Performances of heat pump systems as users of renewable energy for building heating/cooling

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Abstract: The heat pumps are alternative heating/cooling systems more energy efficiency and unless pollutant in comparison with classical systems (liquid or gas fuel boiler). A large number of heat pump systems have been used in residential and commercial buildings throughout the world due to the attractive advantages of high energy and environmental performances. This paper presents the economic, energy and environmental performance criteria which show the opportunity to implement a heat pump in a heating/cooling system. 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 is developed. In addition, from a case study a comparative economical analysis of heating solutions for a building is performed and the energy and economic advantages of building heating solution with a water-to-water heat pump are reported. Finally, the renewable energy sources contribution from heat pump sales in EU is shown.

Key-Words: Renewable energy, Heating-cooling, Heat pumps, Performance indices, Annual energy consumption, Energy–economical analysis.

1 Introduction

Economical strategy of a sustainable development imposes certainly to promote efficiency and a rational energy use in buildings as the major energy consumer in Romania and the other member states of the European Union (UE). Buildings represent the biggest and most cost effective potential for energy savings. Also, studies have shown that saving energy is the most cost effective method to reduce green house gas (GHS) emissions.

The buildings sector is the largest user of energy and CO2 emitter in the EU, and is responsible for more than 40% of the EU's total final energy use and CO2 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 environmentally sound heating and cooling systems [7, 19, 20]. Furthermore EU member states must stimulate the transformation of existing buildings undergoing renovation into nearly zero-energy buildings (nZEBs). Conversion to heating and cooling systems based on ground source heat pumps and air-to-water heat pumps is a well-proven measure to approach nZEB requirements.

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 [5, 12].

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 (RES). 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. Aero-thermal, 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 [24]:

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

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 performance factor (SPF) should be SPF>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/cooling. 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 [11, 14, 25].

This paper presents the economic, energy and environmental performance criteria which show the opportunity to implement a heat pump in a heating/cooling system. A computational model of annual energy consumption for an air-to-water heat pump based on the degree–day method and the bin method is developed. In addition, a comparative economical analysis of different heating solutions for a building is performed. Finally, the RES contribution from heat pump sales in EU is shown.

2 Performance indicators for heat pumps

The performances of the heat pump and the system building – heating/cooling installation are 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 [21].

• *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 $\Delta C = C_{TS} - C_{HP}$:

$$TR = \frac{\Delta I}{\Delta C} \le TR_n \quad (2)$$

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*):

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

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:

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

and is defined update rate

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

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

$$TUC = I_0 + r_a C \quad (6)$$

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

$$\mathrm{COP} = \varepsilon_{HP} = \frac{E_U}{E_D} \quad (7)$$

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 the COP is defined by equation:

$$\mathrm{COP} = \varepsilon_{HP} = \frac{Q_{HP}}{P_e} \quad (8)$$

in which: Q_{HP} is the thermal power (capacity) of heat pump, in W; P_e – the drive power of heat pump, in W.

In cooling mode, a heat pump operates exactly like a central air conditioner. The *energy efficiency ratio* (EER) is analogous to the COP but tells the cooling performance. The EER, in Btu/(h·W) is defined by equation:

$$\text{EER} = \frac{Q_0}{P_e} \tag{9}$$

in which: Q_0 is the cooling power of heat pump, in British thermal unit per hour (Btu/h); P_e – drive power of heat pump, in W.

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

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

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

The sizing factor (SF) of the heat pump is defined as ratio of the heat pump capacity Q_{HP} to the maximum heating demand $Q_{\max}$:

$$\text{SF} = \alpha_{HP} = \frac{Q_{HP}}{Q_{\max}} \tag{11}$$

The sizing factor can be optimized in terms of energy and economic, depending on the source temperature and the used adjustment schedule.

From the energy balance of the heat pump:

$$E_U = E_S + E_D \tag{12}$$

can highlight the link between the efficiency of a plant working as a heat pump (ε_{HP}) and as refrigeration plant (ε_{RP}):

$$\varepsilon_{HP} = \frac{E_S + E_D}{E_D} = 1 + \frac{E_S}{E_D} = 1 + \varepsilon_{RP} \tag{13}$$

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

$$\varepsilon_{HP+RP} = \frac{E_U + E_S}{E_D} = \frac{E_S + E_D + E_S}{E_D} = \varepsilon_{HP} + \varepsilon_{RP} \tag{14}$$

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 $\varepsilon_{HP,r}$ and its expression is [21]:

$$\varepsilon_{HP,r} = \frac{t_c}{t_c - t_o}(1 - \Sigma\Pi_j) \tag{15}$$

where t_c and t_o are the condensation and vaporization absolute temperatures of refrigerants, in K.

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

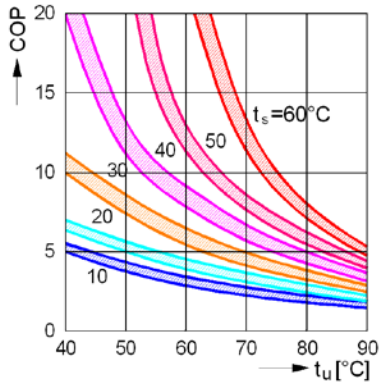

Fig. 1 Variation of heat pump efficiency

To determine the real efficiency of the heat pump with electro-compressor can be used the equation [18]:

$$\varepsilon_{\text{HP,r}} = \frac{t_u + \Delta t_c}{t_u + \Delta t_c - (t_s - \Delta t_o)}\eta_r \eta_i \eta_m \eta_{em} + \eta_m \eta_{em}(1 - \eta_i) \tag{16}$$

where:

$$\eta_r = 1.666 - 0.004(t_s - \Delta t_o) - 0.00625(t_u + \Delta t_c) \tag{17}$$

$$\eta_i = \left(0.425 + \frac{0.493 Q_{HP}}{1.16 Q_{HP} + 0.06}\right)\left(3.23 - 1.835\frac{t_u + \Delta t_c}{t_s - \Delta t_o}\right) \tag{18}$$

$$\eta_m = 0.85 + \frac{0.158 Q_{HP}}{1.16 Q_{HP} + 0.1513\dfrac{t_u + \Delta t_c}{(t_u + \Delta t_c) - (t_s - \Delta t_o)}} \tag{19}$$

$$\eta_{em} = 0.85 + \frac{0.139 Q_{HP}}{1.335 Q_{HP} + 0.0904\dfrac{t_u + \Delta t_c}{(t_u + \Delta t_c) - (t_s - \Delta t_o)}} \tag{20}$$

in which: t_u, t_s are the absolute temperature of hot and cold source, respectively; Δt_c, Δt_o – temperature differences between the condensation temperature and hot source temperature, respectively, between the 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_{HP} – thermal power of heat pump.

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

$$w_{HP} = \frac{10^3}{3.6\varepsilon_{HP,r}} \tag{21}$$

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

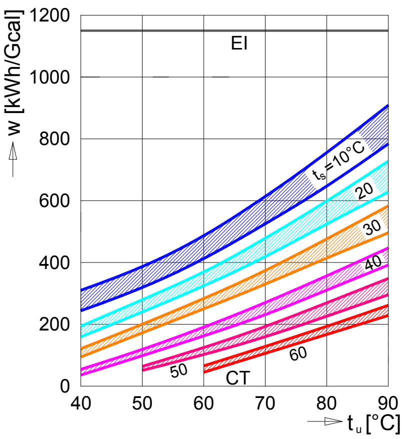

Fig. 2 Electricity consumption for the heat production

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 consumption, depending on α_{HP} and different graphics adjustments.

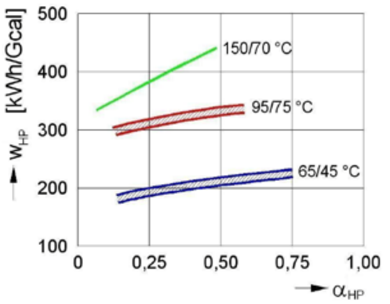

Fig. 3 Variation of the average annual electricity consumption

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 [23]:

$$\varphi_{year} = \frac{Q_{u,\,year}}{B_{fe,\,year}} \tag{22}$$

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

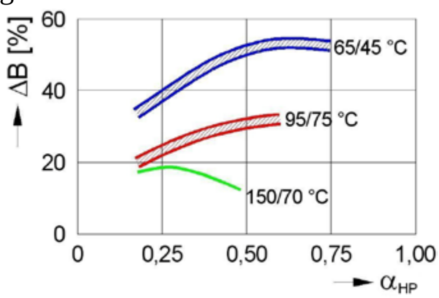

Fig. 4 Variation of annual fuel economy

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	System type	Fuel use degree 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

• *Profitability and capabilities of heat pump with electro-compressor.* Factor that can effect the life–cycle efficiency of a heat pump are: (1) local method of electricity generation; (2) climate: (3) type of heat pump (ground vs. air source); (4) refrigerant used; (5) size of heat pump; (6) thermostat controls; (7) quality of work during installation.

Taking into account that the heat pump has an over–unit efficiency, for the evaluation in which way is valued the consumed primary energy is using a synthetic indicator [22]:

$$\eta_s = \eta_g \mathrm{COP} \tag{23}$$

where

$$\eta_g = \eta_p \eta_t \eta_{em} \tag{24}$$

in which η_g is the global efficiency; η_p, η_t, η_{em} are the electricity production; the transportation, and the electromotor efficiency, respectively.

For justify the use of heat pump, the synthetic indicator has to satisfy the condition $\eta_s > 1$. Also, only if the COP>2.78 the use of the heat pump can be considered.

The COP of a heat pump is restricted by the second law of thermodynamics:

– in the heating operate mode:

$$\mathrm{COP} \le \frac{t_u}{t_u - t_s} = \varepsilon_C \tag{25}$$

– in the cooling operate mode:

$$\mathrm{COP} \le \frac{t_s}{t_u - t_s} \tag{26}$$

where t_u, t_s are the absolute temperatures of hot (condensation) source and cold (evaporation) source, respectively, in K.

The maximum value ε_C of the efficiency can be obtained in reverse Carnot cycle.

3 Types of heat pumps

Heat pumps basified by (1) heat source and sink, (2) heating and cooling distribution fluid, (3) thermo-dynamic cycle.

• *Air-to-air heat pumps*. This type of heat pump is the most common and is particularly suitable for factory-built unitary heat pumps.

• *Water-to-air heat pumps*. These heat pumps rely on water as the heat source and sink, and use air to transmit heat to or from the conditioned space. They include the following:

– ground-water heat pumps, which use ground-water from wells as a heat source and/or sink;

– surface water heat pumps, which use surface water from a lake, pond, or stream as a heat source or sink;

– solar-assisted heat pumps, which rely on low-temperature solar energy as the heat source.

• *Water-to-water heat pumps*. These heat pumps use water as the heat source and sink for heating and cooling. Heating/cooling changeover can be done in the refrigerant circuit, but it is often more convenient to perform the switching in the water circuits. Several water-to-water heat pumps can be grouped together to create a central cooling and heating plant to serve several air-handling units. This application has advantages for better control, centralized maintenance, redundancy, and flexibility.

• *Ground-couplet heat pumps*. These use the ground as a heat source and sink. A heat pump may have a refrigerant-to-water heat exchanger or may be direct-expansion (DX). In systems with refrigerant-to-water heat exchangers, a water or antifreeze solution is pumped through horizontal, vertical, or coiled pipes embedded in the ground. Direct-expansion ground-coupled heat pumps use refrigerant in direct-expansion, flooded, or recirculation evaporator circuits for the ground pipe coils.

• *Hybrid heat pumps*. A hybrid ground-coupled heat pump is a variation that uses a cooling tower or air-cooled condenser to reduce the total annual heat rejection to the ground coupling. A hybrid air-to-water heat pump system integrates an air-to-water heat pump with another non-renewable heat source.

Recently, the ground-source heat pump (GSHP) system has attracted more and more attention due to its superiority of high energy-efficiency and environmental friendliness [6, 20]. Renewable forms of energy such as solar, wind, biomass, hydro, and earth energy produce low or no GHG emissions. The temperature of the ground is fairly constant below the frost line. The ground is warmer in the middle of winter and cooler in the middle of summer than the outdoor air. Thus, the ground is an efficient heat source. A GSHP system includes three principle components: (1) a ground connection subsystem, (2) heat pump subsystem, and (3) heat distribution subsystem.

The GSHPs comprise a wide variety of systems that may use ground–water, ground, or surface water as heat sources or sinks. These systems have been basically grouped into three categories by ASHRAE [3]: (1) ground-water heat pump (GWHP) systems, (2) surface water heat pump (SWHP) systems, and (3) ground-coupled heat pump (GCHP) systems.

The GWHP system, which utilizes ground-water as heat source or sink, has some marked advantages including low initial cost and minimal requirement for ground surface area over other GSHP systems [1]. In a SWHP system, heat rejection/extraction is accomplished by the circulating working fluid through high-density polyethylene (HDPE) pipes positioned at an adequate depth within a lake, pond, reservoir, or the suitable open channels. The major disadvantage of the system is that the surface water temperature is more affected by weather condition, especially winter. In Table 2 are summarized the calculated values for COP of GWHP and SWHP systems, operating as water-to-water heat pump.

Table 2. The COP of GWHP and SWHP systems operating as water-to-water heat pump

Water temp. at evaporator inlet t_s [°C]	Water temp. at condenser outlet, t_u [°C]				
	30	35	40	45	50
5	4.55	4.10	3.70	3.40	3.15
10	5.30	4.65	4.15	3.75	3.45
15	6.25	5.35	4.70	4.20	3.85
20	7.70	6.35	5.45	4.80	4.30
25	9.95	7.80	6.45	5.55	4.85
30	14.10	10.10	7.95	6.55	5.60

In a GCHP system, heat is extracted from or rejected to the ground via a closed-loop, i.e. ground heat exchanger (GHE), through which pure water or antifreeze fluid circulates. The GHEs commonly used in the GCHP systems typically consist of HDPE pipes which are installed in either vertical boreholes (called vertical GHE) or horizontal trenches (horizontal GHE).

The GSHPs work best with heating systems, which are optimized to operate at lower water temperature than is radiator and radiant panel systems (floor, wall, and ceiling). GSHPs have the potential to reduce cooling energy by 30–50% and reduce heating energy by 20–40% [17].

4 Hybrid air-to-water heat pumps

A hybrid heat pump system integrates an air-to-water heat pump with another non-renewable heat source, such as a condensation gas boiler, to create a highly energy efficient domestic heating and hot-water system. This system can produce water flow temperatures from 25 °C up to 80 °C, making it suitable for any type of heat emitter, including floor heating and radiators.

The intelligent hybrid heat pump measures the outdoor temperature, automatically adjusting the flow temperature to the emitters and calculating the efficiency of the heat pump. The system continuously evaluates whether or not the efficiency of the heat pump is higher than that of the condensing gas boiler. Based upon this evaluation, the energy source is selected, ensuring the most efficient heat source is being used at any one time. There are three operating conditions:

– heat pump only: for about 60% of the year, when outdoor temperature are mild, the heat pump will supply energy for space heating. The primary energy based efficiency in this mode is about 1.5.

– hybrid operation: for about 20% of the year, when outdoor temperatures are between –2 °C and 3 °C, the heat pump and condensing gas boiler work together to provide energy for space heating. The system efficiency is about 1.0 in this mode.

– boiler only: when outdoor temperatures are below –2 °C the condensation gas boiler provides the energy for space heating.

Across the year, the overall weighted primary energy efficiency is between 1.2 and 1.5, which is 30 to 60% higher compared with the best gas condensation boiler [4].

The hybrid heat pump system consists of three main components:

- *The outdoor unit* transmits the renewable energy extracted from the air to the indoor unit (hydrobox). The compact and whisper-quiet outdoor unit contains the inverter driven compressor, which has a modulation ratio from approximately 20 to 100%. In partial load conditions, the outdoor heat exchanger is over-sized which increases the efficiency by up to 30%.
- *The hydrobox* is mounted on the wall behind the condensing boiler. As well as the controls for the system, it contains the water-side elements of the system, such as the expansion tank and pump, and also the heat exchanger, which converts the renewable energy extracted from the air into hot-water.
- *The condensing gas* is installed in front of the hydrobox. The combined dimensions of the boiler and hydrobox are about the same as a conventional wall-hung boiler.

The hybrid heat pump has been field tested in various climates and house types (size, age, and energy rating) with a range of different heat emitters. The $COP_{seasonal}$ measured during the winter of 2011-12 varied between 1.25 and 1.6 [4].

5 Environmental performances

The GSHPs work with the environment to provide clean, efficient, and energy saving heating and cooling year round. GSHPs use less energy than alternative heating and cooling systems, helping to conserve natural resources. These are an important technology for reducing emissions of gases that harm the environment, such as carbon dioxide (CO_2), sulphur dioxide (SO_2) and nitrogen oxides (NO_x).

Heat pumps driven by electricity from, for instance, hydropower or renewable energy reduce emissions more significantly than if the electricity is generated by coal, oil or natural gas power plants. The CO_2 emissions for different primary energy sources are summarized in Table 3 [13].

Table 3. CO_2 emissions for different primary energy sources

No.	System	Efficiency	CO_2 emission per kWh of fuel [kg CO_2/kWh]	CO_2 emission per kWh of useful heat [kg CO_2/kWh]
0	1	2	3	4
1	Coal boiler	0.70	0.34	0.49
2	Gas–oil boiler	0.80	0.28	0.35
3	LPG boiler	0.80	0.25	0.31
4	Natural gas boiler	0.80	0.19	0.24
5	Air-to-air heat pump	2.50	0.47	0.19
6	Ground-to-water heat pump	3.20	0.47	0.15

The GSHPs utilise renewable or solar energy stored in the ground near the surfaces. The renewable component (66%) displaces the need for primary fuels, which, when burned, produce GHGs emissions and contribute to global warming. An analysis was performed [8] to estimate the total equivalent warming impact (TEWI) of GSHPs compared to other heating and cooling systems in residential, commercial and institutional buildings. The modelling results show CO_2 emissions reductions from 15 to 77% through the application of GSHPs in both residential and commercial buildings.

With increasing proportions of electricity generated from renewable sources, installing heat pumps in existing buildings becomes a more and more attractive option with respect to both primary energy demand and CO_2 emissions.

6 Computation of energy consumption for 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 [2].

• *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:

$$Q_{ap} = U\left(t_i - t_{ech}\right) \tag{27}$$

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:

$$Q_{inc} = \frac{U}{\eta}\left[t_{ech} - t_e(\tau)\right]_{t_e < t_{ech}} \tag{28}$$

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:

$$E_{inc} = \frac{U}{\eta}\int\left[t_{ech} - t_e(\tau)\right]_+ \mathrm{d}t \tag{29}$$

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:

$$N_{inc} = (1\,day)\sum_{days}\left(t_{ech} - t_e\right) \tag{30}$$

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:

$$E_{inc} = \frac{U}{\eta}N_{inc} \tag{31}$$

Cooling degree-days can be calculated using an equation analogous to equation (30) for heating degree-days as:

$$N_{rac} = (1\,day)\sum_{days}\left(t_e - t_{ech}\right) \tag{32}$$

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.* [9] developed a model that needs as input only the average $\bar{t}_{ej}$ for each month of the year. The standard deviation σ_j, in °C, for each month is then estimated from the correlation:

$$\sigma_j = 1{,}45 - 0{,}029\bar{t}_{ej} + 0{,}0664\sigma_{an} \quad (33)$$

where:

$$\sigma_{an} = \sqrt{\frac{1}{12}\sum_{j=1}^{12}\left(\bar{t}_{ej} - \bar{t}_{e,an}\right)^2} \quad (34)$$

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]:

$$N_{inc,j} = \sigma_j n^{1.5}\left[\frac{\theta_j}{2} + \frac{\ln\left(e^{-a\theta_j} + e^{a\theta_j}\right)}{2a}\right] \quad (35)$$

where:

$$\theta_j = \frac{t_{ech} - \bar{t}_{ej}}{\sigma_j \sqrt{n}} \quad (36)$$

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:

$$N_{inc} = \sum_{j=1}^{12} N_{inc,j} \quad (37)$$

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 temperature 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) centred on that temperature:

$$Q_{bin} = N_{bin}\frac{U}{1000\eta}\left(t_{ech} - t_e\right)_+ \quad (38)$$

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) centred around outdoor temperature; U – heat transfer coefficient of building, in W/K; t_{ech} – balance point temperature, in °C; t_e – outdoor temperature, in °C; 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 (38) 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 [26].

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

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

$$Q_{nec} = \frac{U}{1000}\left(t_{ech} - t_e\right) \quad (39)$$

– Heat pump efficiency, ε_{HP}:

$$\varepsilon_{HP} = \frac{Q_{HP}}{P_e} \quad (40)$$

– Heat pump operation coefficient, f:

$$f = \min\left(1, \frac{Q_{nec}}{Q_{HP}}\right) \quad (41)$$

– Thermal energy provided by heat pump E_{HP}, in kWh:

$$E_{HP} = f Q_{HP} N_{bin} \quad (42)$$

– Electric energy to drive heat pump E_D, in kWh:

$$E_D = f P_e N_{bin} \quad (43)$$

Energy requirement E_{bin}, in kWh, is obtained by summing the values Q_{bin} given by (38).

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

$$E_{aux} = E_{bin} - E_{HP} \quad (44)$$

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

$$E_t = E_D + E_{aux} \quad (45)$$

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 °C, and is determined energy consumption during heating period using METBIN program. The results are summarized in Table 4. In Figure 5 is shown the variation of heat loss and thermal power of the heat pump depending on the outdoor temperature.

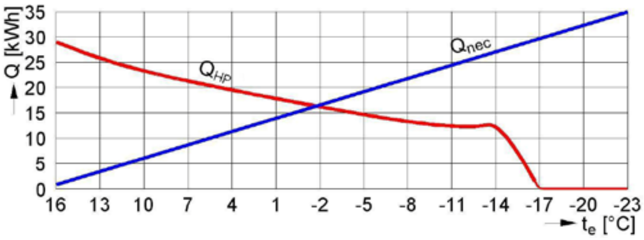

Fig. 5 Variation of heat requirement and HP thermal power with outdoor temperature

7 Comparative economic analyses of some 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.

Table 4. Results provided of computer program METBIN

Temp. (bin) t_e [°C]	t_{ech}-t_e [°C]	Hours N_{bin} [h]	Q_{nec} [kW]	Q_{HP} [kW]	P_e [kW]	ε_{HP}	Coef. f	E_{HP} [kWh]	E_D [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
T O T A L								54259.47	18138.2	66827.9	12568.4	30706.0

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. Construction 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 5) in order to choose efficient heat source.

For the domestic hot-water production 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, bed-rooms, and stairway) with floor convector-radiator;

Table 5. Heat demand for heating

t_e [°C]	Q_{nec} [kW]	
	Actual 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

– 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 litters. 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_{HP} = 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 6 and 7 are presented the necessary investments and operating costs over a period of 10 years for the considered variants.

Table 6. 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 7. Operating costs *C*, in €, 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]; [m^3/h] / electric energy, [kW])	9.00	4.23	3.02	2.84
Annual operating, [h/year]	1870*)	1700	1700	1700
Fuel price, [€/l]; [€/m^3] / Electricity price, [€/kWh]	0.087	0.500	0.900	0.300
Annual consumption, [l/year; m^3/year; kWh/year]	16830	7191	5134	4828
Annual energy cost, [€/year]	1464	3595.5	4620.5	1448.5
Estimated energy price increase in 10 years	1.30	1.40	1.40	2.00
Operating costs (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:

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

– 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.

8 RES contribution from heat pump sales in UE

Member States are obliged to set trajectories on how to achieve their mandatory RES targets for 2020. This is done via their National Renewable Energy Action Plan (NREAP).The assessment of all plans shows a target contribution from heat pumps towards the 2020 use of final energy of 1298 TWh [15]. Ambition among Member States is however not evenly spread. While the UK aims to cover 36% of its RES target by contributions from heat pumps (Fig. 6), other like Portugal, Bulgaria, Estonia, Malta and Romania have not included the technology into their plans [10].

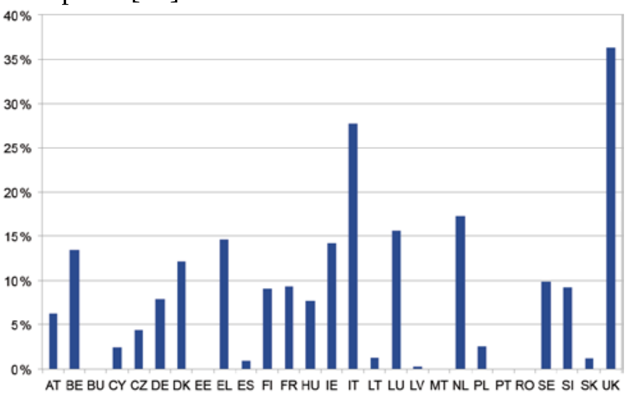

Fig. 6 Contribution from heat pumps to achieve the designated RES share in heating and cooling

Today's contribution of the heat pump stock can be determined from industry sales statistics. A total of 4.5 million heat pumps were sold from 2005 to 2011 (Fig. 7). The actual stock is higher, as significant heat pump markets existed before 2005 in at least Austria, France, Germany, Italy, Sweden, and Switzerland. Using average values for SPF and E_U the total annual contribution of the heat pump stock is 27.37 TWh, saving 6.83 Mt of GHG emissions annually [16].

Additionally, the growing share of intermittent renewable source from solar and wind requires peak shaving and storage options to better integrate them. Heat pumps are well equipped to provide demand side potential, thus helping indirectly to further increase the share of renewable sources in the energy mix.

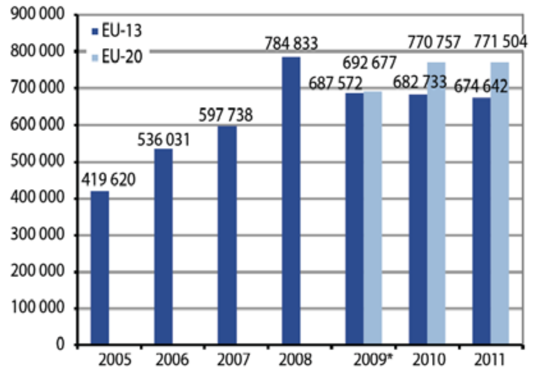

Fig. 7 Development of heat pump sales 2005 to 2011

9 Conclusions

Correct adaptation of the heat source and the heating system for operating mode 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 systems 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.

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