Energy-economical efficiency of building heating/cooling by heat pump systems

Ioan Sarbu and Emilian Stefan Valea

Abstract—In the actual economic and energy juncture, the reduction of thermal energy consumption in buildings became a major, necessary and opportune problem, general significance. The heat pumps are alternative heating systems more energy efficiency and unless pollutant if we make a comparison with classic plants (liquid or gas fuel thermal boiler). This paper presents the energy and economical efficiency criteria which show the opportunity to implement a heat pump in a heating/cooling system. It is developed a computational model of annual energy consumption for an air-to-water heat pump based on the degree–day method and the bin method implemented in a computer program. Also, from a case study is performed a comparative economical analysis of heating solutions for a building and are presented the energy and economic advantages of building heating solution with a water-to-water heat pump.

Keywords— Building heating/cooling, Heat pumps, Performances, Annual energy consumption, Energy–economical analysis.

I. Introduction

BUILDING are an important part of European culture and heritage, and they play an important role in the energy policy of Europe. Studies have shown that saving energy is the most cost effective method to reduce green house gas emissions (GHG). It has also pointed out that buildings represent the biggest and most cost effective potential for energy savings. The reduction of 26% energy use is set as a goal for buildings by the year 2020 which corresponds to 11% of the reduction of total energy use in European Union (EU) countries.

The buildings sector is the largest user of energy and CO_2 emitter in the EU, and is responsible for more than 40% of the EU's total final energy use and CO_2 emissions. At present heat use is responsible for almost 80% of the energy demand in houses and utility buildings for space heating and hot water generation, whereas the energy demand for cooling is growing year after year. There are more than 150 millions dwellings in Europe. Around 30% are built before 1940, around 45% between 1950 and 1980 and only 25% after 1980. Retrofitting is a means of rectifying existing building deficiencies by improving the standard and the thermal insulation of buildings and/or the replacement of old space conditioning systems by energy-efficient and environmen-tally sound heating and cooling systems.

In order to realize the ambitious goals for the reduction of fossil primary energy consumption and the related CO_2 emissions to reach the targets of the Kyoto-protocol besides improved energy efficiency the use of renewable energy in the existing building stock have to be addressed in the near future.

On 17 December 2008, the European Parliament adopted the Renewable Energy Directive. It is establishes a common framework for the promotion of energy from renewable sources. For the first time, this Directive recognizes aero-thermal, geothermal and hydrothermal energy as renewable energy source. This directive opens up a major opportunity for further use of heat pumps for heating and cooling of new and existing buildings.

Heat pumps enabling the use of ambient heat at a useful temperature level need electricity or other auxiliary energy to function. Therefore, the energy used to drive heat pumps should be deducted from the total usable heat. Aerothermal, geothermal and hydrothermal heat energy captured by heat pumps shall be taken into account for the purposes provided that the final energy output significantly exceeds the primary energy input.

The amount of ambient energy captured by heat pumps to be considered renewable energy E_{res}, shall be calculated in accordance with the following formula [14]:

$$E_{res} = E_U\left(1-\frac{1}{\mathrm{SPF}}\right) \tag{1}$$

where: E_U is the estimated total usable thermal energy delivered by heat pumps; SPF – the estimated average seasonal performance factor for these heat pumps.

Only heat pumps for which SPF>1.15/η shall be taken into account, where η is the ratio between total gross production of electricity and the primary energy consumption for electricity production. For EU-countries Average η=0.4. Meaning that minimum value of seasonal coefficient of performance should be $\mathrm{SPF}=\mathrm{COP}_{seasonal}>2.875$.

Heat pump enables the use of ecological heat (solar energy accumulated in the soil, water and air) for an economic and ecological heating. For practical use of these energy sources we have to respect the following criteria: sufficient availability, higher accumulation capacity, higher temperature, sufficient regeneration, economical capture, reduced waiting time. In the development of modern constructions with improved thermal insulation and reduced heat demand use heat pumps are a good alternative.

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This paper presents the energy and economical efficiency criteria which show the opportunity to implement a heat pump in a heating/cooling system. It is developed a computational model of annual energy consumption for an air-to-water heat pump based on the degree-day method and the bin method and it is performed a comparative economical analysis of different heating solutions for a building.

II. Energy-Economical Calculation Elements

The performances of heat pump and building – heating/cooling installation system is determined based on economical and energy indicators of these systems. The opportunity to implement a heat pump in a heating/cooling system results on both energy criteria and the economic.

• *Economical indicators.* Usually the heat pump (HP) realizes a fuel economy ΔC (operating expenses) comparatively of the classical system with thermal station (TS), which is dependent on the type of heat pump. On the other hand, heat pumps involve an additional investment I_{HP} from the classical system I_{TS}, which produces the same amount of heat.

Thus, it can be determined *the recovery time TR*, in years, to increase investment, $\Delta I = I_{HP} - I_{TS}$, taking into account the operation economy realized through low fuel consumption $\Delta C = C_{TS} - C_{HP}$:

$$TR = \frac{\Delta I}{\Delta C} \le TR_n \tag{2}$$

where TR_n is normal recovery time.

It is estimated that for TR_n a number 8–10 years is acceptable, but this limit varies depending on the country's energy policy and environmental requirements.

Another economical indicator is total updated cost (TUC):

$$TUC = I_0 + \sum_{j=1}^{\tau} \frac{C}{(1+\beta_0)^j} \tag{3}$$

in which: I_0 is the initial investment cost, in the operation beginning date of the system; C – annual operating cost of the system; β_0 – the average rate of the inflation; τ – number of years for which is made update (20 years).

Could be rather easy demonstrated the equality:

$$\sum_{j=1}^{\tau} \frac{1}{(1+\beta_0)^j} = \frac{(1+\beta_0)^\tau - 1}{\beta_0 (1+\beta_0)^\tau} \tag{4}$$

and is defined update rate

$$r_a = \frac{(1+\beta_0)^\tau - 1}{\beta_0 (1+\beta_0)^\tau} \tag{5}$$

Taking into account (4) and (5) equation (3) gets the form:

$$TUC = I_0 + r_a C \tag{6}$$

• *Energetically indicators.* The operation of a heat pump is characterized by *the coefficient of performance* COP or *thermal efficiency* ε^{PC}, defined as the ratio between useful effect produced (useful thermal energy E_U) and energy consumed to obtain it (action energy E_A):

$$\mathrm{COP} = \varepsilon^{PC} = \frac{E_U}{E_A} \tag{7}$$

If both usable energy and consumed energy are summed during a season (year) is obtained by equation (7) seasonal (annual) coefficient of performance ($\mathrm{COP}_{seasonal}$), which is often expressed as SPF.

In the heating operate mode is defined COP by equation:

$$\mathrm{COP} = \varepsilon^{PC} = \frac{Q_{PC}}{P_A} \tag{8}$$

in which: Q_{PC} is the thermal power of heat pump, in W; P_A – the drive power of heat pump, in W.

If the reversible heat pump operate in cooling mode is defined *energy efficiency ratio* EER, in Btu/(h·W) by equation:

$$\mathrm{EER} = \frac{Q_0}{P_A} \tag{9}$$

in which: Q_0 is the cooling thermal power, in Btu/h; P_A – the drive power of heat pump, in W.

The coefficient of performance of heat pump in cooling state is obtained by equation:

$$\mathrm{COP} = \frac{\mathrm{EER}}{3.413} \tag{10}$$

in which 3.413 is the transformation factor from Watt to Btu/h.

From the energy balance of the heat pump:

$$E_U = E_S + E_A \tag{11}$$

can highlight the link between the efficiency of a plant working as a heat pump (ε^{PC}) and as refrigeration plant (ε^{IF}):

$$\varepsilon^{PC} = \frac{E_S + E_A}{E_A} = 1 + \frac{E_S}{E_A} = 1 + \varepsilon^{IF} \tag{12}$$

The most effective systems are those which use simultaneously the produced heat and the adjacent refrigeration effect, in which case the total efficiency is:

$$\varepsilon^{PC+IF} = \frac{E_U + E_S}{E_A} = \frac{E_S + E_A + E_S}{E_A} = \varepsilon^{PC} + \varepsilon^{IF} \tag{13}$$

If you take into account the Π_j energy losses that are accompanying both the accumulation and release heat from the real processes, the efficiency becomes real ε_r^{PC} and its expression is:

$$\varepsilon_r^{PC} = \frac{T_c}{T_c - T_o}(1 - \Sigma\Pi_j) \tag{14}$$

where T_c and T_o are the condensation and vaporization absolute temperatures of refrigerants.

In Figure 1 is represented the real efficiency variation of heat pumps according to the source temperature t_o and temperature t at the consumer.

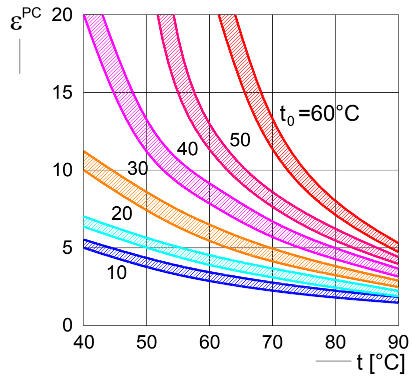

Fig. 1 Variation of heat pumps efficiency

To determine the real efficiency of the heat pump with electro-compressor we can use the relation bellow [10]:

$$\varepsilon_r^{PC} = \frac{T + \Delta t}{T + \Delta t - (T_o - \Delta t_o)} \eta_r \eta_i \eta_m \eta_{em} + \eta_m \eta_{em} (1 - \eta_i) \quad (15)$$

where:

$$\eta_r = 1.666 - 0.004(T_o - \Delta t_o) - 0.00625(T + \Delta t) \quad (16)$$

$$\eta_i = \left(0.425 + \frac{0.493 Q_{PC}}{1.16 Q_{PC} + 0.06}\right)\left(3.23 - 1.835 \frac{T + \Delta t}{T_o - \Delta t_o}\right) \quad (17)$$

$$\eta_m = 0.85 + \frac{0.158 Q_{PC}}{1.16 Q_{PC} + 0.1513 \frac{T + \Delta t}{(T + \Delta t) - (T_o - \Delta t_o)}} \quad (18)$$

$$\eta_{em} = 0.85 + \frac{0.139 Q_{PC}}{1.335 Q_{PC} + 0.0904 \frac{T + \Delta t}{(T + \Delta t) - (T_o - \Delta t_o)}} \quad (19)$$

in which: T, T_o are the hot and cold source absolute temperatures; Δt, Δt_o – temperature differences between condensation temperature and hot source temperature, respectively, between cold source temperature and vaporization temperature; η_r – efficiency of the real cycle toward a reference Carnot cycle; η_i, η_m – internal and mechanical efficiency of the compressor; η_{em} – electromotor efficiency; Q_{PC} – heat pump thermal power.

In case of a heat pump with electro-compressor is introduced the global efficiency η_g as a product between the electric energy production efficiency η_p, its transportation efficiency η_t and the electromotor efficiency η_{em}:

$$\eta_g = \eta_p \eta_t \eta_{em} \quad (20)$$

Taking into account that the heat pump has an over-unit theoretical efficiency, for the evaluation in which way is valued the consumed primary energy is using the synthetic indicator η_s, representing the product:

$$\eta_s = \eta_g \varepsilon^{PC} \quad (21)$$

which has to satisfy the condition $\eta_s > 1$ for justify the use of heat pump

Also, only if the real efficiency $\varepsilon_r^{PC} > 3$ the use of the heat pumps can be considered.

Another energy indicator for heat pumps is *the specific consumption of electricity* w^{PC}, in kW/GJ:

$$w^{PC} = \frac{10^3}{3.6 \varepsilon_r^{PC}} \quad (22)$$

In Figure 2 is illustrated the electricity consumption for heat pumps depending on the heat source temperature t_o and the consumer temperature t.

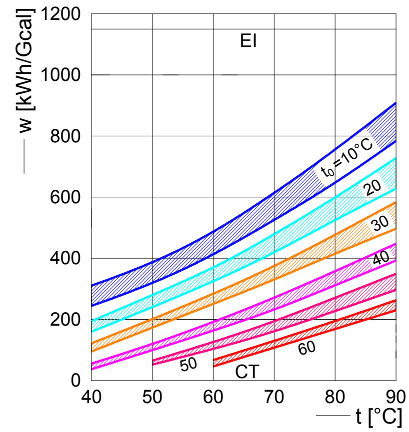

Fig. 2 Specific electricity consumption for the heat production

The sizing factor (SF = α^{PC} = Q_{PC}/Q_{max}) of the heat pump is defined as ratio of the heat pump capacity Q_{PC} to the maximum heating demand Q_{max} and can be optimized in terms of energy and economic, depending on the source temperature and the used adjustment schedule.

The energy indicators of heat pumps are determined as average values, taking into account the annual heat consumption variation.

In Figure 3 is represented variation of the average annual electric energy specific consumption, in function of α^{PC} and different graphics adjustments.

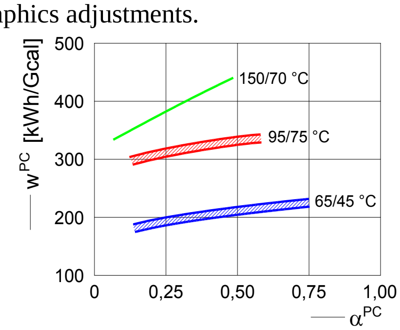

Fig. 3 Variation of the average annual electricity specific consumption

The annual fuel economy variation ΔB, obtained by using heat pump, expressed as percentage of total annual fuel consumption in a referential classic system is presented in Figure 4.

For absorption heat pump system, driven by thermal energy, it is agreed at European level to consider η = 1.0 and therefore SPF ≥ 1.15.

In order to properly compare the performances of various heat pumps types, have to uniform the action energy. In this sense, is reported the useful heat delivered annually $Q_{u,year}$ at annual equivalent fuel consumption $B_{fe,year}$, necessary for driving power production, achieving the degree of fuel use φ_{year}, in kW/kg:

$$\varphi_{year} = \frac{Q_{u,\,year}}{B_{fe,\,year}} \qquad (23)$$

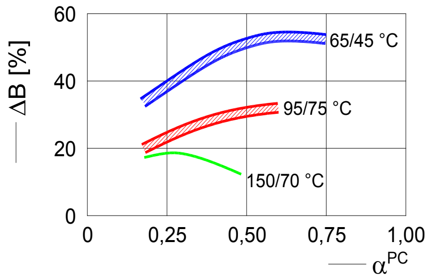

Fig. 4 Variation of annual fuel economy

The fuel economy depends by heat pump type, according to Table 1.

Reduction of GHG emissions, key to limiting global warming is associated with the replacement of classical solutions for heating/cooling with heat pumps, especially ground-source heat pumps (GSHP). But must be taken into account also items related to electricity production, mainly used to drive them.

Nowadays it is not recommended to replace a heating gas boiler with electrically operated heat pump if electricity is produced using coal or based on old technologies, because resulting carbon dioxide emissions may increase with 1–2 tons/year.

Table 1. Energy analysis of heat generation

No	Plant type	Degree of fuel use φ_{year} [kW/kg]	Primary energy E_p [%]	Fuel economy ΔC [%]
0	1	2	3	4
1	Gas boiler	0.800	125.00	0
2	Heat pump with electro-compressor	1.083	92.34	–32.66
3	Heat pump with electro-compressor and thermal boiler	0.969	103.20	–21.80
4	Heat pump with thermal motor compressor	1.416	70.62	–54.38
5	Absorption heat pump	1.219	82.03	–42.97
6	Ejection heat pump	0.970	103.09	–21.91

III. Energy Consumption Computation of an Air-to-Water Heat Pump

Annual energy consumption of heating/cooling system for a building contributes to minimizing the life cost of the building. This consumption is obtained by time integration of instantaneous consumption during the cold season, warm season respectively. Instantaneous consumption depends on the efficiency of the HVAC system.

For computation of the annual energy consumption of a heating/cooling system can be used the degree-day method or bin method.

- *Degree-day method***.** The degree-day method and its generalizations can provide a simple estimate of annual loads, which can be accurate if the indoor temperature and internal gains are relatively constant and if the heating or cooling systems operate for a complete season.

The balance point temperature t_{ech} of a building is defined as that value of the outdoor temperature t_e at which, for the specified value of the interior temperature t_i, the total heat loss is equal to the heat gain Q_{ap} from sun, occupants, lights, and so fort:

$$Q_{ap} = U\left(t_i - t_{ech}\right) \qquad (24)$$

in which U is the heat transfer coefficient of the building, in W/K.

Heating is needed only when t_e drops below t_{ech}. The rate of energy consumption of the heating system is:

$$Q_{inc} = \frac{U}{\eta}\left[t_{ech} - t_e(\tau)\right]_{t_e < t_{ech}} \qquad (25)$$

in which: η is the efficiency of the heating system; τ – time.

If η, t_{ech}, and U are constant, the annual heating consumption can be written as an integral:

$$E_{inc} = \frac{U}{\eta}\int\left[t_{ech} - t_e(\tau)\right]_+ \mathrm{d}t \qquad (26)$$

where the plus sign (+) above the bracket indicates that only positive values are counted.

This integral of the temperature difference conveniently summarizes the effect of outdoor temperature on a building. In practice, it is approximated by summing averages over short time intervals (daily) and the result N_{inc}, in (K·days) is called degree-days:

$$N_{inc} = (1\,day)\sum_{days}\left(t_{ech} - t_e\right) \qquad (27)$$

Here the summation is to extend over the entire year or over the heating season. The balance point temperature t_{ech} is also known as the base of the degree-days. In terms of degree-days, the annual heating consumption is:

$$E_{inc} = \frac{U}{\eta}N_{inc} \qquad (28)$$

Cooling degree-days can be calculated using an equation analogous to equation (27) for heating degree-days as:

$$N_{rac} = (1\,day)\sum_{days}\left(t_e - t_{ech}\right) \tag{29}$$

Since the balance point temperature varies widely from one building to another because of widely differing personal preferences for thermostat settings and setbacks and because of different building characteristics is used the variable-base model. The basic idea is to assume a typical probability distribution of temperature data, characterized by its average $\bar{t}_{ej}$ and by its standard deviation σ. Erbs *et al.* [6] developed a model that needs as input only the average $\bar{t}_{ej}$ for each month of the year. The standard deviations σ_j, in ^oC, for each month are then estimated from the correlation:

$$\sigma_j = 1{,}45 - 0{,}029\bar{t}_{ej} + 0{,}0664\sigma_{an} \tag{30}$$

where:

$$\sigma_{an} = \sqrt{\frac{1}{12}\sum_{j=1}^{12}\left(\bar{t}_{ej} - \bar{t}_{e,an}\right)^2} \tag{31}$$

in which: σ_{an} is the standard deviation of the monthly temperature about the annual average $\bar{t}_{e,an}$.

The monthly heating degree-days $N_{inc,j}$ for any location are well approximated by [2]:

$$N_{inc,j} = \sigma_j\, n^{1.5}\left[\frac{\theta_j}{2} + \frac{\ln\left(e^{-a\theta_j} + e^{a\theta_j}\right)}{2a}\right] \tag{32}$$

where:

$$\theta_j = \frac{t_{ech} - \bar{t}_{ej}}{\sigma_j\sqrt{n}} \tag{33}$$

in which: θ_j is a normalized temperature variable; n – number of days in the month; a = 1.698.

The annual heating degree-days can be estimated with relation:

$$N_{inc} = \sum_{j=1}^{12} N_{inc,j} \tag{34}$$

The computer program GRAZIL has been elaborated based on variable-base model, in EES for PC microsystems.

• *Bin method***.** For many applications, the degree-day method should not be used, even with the variable-base method, because the heat loss coefficient, the efficiency of the HVAC system, or the balance point temperature many not be sufficiently constant. Heat pump efficiency, for example, varies strongly with outdoor temperature t_e; efficiency of HVAC equipment may be affected indirectly by t_e when efficiency varies with load (common for boilers and chillers). Furthermore, in most commercial buildings, occupancy has a pronounced pattern, which affects heat gain, indoor temperature, and ventilation rate.

In such cases, steady-state calculation can yield good results for annual energy consumption if different tempe-rature intervals and time periods are evaluated separately. This approach is known as the *bin method* because consumption is calculated for several values of the outdoor temperature t_e and multiplied by the number of hours N_{bin} in the temperature interval (bin) centered on that temperature:

$$Q_{bin} = N_{bin}\frac{U}{1000\,\eta}\left(t_{ech} - t_e\right)_+ \tag{35}$$

in which: Q_{bin} is the energy consumption, in kW, for each temperature interval; N_{bin} – number of yearly hours in the temperature interval (bin) centered around outdoor temperature; U – heat transfer coefficient of building, in W/K; t_{ech} – balance point temperature, in ^oC; t_e – outdoor temperature, in ^oC; η – efficiency of the HVAC system.

The superscript plus sign indicates that only positive values are counted; no heating is needed when t_e is above t_{ech} ($t_e > t_{ech}$). Equation (35) is evaluated for each bin, and the total energy requirement E_{bin}, in kWh, is the sum of the Q_{bin} over all bins.

This method is defined in European Standard EN 15316-4.2 [17].

Knowing the thermal power Q_{PC} and power drive P_A of the heat pump for each bin temperature interval, can determinate the following:

– heat loss (heat demand) of the building Q_{nec}, in kW:

$$Q_{nec} = \frac{U}{1000}\left(t_{ech} - t_e\right) \tag{36}$$

– heat pump efficiency, ε^{PC}:

$$\varepsilon^{PC} = \frac{Q_{PC}}{P_A} \tag{37}$$

– heat pump operation coefficient, f:

$$f = \min\left(1, \frac{Q_{nec}}{Q_{PC}}\right) \tag{38}$$

– thermal energy provided by heat pump E_{PC}, in kWh:

$$E_{PC} = f\,Q_{PC}\,N_{bin} \tag{39}$$

– electric energy to drive heat pump E_A, in kWh:

$$E_A = f\,P_A N_{bin} \tag{40}$$

energy requirement E_{bin}, in kWh, is obtained by summing the values Q_{bin} given by (35).

– energy delivered by auxiliary source E_{aux}, in kWh:

$$E_{aux} = E_{bin} - E_{PC} \tag{41}$$

– total energy consumed by the heat pump and auxiliary source E_t, in kWh:

$$E_t = E_A + E_{aux} \tag{42}$$

The computer program METBIN has been elaborated based on this computational model, in EXCEL for PC compatible microsystems.

• *Numerical application***.** For a building heated by a heat pump are known: heat transfer coefficient U = 850 W/K and balance temperature t_{ech} = 17.8 ^oC, and is determined energy consumption during heating period using METBIN program. The results are summarized in Table 2. In Figure 5 is shown the variation of heat loss and thermal power of the heat pump depending on the outdoor temperature.

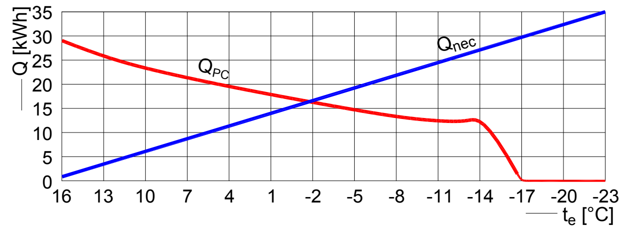

Fig. 5 Variation of heat requirement and HP thermal power with outdoor temperature

IV. Better Energy Efficiency with Combined Heating and Cooling by Heat Pumps

The possibilities of heat pump solutions in combined cooling and heating systems have been unclear for a major part of the designers of the air-conditioning systems. The-refore, a survey was made to find out a proper dimensioning and disseminate the know-how. More general study was made find out the influence of different factors.

Table 2. Results provided of computer program METBIN

Temp. (bin) t_e [°C]	t_{ech}-t_e [°C]	Hours N_{bin} [h]	Q_{nec} [kW]	Q_{PC} [kW]	P_A [kW]	ε^{PC}	Coef. f	E_{PC} [kWh]	E_A [kWh]	E_{bin} kWh]	E_{aux} kWh]	E_t [kWh]
0	1	2	3	4	5	6	7	8	9	10	11	12
16	1.8	904	1.53	28.9	7.11	4.06	0.05	1383.12	340.3	1383.1	0	340.3
13	4.8	766	4.08	26.8	6.87	3.90	0.15	3125.28	801.1	3125.3	0	801.1
10	7.8	647	6.63	24.1	6.58	3.66	0.28	4289.61	1171.2	4289.6	0	1171.2
7	10.8	601	9.18	21.6	6.31	3.42	0.43	5517.18	1611.7	5517.2	0	1611.7
4	13.8	650	11.73	18.2	5.80	3.14	0.64	7624.50	2429.8	7624.5	0	2429.8
1	16.8	691	14.28	16.1	5.47	2.95	0.89	9867.48	3349.4	9867.5	0	3349.4
–2	19.8	644	16.83	14.6	5.23	2.79	1.00	9402.45	3368.1	10838.5	1430.1	4804.2
–5	22.8	497	19.38	13.3	5.01	2.65	1.00	6610.15	2490.0	9631.9	3021.8	5511.7
–8	25.8	312	21.93	12.1	4.76	2.59	1.00	3775.25	1485.1	6842.2	3067.0	4552.1
–11	28.8	162	24.48	11.6	4.66	2.49	1.00	1879.25	754.6	3965.8	2086.6	2841.5
–14	31.8	77	27.03	10.2	4.37	233	1.00	785.45	336.5	2081.3	1295.9	1632.4
–17	34.8	34	29.58	0	0	0	0	0	0	1005.7	1005.7	1005.7
–20	37.8	15	32.13	0	0	0	0	0	0	482.0	482.0	482.0
–23	40.8	5	34.68	0	0	0	0	0	0	173.4	173.4	173.4
TOTAL								54259.47	18138.2	66827.9	12568.4	30706.0

A general study was carried out with a simple modeling tool [1]. Because the goal was to compare different systems and sizing of the heat pump, the required heating and cooling capacities were calculated as the time-series using a simple dependence on outdoor temperature and solar radiation. Variations of a heat source temperature of the heat pump are important for the annual COP. The presumed curves and the influence on COP are shown in Figure 6.

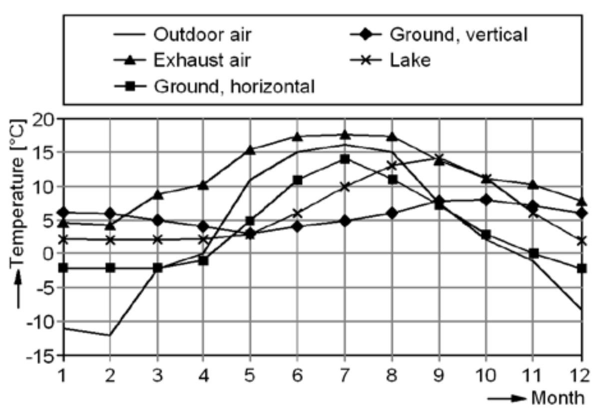

Fig. 6 Temperature profiles of heat sources as used in modeling

When the capacity of the heat pump (SF) increases COP decreases (Fig. 7) because a greater part of heating demand is produced under less favorable conditions, at lower heat source temperature. If the heat pump is dimensioned only for air conditioning cooling duty the sizing factor here is 40%.

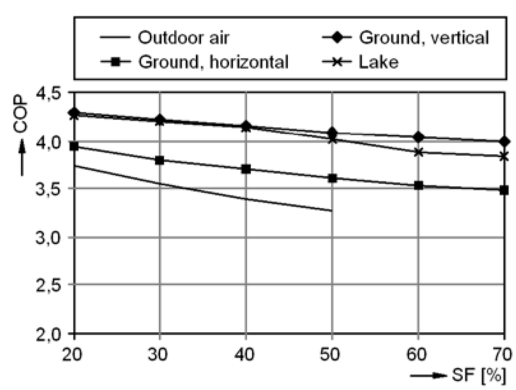

Fig. 7 Annual COP versus sizing factor SF

Free cooling using the low temperature of the heat source is an effective way to decrease energy consumption of the compressor-based cooling. The temperature level of the heat source and the annual cooling demand profile determine how big part can be covered by free cooling as illustrated in Figure 8. Also, the temperature level of the cooling-water network has an essential influence: The higher the temperature, the bigger part can be produced by free cooling.

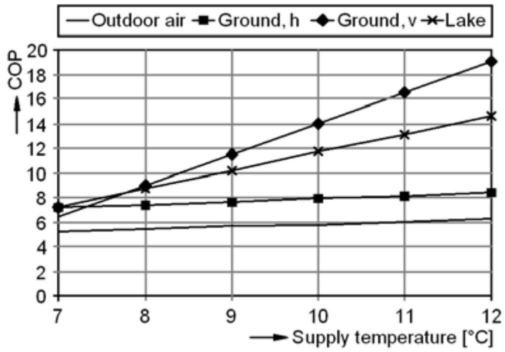

Fig. 8 Influence of supply temperature of cooling water–network on COP of cooling

Exhaust air as a heat source utilizes heat after the normal heat recovery heat exchanger. When the efficiency on the heat exchanger is increased, the temperature before the evaporator falls and required capacity of the heat pump decreases. However, the electricity usage is almost constant, because COP decreases as shown in principle in Figure 9. The main point is that the total energy consumption decreases. In the model of the evaporator, also the energy loss caused by defrosting was calculated. The method was calculation the amount of freezing moisture and evaluation of the heat needed to melt the frost with a given efficiency.

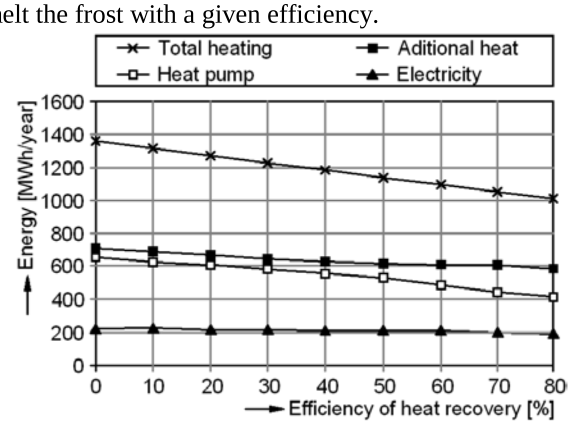

Fig. 9 Influence of efficiency of heat recovery on energy consumption

V. Comparative Economic Analysis of Heating Solutions for a Building

• *Assumptions for calculation.* A study is performed for the heating of a living building in rural areas with a water-water heat pump, using as heat source the underground water comparative to other sources of primary energy.

The building with useful surface of 240 m^2 (basement-floor, ground-floor, floor, and bridge) is heated from 1993 with radiators from thermal station with gas-oil. Indoor air temperatures were considered in accordance with the wishes of the client: +20 °C for the stairway and annex spaces; +22 °C for day rooms and bedrooms; 24 °C for baths. Cons-truction materials which distinguish heated spaces are: 50 cm brick for exterior walls, concrete 10 cm and 15 cm layer of expanded polystyrene insulation for the bridging, double glazing in oak. Exterior walls will be isolated from the outside with expanded polystyrene (10 cm).

Calculation of heat demand Q_{nec} was performed for the existing building envelope (exterior walls without insulation) and after thermal rehabilitation of it (exterior walls insulated with 10 cm expanded polystyrene), for more outdoor air temperatures (Table 3) in order to choose efficient heat source.

Table 3. Heat demand for heating

t_e [°C]	Q_{nec} [kW]	
	Existent envelope	Rehabilitated envelope
+5	18.9	13.6
0	20.2	15.5
–5	21.6	17.4
–10	23.0	18.3
–15	24.3	19.1
–20	25.6	21.1

For the preparation of domestic hot water is necessary to consider a heat Q_{dhw} = 3 kW (3 persons, 3 bathrooms and a kitchen).

• *Proposed solution.* Building heating is realized as follows:

– heating of living spaces (living rooms, bedrooms, and stairway) with the floor convector-radiator;

– bathroom heating with radiators (towel– port);

– hot water temperature to radiators and convector-radiator: 50/40 °C;

– for supply of radiators and convector-radiators are used distributor/collector systems;

– distribution network for radiators and convector-radiators, pexal made, is placed at ceiling, basement-floor, ground-floor and floor.

The heat demand of building will be provided by a heat pump type Thermia Eko 180 and a boiler with the capacity of 300 liters. Mechanical compression heat pump (scroll compressor) operates with ecological refrigerant R404A. The heat source is the groundwater aquifers with minimum temperature of 10 °C.

In the operating conditions with t_o = 8 °C and t_c = 50°C the thermal power of heat pump is Q_{PC} = 21 kW. It finds that this thermal power assure part of the building heat demand, only for outdoor temperatures higher than –5 °C, in the actual situation, and almost entirely (even for the outdoor temperature of –20 °C), in conditions of thermal rehabilitated envelope (exterior walls isolated additional). To assure the rest of heat demand (heating and preparation of domestic hot water) heat pump is equipped with 3 electrical resistances by 3 kW, which operate automatically, depending on the set indoor temperature. For flow rate control in the hot water distribution network from the heating circuit, there are provided the following measures:

– a first adjustment of the flows rate that are supplied the terminal units (radiators or convector-radiators), achieved by progressive reduction of the pipe diameters;

– base adjustment, achieved through the regulating valves of flow for each column;

– final adjustment at the terminal units, developed by the thermostat valves set at the comfort temperature in each room.

• *Economical analysis.* Comparing the solution described for building heating with other possible variants of primary energy sources (LPG, gas-oil and natural gas) results a superior investment for heat pump, but also an economy in operating costs, which enable the recovery of additional investment.

In Tables 4 and 5 are presented the necessary investments and operating costs over a period of 10 years for the considered variants.

Table 4. Investment costs I, in €, for heat pump (HP) and different thermal boilers.

Solution components	HP	Thermal boiler with fuel:		
		LPG	Gas-oil	Natural gas
0	1	2	3	4
Heat pump/Boiler	7700	3000	3000	3000
Underground water capture	4900	–	–	–
Heat exchanger	1300	–	–	–
Circulation pumps	1200	–	–	–
Fuel tank	–	3500	3500	–
Gas connection	–	–	–	4000
Total	15100	6500	6500	7000

Table 5. Operating costs for heat pump (HP) and different thermal boilers.

Solution characteristics	HP	Thermal boiler with fuel:		
		LPG	Gas-oil	Natural gas
0	1	2	3	4
Thermal power, [kW]	21+9	24	24	24
Fuel calorific power, [kW/l]	–	6.30	10.0	9.44
TS Efficiency / HP- COP	2.33	0.90	0.85	0.90
Hour consumption (fuel, [l/h] / electric energy, [kW])	9.00	4.23	3.02	2.84
Annual operating, [h/year]	1870*)	1700	1700	1700
Fuel price, [€/l] / Electricity price, [€/kWh]	0.087	0.500	0.900	0.300
Annual consumption, [l/an; kWh/an]	16830	7191	5134	4828
Annual energy cost, [€/an]	1464	3595.5	4620.5	1448.5
Estimated energy price increase in 10 years	1.30	1.40	1.40	2.00
Operating expenses (10 years), C [€]	1903.2	5033.7	6468.7	2897.0
*) Annual operation of electrical resistances is considered 10% of the normal operation period, so at the 1700 hours/year is adding 170 hours/year.				

Results the recovery time of additional investment for heat pump, compared with thermal boilers:

– toward boiler to LPG:

$$TR=\frac{I_{HP}-I_{TS,\mathrm{LPG}}}{C_{TS,\mathrm{LPG}}-C_{HP}}=\frac{15100-6500}{5033.7-1903.2}=2.74\ \text{years}$$

– toward gas-oil boiler:

$$TR=\frac{I_{HP}-I_{TS,\text{gas-oil}}}{C_{TS,\text{gas-oil}}-C_{HP}}=\frac{15100-6500}{6468.7-1903.2}=1.88\ \text{years}$$

– toward natural gas boiler:

$$TR=\frac{I_{HP}-I_{TS,\text{natural gas}}}{C_{TS,\text{natural gas}}-C_{HP}}=\frac{15100-7000}{2897.0-1903.2}=8.15\ \text{years}$$

It is noted that compared to any of the heating solutions to boilers, heating with water-to-water heat pump has a recovery period of investment *TR* smaller than normal recovery period TR_n, of 8–10 years.

VI. Conclusions

Correct adaptation of the heat source and the heating system for operating regime of heat pumps, leads to safe and economic operation of the heating system using heat pumps.

Heat pump provides the necessary technical conditions for efficient use of solar heat for heating and production of domestic hot water.

Heating installations with heat pumps produces minimum energy consumption in operation and are certainly a solution for energy optimization of buildings.

The heat pump mode requires some additional investments. If the capacity of the heat pump is selected larger than the condensing capacity in the pure refrigeration mode, also the additional capacity costs have to be covered by the savings in energy costs.

A combined cooling and heating system with a heat pump is always more effective than a traditional system if its requirements are taken into the consideration in the design process. For renovation, the applicability is more limited and always depending on the case.

The main barrier for the use of heat pumps for retrofitting is the high distribution temperature of conventional heating systems in existing residential buildings with design temperatures up to 70–90 °C which is too high for the present heat pump generation with maximum, economically acceptable heat distribution temperature of around 55 °C. Besides the application of existing heat pumps in already improved standard buildings with reduced heat demand, the development and market introduction of new high temperature heat pumps is a mayor task for the replacement of conventional heating systems with heat pumps in existing buildings.

REFERENCES

[1] A. Aittomäki, Better energy efficiency with combined heating and cooling by heat pumps, *Rehva Journal*, vol. 46, no. 3, Brussels, pp. 29-31, 2009.

[2] ASHRAE, *Fundamentals Handbook*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, 2009.

[3] G.V. Bendea, M.F. Prada, C. Bendea, C. Secui, Ground coupled heat pump systems – a key for a sustainable development of heating and cooling buildings, In: Recent Advances in Environmental Science, *Proceedings of the 9th Int. Conference on Energy, Environment, Ecosystems and Sustainable Development*, Lemesos, Cyprus, March 21-23, 2013, pp. 133-138.

[4] J. Bernier, *La pompe de chaleur, mode demploi*, tome I, P.Y.C. Edition, Paris, 1979.

[5] R.D. Ellison, The effects of reduced indoor temperature and night setback on energy consumption of residential heat pumps, *ASHRAE Transactions*, vol. 84, no. 2, pp. 352-363.

[6] D.G. Erbs, S.A. Klein, W.A. Beckman, Estimation of degree-days and ambient temperature bin data from monthly-average temperatures, *ASHRAE Journal*, vol. 25, no. 6, pp. 60, 1983.

[7] L. Garberi, S. Mehes, System models of different types of heat pumps, *Proceedings of the 2th IASME/WSEAS Int. Conference on Energy & Environment*, Portoroz, Slovenia, May 15-17, 2007, pp. 104-110.

[8] S.P. Kavanaugh, S.A. McInerny, Energy use of pumping options for ground-source heat pump systems, *ASHRAE Transactions*, vol. 107, no. 1, pp. 589-599, 2001.

[9] M. Lubliner, J. Andrews, D. Baylon, Heating with residential heat pumps, *ASHRAE Journal*, vol. 47, no. 10, Atlanta, pp. 36-43, 2005

[10] V. Radcenco, *Heat pump systems* (in Romanian), Technical Publishing House, Bucharest, 1985

[11] I. Sarbu, C. Sebarchievici, *Heat pumps* (in Romanian), Politehnica Publishing House, Timisoara, 2010.

[12] I. Sarbu, H. Bura, H. Vaporization thermal power assurance for vertical closed-loop ground-coupled heat pump system, *Proceedings of the 8th WSEAS Int. Conference on Environment, Ecosystems and Development. In: Advances in Biology, Bioengineering and Environment*, Vouliagmeni, Athens, Greece, December 29-31, 2010, pp. 125-130.

[13] I. Sarbu, C. Sebarchievici, Heat pumps – Efficient heating and cooling solution for buildings, *WSEAS Transaction oh Heat and Mass Transfer*, vol. 5, no. 2, pp. 31-40, 2010.

[14] O. Seppänen, European parliament adopted the directive on the use of renewable energy sources, *Rehva Journal*, vol. 46, no. 1, Brussels, pp. 12-14, 2009.

[15] E. Temos, Using waste heat for energy savings, *ASHRAE Journal*, vol. 48, no. 4, Atlanta, pp. 28-35, 2006.

[16] L. Verstaen, Variable refrigerant flow heat pump technology offers superior heating performance under cold ambient conditions, *Rehva Journal*, vol. 46, no. 2, Brussels, pp.40-43, 2009.

[17] J. Zirngib, Standardization activities for heat pumps, *Rehva Journal*, vol. 46, no. 3, Brussels, 2009.

[18] ∗ ∗ ∗ Grant CNCSIS, no. 46GR/12, *Functional and energetically optimization of thermal building services*, 2007.

[19] ∗ ∗ ∗ http://www.heatpumpcentre.org. *Heat pumps can cut global CO_2 emissions by nearly 8%*. Heat Pump Program, Heat Pump Centre, 2008.

[20] ∗ ∗ ∗ http://www.heatpumpcentre.org. *The potential impact of heat pumps on energy policy concerns*. Policy paper from the heat pump program implementing agreement, 2006.