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Analysis of heat pump performance coefficients

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Abstract. In this paper the authors propose a performance analysis of electrically driven mechanical vapor compression heat pumps. The article is based on the analysis of technical parameters according to construction characteristics, types of refrigerants used, in relation to outdoor temperatures. The article is intended to be a real support for the choice of a particular type of heat pump that will prove its sustainability over time, reducing maintenance costs, energy consumption and, implicitly, contributing to the reduction of carbon dioxide emissions.

Keywords: energy efficiency, heat pumps, refrigerant, temperature.

1. Introduction

According to the IEA (International Energy Agency) report [1,3], global energy demand is projected to increase by 37% and carbon dioxide (CO₂) emissions by 20% in 2040, due to a long-term global average temperature change of 3.6°C. As mentioned in the Annual Energy Outlook, 2015 [2], the increase in energy costs by 18% by 2040 has led to the improvement and development of more energy efficient systems. In particular, the building sector, both residential and commercial, is the largest energy consuming sector in the world. More specifically, it accounts for more than one third of total final energy consumption and at the same time is the main source of carbon dioxide emissions. To reduce end-users' energy consumption for heating and cooling buildings, heat pumps are a valuable economic alternative for harnessing heat from different sources in various applications such as industrial, commercial and residential. Furthermore, heat pumps are considered renewable energy technologies [4].

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In order to reduce energy consumption in the residential sector, improvements such as increasing the thermal resistance of new and existing building envelopes, as well as more energy-efficient heating and cooling systems, are needed. From this perspective, heat pump technology represents one of the most viable solutions and a valid economic alternative to traditional heating systems, as confirmed by the increasing number of heat pump units sold on the European market. The use of heat pumps is recognized for their potential to extract heat from different media such as soil, air or water.

2. Heat pumps. Theoretical concepts

Industrial and residential heat pumps are major contributors to the transformation of the energy system. It will rely largely on electricity. The main impediment to the integration of heat pumps is the purchase cost of the equipment, as well as the adaptation of the installation systems, the building envelope, to create a system that offers maximum energy efficiency. The coefficient of performance depends largely on these aspects as well as on the temperature difference between the source and the distributor. Currently, COP estimation is often carried out by heat pump suppliers and involves choices such as the working fluid and compressor technology, the operating temperature of the installation as well as the temperature of the primary source.

Heat pumps are the equipment that will widely replace power plants, gas, wood, coal, or more precisely all heat generating equipment that converts fossil fuel energy. The performance of heat pumps in heating mode is strongly influenced by various parameters, such as the climate where the building is located, the temperature of the heat transfer medium delivered to the heat exchange surfaces, as well as the oversizing or undersizing of the heat pump in relation to the thermal load of the building, the control system and the heat pump compressor technology.

The aim of this paper is to study the impact of these parameters on the seasonal efficiency for heat pump heating of buildings.

The choice of a heat pump needs to be made following a multi-criteria analysis.

Establishing these criteria is decisive in the operation of a heat pump installation system.

The criteria for choosing heat pumps contribute substantially to the performance of the whole heat pump system.

If we are talking about residential heating, cooling systems the main selection criteria:

- according to the type of compression and drive of the compressors, we note that in most cases we use mechanical vapor compression heat pumps driven by electric compressors.

Another defining criterion is the primary energy source: ground, air or water. In very many situations, the choice of a heat pump where the primary energy source is outside air is made because of economic and design advantages. These air-to-water heat pumps are very easy to install even if the coefficient of performance is affected by external factors: temperature and humidity.

When discussing the performance of heat pumps, the refrigerants used make an important contribution. From the early 1930s until the 1980s halogenated synthetic refrigerants (CFCs and HCFCs) dominated the market for refrigeration aggregates. The international community set deadlines in 1987 in the Montreal Protocol for the reduction and elimination of CFCs and HCFCs (UNEP 2006).

There is a real concern for the choice of refrigerants over time by countless researchers, their tendency is to use a refrigerant with the lowest environmental impact that offers the best performance.

According to those published in the work of Larsen et al., Belman et al. (2010), Zhao et al, Zsembinski et al. (2017), Yang et al. (2017, 2015) and Dalkilic and Wongwises, they focused their analysis on the overall power consumption as well as the optimal operating point to increase the performance coefficient of heat pumps.

As can be seen from Figures 1 and 2 the community of specialists in the field, researchers as well as heat pump manufacturers, has a real concern for finding refrigerants with a low environmental impact and which contribute to providing outstanding energy performances.

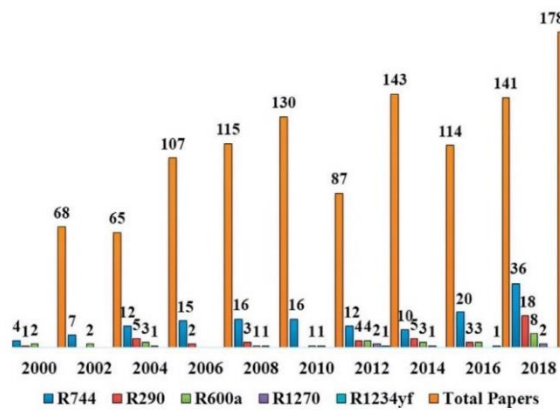


Fig 1. Published papers focusing on refrigerants R744, R290, R600a, R1270, R1234yf at the Gustav Lorentzen Conference.

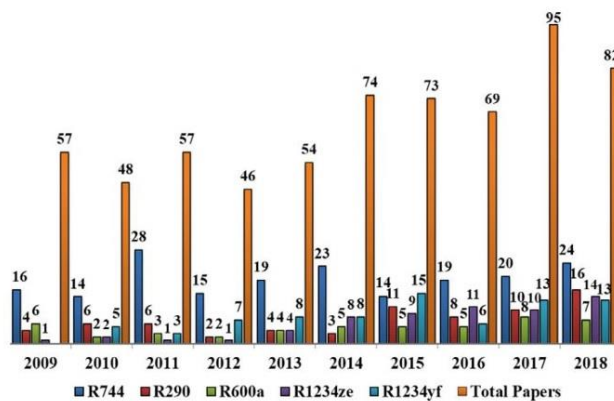


Fig. 2. Published papers focusing on refrigerants R744, R290, R600a, R1234ze, R1234yf in the International Journal of Refrigeration

3. Refrigerant essential for heat pump functionality

Refrigerant is essential for the heat pump to perform its function. An important characteristic is its low boiling point, which makes the liquid change from liquid to gas even at low temperatures. Even temperatures of minus 20 degrees Celsius are sufficient for this to happen. This is why the heat pump also works in winter at low outdoor temperatures. State-of-the-art heat pumps already use refrigerants such as *propane*, a natural refrigerant (R290), which is in no way inferior to conventional refrigerants in terms of its properties.

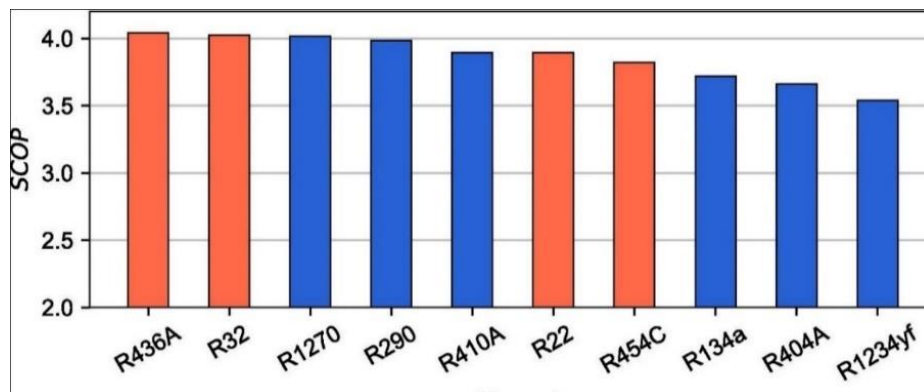


Fig. 3 Influence of refrigerants on the coefficient of performance [5]

The choice of refrigerant directly influences efficiency, operating costs and compliance with environmental regulations. R290 (propane) and R32 are two of the most widely used choices in air conditioning and heat pump systems, each with specific advantages and limitations.

According to Ghanbarpour et al. compare three refrigerants with low GWP in three-cycle configurations for a supermarket refrigeration system. In their study, R290 leads to the highest efficiencies and lowest *TEWI*. Staubach et al. analyze 36 low GWP refrigerant pairs for a cascade refrigeration system. All this research is aimed to find the refrigerant with the best performance.

According to Ovidiu-Mircea Talabă's research in comparison with R 410 A the volumetric capacity ratio of R32 and COP tend to increase as the evaporation temperature decreases. R32 is advantageous in cold areas because the lower the vaporization temperature, the higher the volumetric capacity ratio [8].

Taira et al. proposed a notion of diversity of refrigerant choice and suggested that R32 is a refrigerant that enables rapid action against global warming. Compared the performance using R32 and R410A in a thermodynamic model and conducted experiments at different operating conditions of a residential area heat pump. Analysis of the thermodynamic cycle of a refrigeration plant in a compression step showed that the heat load with R32 agent is 8% higher in cooling mode and 3% higher in heating mode compared to R410A agent, while the COP is 3% higher in cooling and 2% higher in heating mode [8].

4. Contribution of the heating curve to the optimization of heat pump performance coefficients

The heating curve requires the setting of several parameters, such as supply and outdoor temperatures. Recent experimental research has shown that the performance, in both temperate continental, and cold climates [10] is often influenced by suboptimal choice of heat pump control parameters. Therefore, many researchers have explored alternative methods to improve the traditional weather-compensated heating system control. The main emphasis has been on dynamic adjustment of the lap temperature, ambient temperature, scheduling, which optimizes the parameters based on the estimated system responses. Changing the heating curve has a significant influence on energy efficiency, since a parallel decrease of a heating curve by one degree is reported to increase the COP for heat pumps by 2.6%-13%. A well-adjusted heating curve configuration is the basis for constant comfort of building occupants, which increases the willingness of users to adopt energy-saving strategies (e.g., reducing the supply temperature while the building is unoccupied, weather-dependent room temperature adjustments or preheating) when energy prices are low), thus making operation cheaper, more energy-efficient.

Calculating the heating curve parameters for heat pumps is a complex process, prone to inaccuracies. This is because it involves numerous variables and building-specific assumptions.

A study by Weigert [7] showed that about 60% of the buildings analyzed during an energy assessment had incorrect heating curve settings. The reasons for the incorrect settings are various: first of all, many parameters such as type and size of heating equipment, room size, house insulation, window sizes, etc. need to be known before calculations. In the absence of such real information, for example: type of wall insulation, assumptions have been made, which does not bring the expected result.

Installers or service engineers tend to set the heating to a higher curve than necessary to avoid post-installation adjustments, extra visits and service calls [9]. This is despite the fact that the guidelines suggest setting the heating curve 3-5 degrees lower than calculated and allowing the informed user to adjust the heating curve when they feel discomfort.

The heating curve captures the relationship between the supply temperature and the outside temperature in order to compensate for weather variations and maintain a constant indoor warmth.

An ideal heating curve ensures that the feed water is heated to the optimum temperature to meet the heating requirements at different outdoor temperatures. When the configured heating curve is not equivalent to the ideal one, deviations between expected and actual supply temperatures lead to lower temperatures that cannot meet the required energy demand. To alleviate the discomfort, modern high-performance systems allow users to change room temperatures via controllers or apps, resulting in a parallel shift of the heating curve.

Choosing settings close to the ideal heating curve not only increases user comfort and satisfaction, but also improves energy efficiency for several reasons:

- (1) It prevents users from making adjustments to thermostatic valves, which can be inefficient and cause imbalances in the heating system [8];
- (2) A functional and reliable heating system increases the willingness of users to participate in energy-saving programs, such as temperature reduction, or cost-saving programs, such as flexible electricity rates.

5. Compressor technology as a factor influencing heat pump performance

Air-to-water heat pumps have a problem adapting to very low outdoor temperatures, with compressor performance dropping dramatically.

Studies over the last decade are improving the performance of the compressor and the heat pump as a whole. Vapor injection technology has attracted the attention of many researchers as well as major heat pump manufacturers. For manufacturers, the development of vapor injection technology has made it possible to move from piston compressor and screw compressor to scroll compressor and rotary compressor [9]. Researchers are paying more attention to improving the heating performance for vapor injection applied to compressors, including vapor injection configurations, type of agent. All recent studies in the field are related to vapor injection effectiveness.

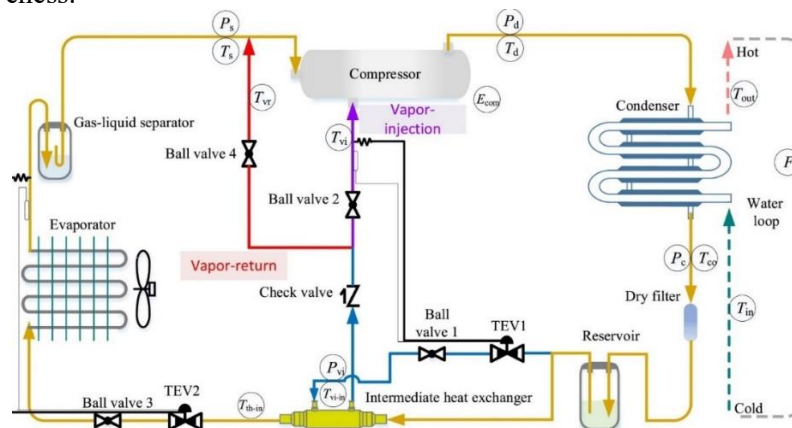


Fig. 4. Functional scheme of a vapor injection heat pump [34].

The results showed that the heating capacity improves by at least 1 kW and the *COP* increases by at least 0.2 for all refrigerants used in the vapor injection, since the condensing temperature is 45.0 °C and the evaporating temperature is -10.0 °C. According to the research of C. A. Redón *et al*, four refrigerants (R407C, R290, R22 and R32) were tested in a two-stage cycle with vapor injection, the coefficient of performance improved from 15% to 20% and the capacity improved from 30% to 35% for the nominal conditions considered, compared to the single-stage cycle. In the study of substituted low global warming potential refrigerants, the capacity and *COP* of vapor injection heat pumps using R152a and R1234yf are optimized compared to those using R134 A at different injection conditions [11].

The effectiveness of vapor injection is discussed with different modes of vapor injection using different refrigerants. It is more than simply increasing the mass flow rate of the refrigerant. It focuses on reducing the relative entropy at the compressor outlet for a vapor injection heat pump. Knowing the effectiveness of vapor injection can help manufacturers and researchers find a way to improve the heating performance of vapor injection heat pumps at low ambient temperatures

According to the study by Wang *et al.*, they found that vapor injection increases heating capacity by 2-2.39 kW and COP by 0.26-0.41.

In vapor injection pump experiments with different refrigerants, vapor injection increases the heating capacity and COP of heat pumps. According to Xu *et al.* compared the heating performance of two-stage vapor injection heat pump systems with R1234yf, R32 and R1234yf/R32 mixture. Compared to non-vapor injection, vapor injection increases the heating capacity by 1.16 kW for using R1234yf, 2.27 kW for using R32 and 1.5 kW for using R1234yf/R32 mixture, and the COP increases by 0.287, 0.363 and 0.223 individually.

6. Operating temperatures and external factors another decisive factor on performance

So far, several systems are available in the field of building installations for heating and cooling buildings. The current trend is to use renewable energy wherever possible. The choice of a suitable reversible heat pump system that combines heating and cooling is made by considering the following characteristics:

- Space users and type of building;
- Duration of occupancy of the building;
- Size of thermal load (heating/cooling) required;
- Primary energy sources available;
- Possibilities of using renewable energy resources;
- Energy performance of component parts;
- Investment and operating costs;
- Importance of the building

- The type of installations is also a defining factor: more precisely underfloor heating, radiators, fan convectors.

From current practice and countless certifications, a decisive factor in the performance of heat pumps is the operating temperature, the external temperature and the external humidity.

According to both practice and research, the performance of heat pumps is influenced by temperature parameters leading to changes in the coefficient of performance.

In the case of heat pumps, low temperature installations with large radiating surface are preferred. This allows the heat pump to operate at the lowest possible working temperatures. Also in the case of air-to-water pumps the outside temperatures have a major influence on the performance.

In Table 1 of a world renowned manufacturer of air-to-water heat pumps we observe that at an outdoor temperature of 7 degrees and a 35 degrees lap temperature for a 14 kw capacity pump the COP is 4.45, as soon as the lap temperature increases to 40 degrees the COP drops to 4. At the same outdoor values but with a lap temperature

of 60 degrees the COP of the pump drops to 2. All these values of the coefficient of performance decrease further with decreasing outdoor temperature. All these values can be influenced by the degree of insulation of the building, its position in relation to the cardinal points, solar gains, and the operating mode of the building.

Table 1. Influence of outdoor and operating temperature on the performance of air-water pumps

Outdoor unit	■ PUZ-HWM140VHA(-BS)		■ PUZ-HWM140YHA(-BS)		■ PUZ-HWM140VHA(-BS)		■ PUZ-HWM140YHA(-BS)		■ PUZ-HWM140VHA(-BS)		■ PUZ-HWM140YHA(-BS)		■ PUZ-HWM140VHA(-BS)		■ PUZ-HWM140YHA(-BS)		
	Water outlet temperature [°C]		25		35		40		45		50		55		60		
	Ambient temperature [°C]	Capacity	COP	Capacity	COP	Capacity	COP	Capacity	COP	Capacity	COP	Capacity	COP	Capacity	COP	Capacity	COP
Max	-28	-	-	9.1	1.60	8.8	1.45	8.5	1.30	-	-	-	-	-	-	-	-
	-25	-	-	10.0	1.65	9.7	1.50	9.3	1.35	-	-	-	-	-	-	-	-
	-20	-	-	12.0	1.75	11.6	1.60	11.2	1.45	-	-	-	-	-	-	-	-
	-15	-	-	14.0	1.85	13.5	1.70	13.1	1.55	12.6	1.45	12.2	1.30	-	-	-	-
	-10	14.5	2.40	14.4	2.25	14.2	2.10	14.0	1.90	14.0	1.85	14.0	1.75	-	-	-	-
	-7	16.1	2.70	15.9	2.50	15.7	2.30	15.5	2.10	14.7	2.05	14.0	1.95	-	-	-	-
	2	16.5	3.25	16.3	3.00	16.0	2.75	15.8	2.50	15.1	2.45	14.3	2.35	14.0	2.10	-	-
	7	16.8	4.70	16.6	4.25	16.4	3.80	16.1	3.30	15.4	2.90	14.6	2.50	14.0	2.50	-	-
	12	17.1	5.25	16.8	4.90	16.6	4.55	16.4	4.20	15.6	3.70	14.8	3.20	14.1	2.70	-	-
	15	18.5	5.35	18.2	5.00	17.9	4.75	17.7	4.50	16.9	4.00	16.0	3.50	15.2	3.00	-	-
20	21.1	7.25	20.8	6.50	20.5	5.75	20.2	4.95	19.3	4.40	18.3	3.80	17.3	3.25	-	-	
Nominal	-28	-	-	9.1	1.60	8.8	1.45	8.5	1.30	-	-	-	-	-	-	-	-
	-25	-	-	10.0	1.65	9.7	1.50	9.3	1.35	-	-	-	-	-	-	-	-
	-20	-	-	10.5	2.00	10.2	1.85	9.8	1.65	-	-	-	-	-	-	-	-
	-15	-	-	11.0	2.30	11.0	2.10	11.0	1.90	11.0	1.75	11.0	1.60	-	-	-	-
	-10	14.0	2.80	14.0	2.50	14.0	2.20	14.0	1.90	14.0	1.85	14.0	1.75	-	-	-	-
	-7	14.0	3.05	14.0	2.80	14.0	2.55	14.0	2.30	14.0	2.15	14.0	1.95	-	-	-	-
	2	14.0	3.40	14.0	3.15	14.0	2.90	14.0	2.65	14.0	2.55	14.0	2.40	14.0	2.10	-	-
	7	14.0	4.90	14.0	4.45	14.0	4.00	14.0	3.50	14.0	3.15	14.0	2.75	14.0	2.50	-	-
	12	14.0	5.50	14.0	5.15	14.0	4.80	14.0	4.45	14.0	4.00	14.0	3.50	14.0	3.00	-	-
	15	14.0	5.50	14.0	5.25	14.0	5.00	14.0	4.75	14.0	4.30	14.0	3.85	14.0	3.40	-	-
20	14.0	7.65	14.0	6.85	14.0	6.05	14.0	5.25	14.0	4.75	14.0	4.20	14.0	3.70	-	-	
Mid	-28	-	-	7.3	1.70	7.0	1.60	6.8	1.45	-	-	-	-	-	-	-	-
	-25	-	-	8.0	1.75	7.7	1.65	7.5	1.50	-	-	-	-	-	-	-	-
	-20	-	-	8.4	2.15	8.1	2.00	7.8	1.85	-	-	-	-	-	-	-	-
	-15	-	-	8.8	2.50	8.8	2.30	8.8	2.10	8.8	1.90	8.8	1.70	-	-	-	-
	-10	11.2	2.85	11.2	2.70	11.2	2.55	11.2	2.35	11.2	2.10	11.2	1.85	-	-	-	-
	-7	11.2	3.25	11.2	3.00	11.2	2.75	11.2	2.50	11.2	2.30	11.2	2.10	-	-	-	-
	2	11.2	3.65	11.2	3.40	11.2	3.15	11.2	2.90	11.2	2.75	11.2	2.55	11.2	2.30	-	-
	7	11.2	5.25	11.2	4.80	11.2	4.35	11.2	3.85	11.2	3.40	11.2	2.90	11.2	2.50	-	-
	12	11.2	5.85	11.2	5.55	11.2	5.25	11.2	4.90	11.2	4.30	11.2	3.70	11.2	3.00	-	-
	15	11.2	6.00	11.2	5.65	11.2	5.45	11.2	5.25	11.2	4.65	11.2	4.05	11.2	3.40	-	-
20	11.2	8.10	11.2	7.35	11.2	6.60	11.2	5.80	11.2	5.10	11.2	4.40	11.2	3.70	-	-	
Min	-28	-	-	4.8	1.70	4.4	1.45	4.0	1.15	-	-	-	-	-	-	-	-
	-25	-	-	5.5	1.75	5.0	1.50	4.8	1.20	-	-	-	-	-	-	-	-
	-20	-	-	6.7	2.05	6.1	1.75	5.5	1.40	-	-	-	-	-	-	-	-
	-15	-	-	7.8	2.35	7.2	2.00	6.5	1.60	5.7	1.30	4.8	1.00	-	-	-	-
	-10	6.2	2.55	5.9	2.30	5.6	2.05	5.3	1.75	4.6	1.45	4.0	1.10	-	-	-	-
	-7	5.1	3.65	4.0	2.25	4.0	2.05	4.0	1.85	3.6	1.50	3.1	1.15	-	-	-	-
	2	5.6	4.20	5.1	3.65	4.7	3.10	4.2	2.50	3.7	2.05	3.2	1.55	-	-	-	-
	7	4.5	6.60	4.2	4.45	3.7	3.50	3.2	2.55	2.7	2.00	2.2	1.45	-	-	-	-
	12	6.6	5.15	6.2	4.90	5.8	4.65	5.4	4.35	5.2	3.70	5.0	3.05	-	-	-	-
	15	6.9	5.15	6.4	5.10	5.9	5.05	5.4	4.95	5.3	4.35	5.2	3.70	-	-	-	-
20	7.3	14.00	6.7	8.00	6.4	6.65	6.0	5.30	5.6	4.40	5.1	3.45	-	-	-	-	

If we discuss primary energy source heat pumps using soil or groundwater the situation changes radically.

7. The earth as the primary heat source of energy, the impact of this source on the performance of the heat pump

Soil captures solar radiant energy. Energy is captured by the ground either directly in the form of solar radiation or indirectly as heat from rain or air. Geothermal energy is part of the renewable (green) energy class and is heat that comes from inside the Earth (through underground rocks and fluids). It is produced by capturing hot water and steam from volcanically and tectonically active areas or heat from underground.

Soil temperature as well as external air temperature have a periodic variation. The natural variation of soil temperature is influenced by several external parameters (climatic: solar radiation, precipitation, wind speed, etc.), soil composition, soil moisture (which in turn depends on precipitation as well as on the dynamics of the water table). As in any thermodynamic system, the temperature values in the soil are

different. The temperature field generally depends on position and time coordinates. Soil can be considered as a semi-infinite wall with periodic thermal stress [14][15]. Geothermal energy is accumulated from three distinct sources, solar radiation and energy from precipitation which is captured by flat plate collectors mounted on the earth's surface and geothermal heat from within the earth which is captured by vertical deep boreholes. An enormous amount of heat is available in the earth's crust, which is on average 40 km thick, but at present due to technology and cost we can only profitably use a small fraction of it. We usually use heat from depths between 70 and 200 meters. This type of geothermal energy is characterized by low temperatures, but the advantage is that starting from shallow depths the earth's temperature is relatively constant throughout the year, for example:

- at 1 m depth the earth temperature varies between 5 °C in February and 15 °C in August
- at 1.5 m depth the earth temperature varies between 7 °C in February and 13 °C in August
- at a depth of 10 m the earth temperature varies between 9 °C in February and 11 °C in August
- at depth over 18 m the ground temperature is relatively constant at about 10 °C
- above 18 m depth, the ground temperature increases by 1 °C for every 33 meters depth
- at 100 m depth the earth temperature is about 12 °C
- at 200 m depth the earth temperature is about 15 °C

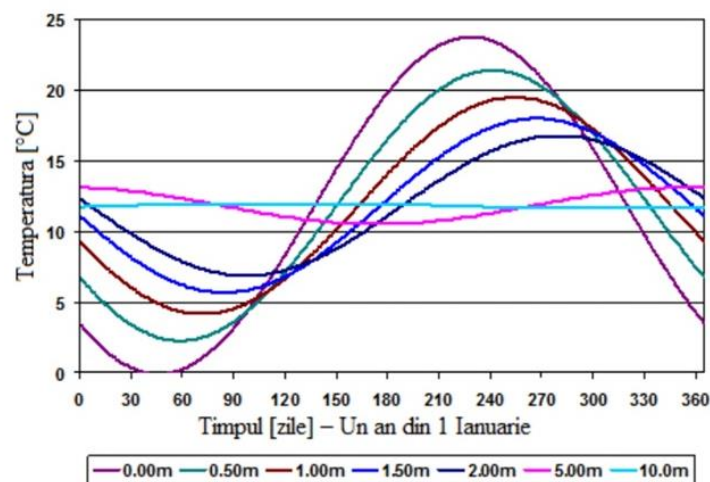


Fig. 5. Soil temperature variation over one year in Cluj- Napoca up to a depth of 10 meters.

In the case of heat pumps the primary energy source has a decisive factor on the performance of the heat pump. Disregarding that table no.1 would belong to air-water heat pumps, we will report the temperature of the primary source as if it were the ground temperature and we will take an average of 7 degrees.

At a primary source temperature of 7 degrees the COP is 4.45, at a tower temperature of 40 degrees the COP is 4. This 7 degree temperature at a given depth can be a constant average over the heating season.

In the case of air-to-water heat pumps if we are talking about a much lower SCOP, then we refer to the number of degree days corresponding to the climate zone III of Romania as an example.

The temperature degree days according to SR 4839/2014 is 2,275 degrees. At this temperature according to Table 1 the seasonal coefficient of performance is much reduced for an air-to-water heat pump compared to a ground-to-water heat pump.

In conclusion the primary energy source is a defining criterion influencing the performance.

Table 2. Number of degree days

	Number	Q _{e0}	Q _e	Dz	
Month	Day	°C	°C	Days	
July	31	12	19.4	0	2.275
August	31	12	18.9	0	
September	14	12	14.2	198.8	
October	30	12	9.0	270	
November	30	12	3.0	90	
December	31	12	-1.6	-49.6	
January	31	12	-2.9	-89.9	
February	28	12	-1.4	-39.2	
March	31	12	3.8	117.8	
April	20	12	9.5	190	
May	0	12	14.7	0	
June	0	12	17.6	0	
	215			489.1	

$$\theta_{em} = \sum \theta_e(x=1-n)/z \quad \theta_{em} = 2.275 \text{ } ^\circ\text{C}$$

θ_{em} - average out door temperature

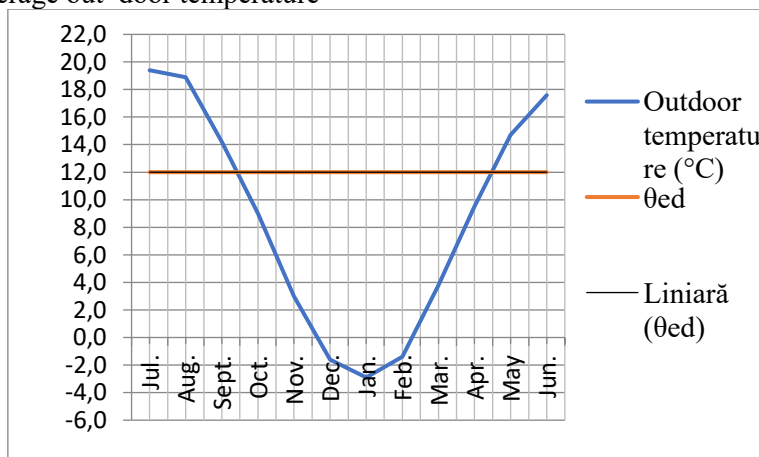


Fig. 6. Representation of monthly mean outdoor temperatures according to SR 4839/2014.

This aspect regarding the choice of pump type according to the primary energy source must be taken into consideration as it may compromise the performance of an entire system if the building is located in a particularly cold zone. (e.g. zone IV.) In such situations the choice of a heat pump with a ground-to-water or water-to-water primary source should be made. As can be seen in Fig. 6 and by correlation with Table 1, the average temperature of 2.25 degrees in zone III corresponds to a much lower COP as shown in Table 1

8. Conclusions

The performance of a heat pump system is influenced by several factors, such as compressor technology, type of refrigerant, type of primary energy source and its temperature, settings such as the temperature curve. All these factors contribute to an energy efficient system. These factors have a major contribution to the performance of the heat pump system in general. These factors need to be taken into account at the design stage, whether we are talking about the installation system to which the heat pump is connected or the equipment itself. Support in complying with these specifications and parameters is provided by European legislation in force through the environmental regulations in force and, for the installation system part, by the specialized personnel: engineers, technicians, designers. They can be a real support. The final goal being a reduced energy consumption that will contribute to reducing greenhouse gas emissions.

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