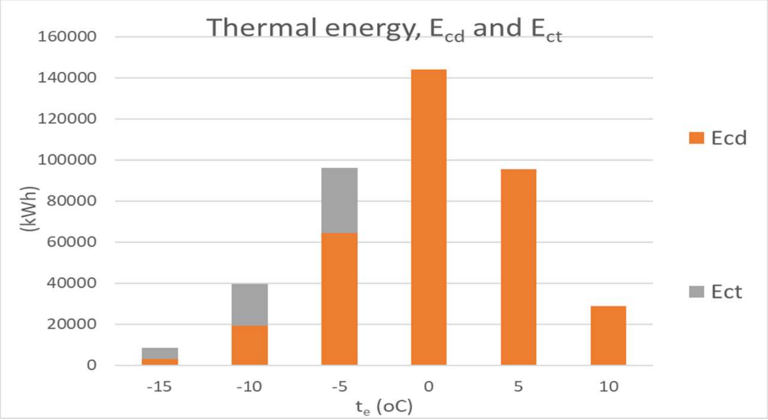

Fig.7

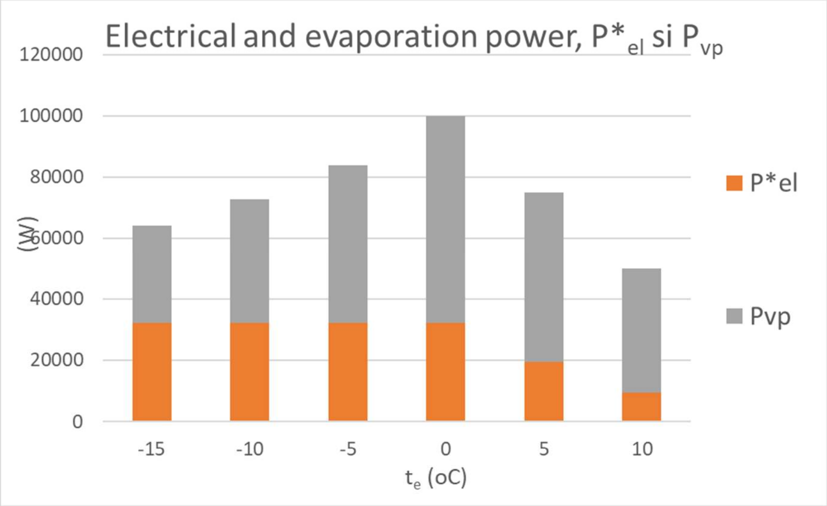

Fig.8

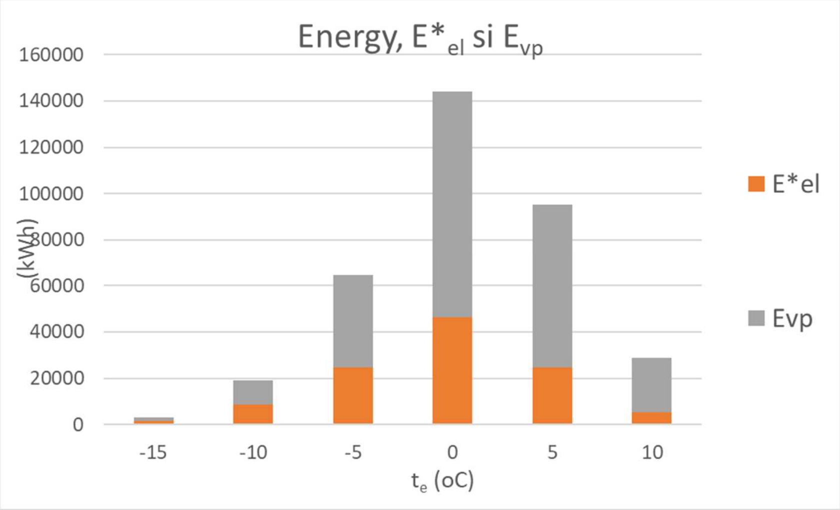

Fig.9

This was done for all variants of sizing the heat pump and finally resulted in the following general situation regarding energy consumption:

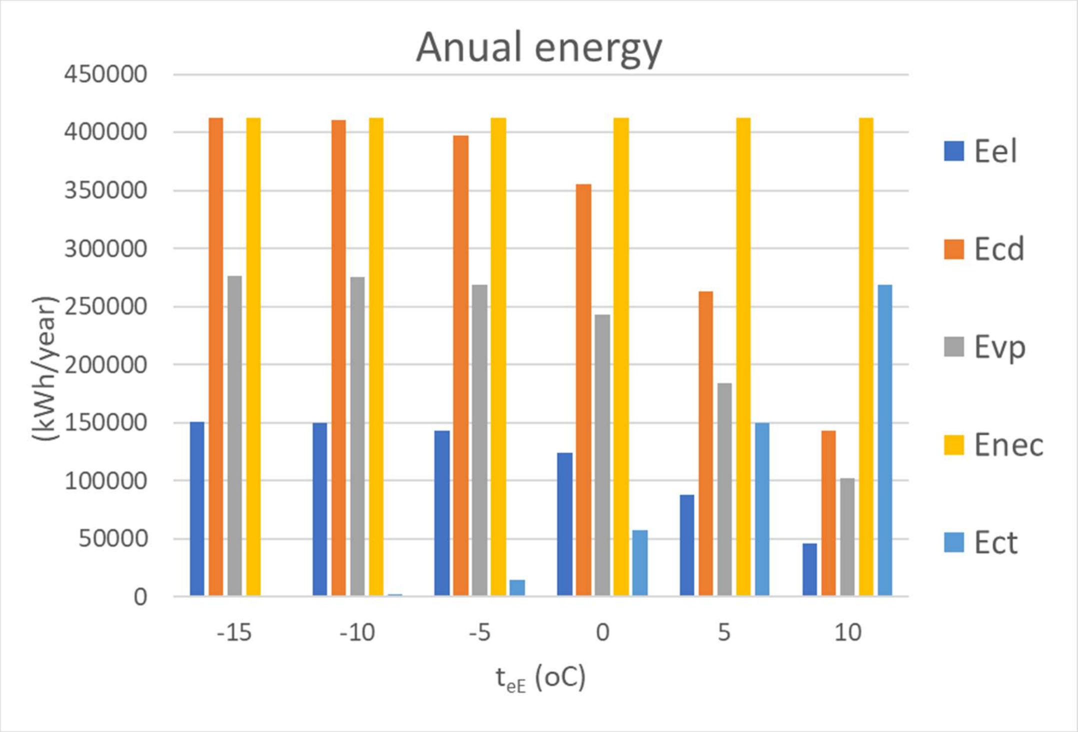

Fig.10

Fig. 10 shows all the categories of energy absorbed and consumed by the source-consumer system. We consider the bar corresponding to the energy absorbed from the environment (renewable) to be acceptable for an external equilibrium temperature, t_{eE}, in the range t_{eE} = -5… 0 °C. Which means an H / Pel ratio = 0.14 and 0.23.

4. Economic considerations

For the economic evaluation was used Fig.11 which is practically identical to fig.5 in which, however, a series of notations of the important points were made. Thus, the AHCJ trapezoid contains the subsequent thermal diagram necessary for the consumer during the winter. The curvilinear polygon DBCJH contains the diagram of the thermal powers delivered by the heat pump to the consumer, and the curvilinear polygon EFGJH contains the diagram of the electrical powers used by the heat pump. The curvilinear triangle ABD contains the diagram of the thermal powers delivered by the thermal power plant to the consumer. The right segment BI represents the maximum thermal power delivered by the heat pump, and the segments EH and FI represent the maximum electrical power used by the heat pump. The right segment AD represents the maximum power of the thermal power plant. For any equilibrium outside temperature, t_{eE}, results the maximum electric power used by the heat pump and the diagrams of the thermal powers delivered by the heat pump and by the thermal power plant and the diagram of the electric power used by the heat pump. These diagrams correspond to homologous diagrams by evaluating the associated energies obtained by multiplying the values of the powers with their duration in hours. The costs associated with these thermal and electrical energies are obtained by multiplying the values of the specific costs (lei / kWh_{th} or lei / kWh_{el}).

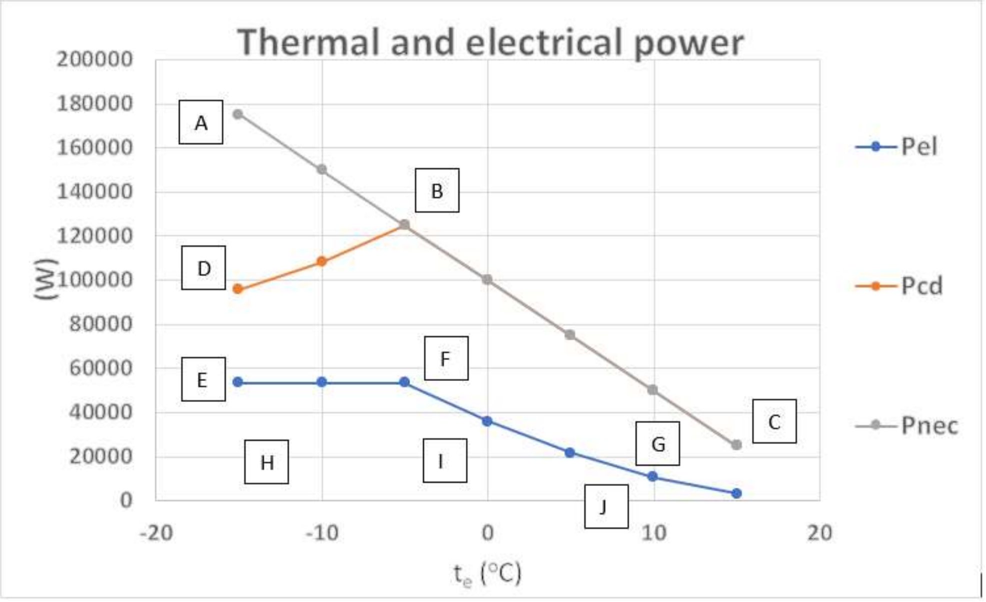

Fig.11

Regarding the investment costs for the heat pump, specific costs were used (lei / Wth or lei / Wel). Thus, for the investment costs, the relations result:

$$\begin{aligned} CI\_CT &= cth\_CT \cdot csi\_CT \\ CI\_PC &= cth\_PC \cdot csi\_PC \end{aligned} \tag{12}$$

And for exploitation costs :

$$\begin{aligned} CE\_CT &= cse\_th \cdot N\_an \cdot \sum_{BIN(-15)}^{BIN(+10)} 24 \cdot Nz_{BIN} \cdot pth\_CT_{BIN} \\ CE\_PC &= cse\_el \cdot N\_an \cdot \sum_{BIN(-15)}^{BIN(+10)} 24 \cdot Nz_{BIN} \cdot pel\_PC_{BIN} \end{aligned} \tag{13}$$

For investment and exploitation costs:

$$CI\_total = CI\_CT + CI\_PC$$

$$\begin{aligned}CE\_total &= CE\_CT + CE\_PC = \\ &= cse\_th \cdot N\_an \cdot \sum_{BIN(-15)}^{BIN(+10)} 24 \cdot Nz_{BIN} \cdot pth\_CT_{BIN} + \\ &+ cse\_el \cdot N\_an \cdot \sum_{BIN(-15)}^{BIN(+10)} 24 \cdot Nz_{BIN} \cdot pel\_PC_{BIN}\end{aligned} \tag{14}$$

And global cost :

$$\begin{aligned}C\_total &= CI\_total + CE\_total = CI\_total + \\ &+ cse\_th \cdot N\_an \cdot \sum_{BIN(-15)}^{BIN(+10)} 24 \cdot Nz_{BIN} \cdot pth\_CT_{BIN} + \\ &+ cse\_el \cdot N\_an \cdot \sum_{BIN(-15)}^{BIN(+10)} 24 \cdot Nz_{BIN} \cdot pel\_PC_{BIN} \\ C\_total &= CI\_total + CE\_total = CI\_total + \\ &+ N\_an \cdot \begin{pmatrix} cse\_th \cdot \sum_{BIN(-15)}^{BIN(+10)} 24 \cdot Nz_{BIN} \cdot pth\_CT_{BIN} + \\ + cse\_el \cdot \sum_{BIN(-15)}^{BIN(+10)} 24 \cdot Nz_{BIN} \cdot pel\_PC_{BIN} \end{pmatrix}\end{aligned} \tag{15}$$

From relation (15) it is observed that the graph of the total cost is composed of 2 right segments: a vertical segment at $\tau = 0$ (initial investment) and further a rising line depending on τ (exploitation). And this for each of the variants $t_{eE} = -15, -10, -5, 0, +5, +10$ °C. The amounts in the relations (13)… (15) have as units of measurement (kWh / year).

The clear data on which the costs involved over time for various variants of the configuration of the source system were:

Investment specific cost:

Tabel 3

Source type	Specific Cost	(RON/kW)
Heat Pump	csi_PC	1000.0
Centrala Termica	csi_CT	100

Exploitation specific cost :

Tabel 4

Energy type	Specific cost	Var.1 (RON/kWh)	Var.2 (RON/kWh)
Electrical energy	cse_el	0.75	1,401
Thermal energy	csi_th	0.31	0.61

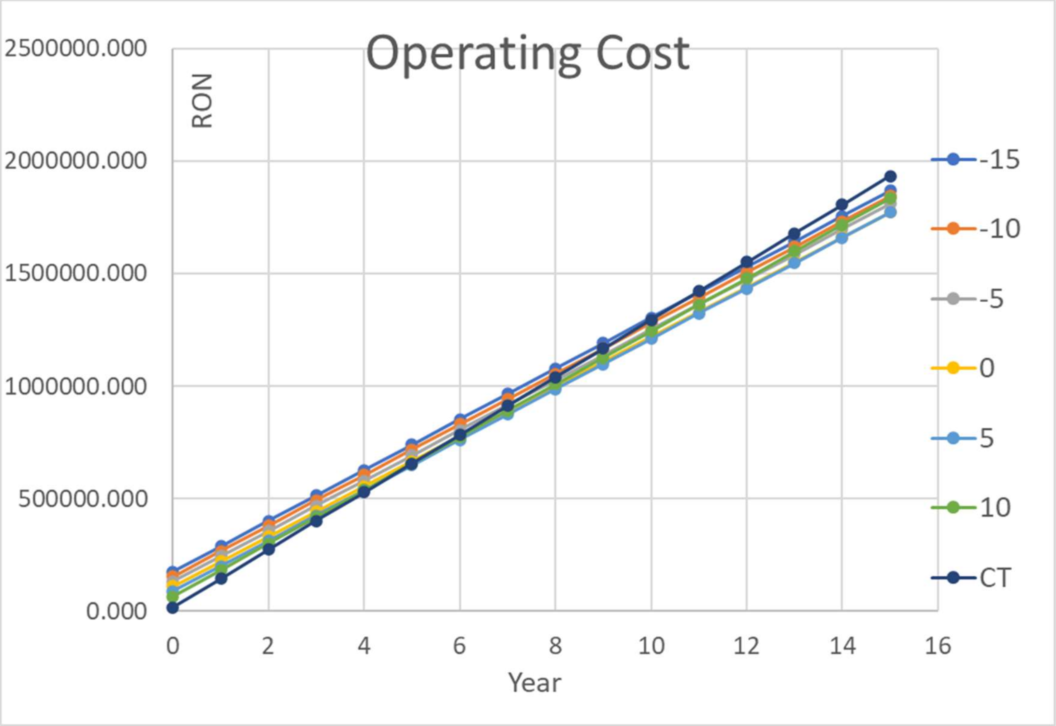

Fig.12

An analysis made on the data presented in fig.12 shows that the recovery times of the investment made for the implementation of a heat pump for serving the space heating consumer depends on the size of the heat pump and therefore on the degree of coverage offered by it. Thus, the results presented in fig.13 were obtained:

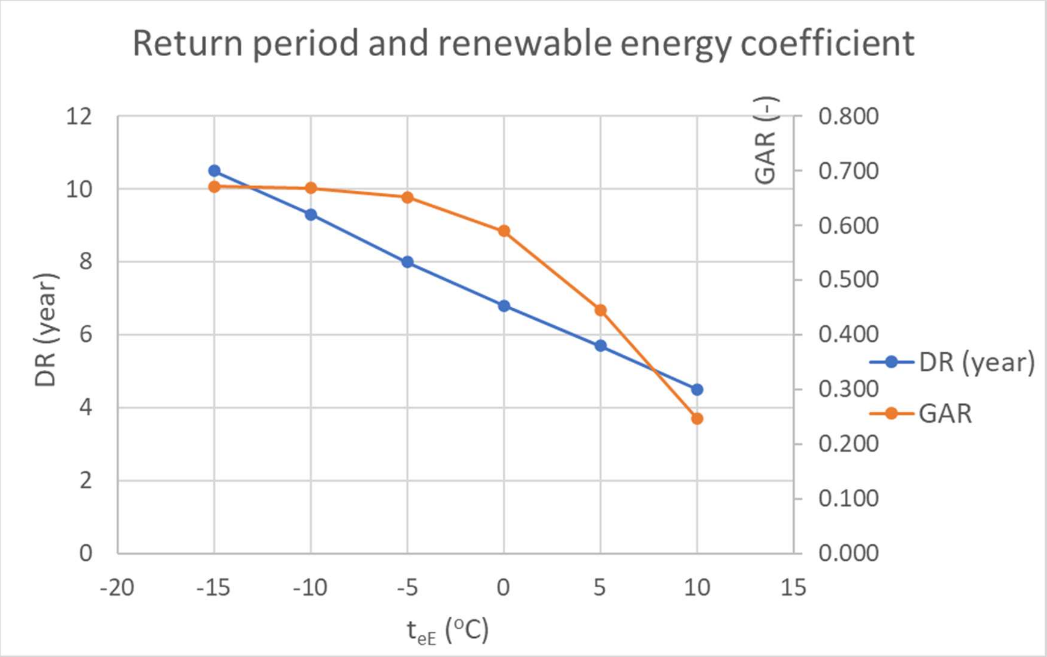

Fig.13

As we believe it to be, a lower equilibrium outside temperature, teE, means a higher heat pump. According to the results presented in fig. 13 we opt for a choice of heat pump so that it allows a coverage of energy consumption of approx. 60% - 65% of the maximum possible of approx. 70%. This results in a recovery of the investment of cc, 7-8 years.

5. Conclusions

The simplified procedure presented in this paper is based on the detailed procedure presented in previous papers [1]… [4], the novelty aspect being the dependence of the COP of the heat pump on the difference between the temperatures of hot and cold environments. θ_{CD} and θ_{VP}. The simplification consists in giving up the iterative process of determining the COP for the situations in which the result is a slight underestimation of the value of the COP. The relation (2) that expresses the dependence of the Carnot refrigeration efficiency on the temperature difference $\Delta\theta$, we can say that it is specific to the case in which the consumer is a central heating installation, in another situation, for example the preparation of hot water. more appropriate correlation. 15 The use of heat pump for space heating leads to the conclusion that the choice the capacity of the heat pump compared to the capacity of the consumer heating system must be made so that the equilibrium outside temperature, teE, is situated in the range te = [-5… 0) ºC, which corresponds to values of the H / Pel ratio = 0.14… 0.23, which means that the heat pump must cover the heat demand of to the consumer at an outside temperature in the range te = (-5… 0) ºC. This is is mainly due to the fact that the frequency of outdoor temperatures is most according to the outside temperature te> -5 ºC. In other words, the optimal ratio between the capacity of the heat pump and the capacity of the heating system should be included in the range 0.57 and 0.71.

ANEXA

We consider it useful to present in this ANNEX the simple procedure by which the isentropic yield can be determined, ηIZ, when a series of information regarding the catalog values for COP0, θVP0, θCD0, PCD0, ηEL is available. This simple procedure was also presented in [4].

- Establishes the catalog power that can be absorbed from the grid:

$$P_{EL0} = \frac{P_{CD0}}{COP_0} \tag{A.1}$$

Catalog CARNOT refrigeration efficiency is established, εCVP0 and catalog isentropic refrigeration efficiency:

$$\varepsilon_{VP0}^{C} = \frac{\theta_{VP0} - \Delta t_{VP} + 273.15}{\theta_{CD0} - \theta_{VP0} + \Delta t_{CD} + \Delta t_{VP}}$$

$$\varepsilon_{VP0}^{IZ} = M \cdot \varepsilon_{VP0}^{C} - N \tag{A.2}$$

1. Establish the isentropic efficiency of the compressor:

$$\eta_{IZ} = \frac{COP_0 - \eta_{EL}}{\varepsilon_{VP0}^{IZ} \cdot \eta_{EL}} \tag{A.3}$$

Nomenclature:

t_{i0} – interior design temperature, ºC;
t_{e0} – exterior design temperature, ºC;
t_{T0} – design turn thermal agent temperature, ºC;
t_{R0} – design return thermal agent temperature, ºC;
t_{m0} – design average temperature, ºC;
t_e – external temperature, ºC;
t_{eE} – equilibrium external temperature, ºC;
T_{VP} – absolute vaporization temperature, K;
T_{CD} – absolute condensing temperature, K;
Δt_{VP} – vaporization temperature difference, ºC;
Δt_{CD} – condensing temperature difference, ºC;

θ_{VP} – cold environment temperature, °C;
θ_{VP0} – design cold environment temperature, °C;
θ_{CD} – hot environment temperature, °C;
θ_{CD0} – design hot environment temperature, °C;
P_{VP} – vaporization heat, W;
P_{CD} – condensing heat, W;
P_{CD0} – design condensing heat, W;
P_{nec} – heat demand, W;
P_{EL} – electrical power of compressor motor, W;
P_{EL0} – maximum electrical power of compressor motor, W;
P_{CT} –boiler power, W;
E_{VP} – evaporation energy, kWh;
E_{CD} – condensing energy, kWh;
E_{EL} – electrical energy absorbed, kWh;
E_{nec} – demand thermal energy, kWh;
E_{CT} – thermal energy from boiler, kWh;
H – building global thermal coefficient, W/K;
ε^{C}_{VP} – heat pump Carnot efficiency, -;
ε^{C}_{VP0} – design heat pump Carnot efficiency, -;
ε^{IZ}_{VP} – vaporization isentropic efficiency, -;
ε^{IZ}_{VP0} – design vaporization isentropic efficiency, -;
COP – coefficient of performance, -;
COP_0 – design coefficient of performance, -;
η_{iz} – isentropic compressor efficiency, -;
η_{EL} – compressor motor electrical efficiency, -;
M = 0.958, N = 1.5321 – isentropic efficiency regression coefficients, -
csi_CT – specific investment cost, boiler, lei/kW;
csi_PC – specific investment cost, heat-pump, lei/kW;
cse_th – thermal energy specific cost, lei/kWh;
cse_el – electrical energy specific cost, lei/kWh;
cth_CT – boiler thermal capacity, kW;
cth_PC – heat pump thermal capacity, kW;
pel_PC – heat pump absorbed electrical energy, kW;
pth_CT – delivered boiler heat, kW;
Nz_{BIN} – BIN days, day;
N_an – operating years of hybrid system, year;
CI_CT – investment cost for boiler, RON;
CI_PC – heat pump investment cost, RON;
CE_CT – yearly operating cost for boiler, RON;
CE_PC – yearly operating cost for heat pump, RON;

CI_total – total investment cost, RON;
CE_total – total operating cost, RON;
C_total – total cost, RON;

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