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Original scientific paper

# Analysis of Energy Consumption of a Thermo-Technical System with an Absorption Heat Pump

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**Abstract:** This paper discusses two different thermo-technical systems for heating and cooling the three-story office building under consideration. Data were collected on natural gas energy consumption over three-year period. The measured data on energy consumption for heating and cooling the building with an absorption heat pump using natural gas as fuel was analyzed. The only device that can replace the absorption heat pump in both the heating and cooling seasons is the vapor compression heat pump. The absorption heat pump has higher energy consumption than the vapor compression heat pump and its price is about 30% higher, but the financial cost of energy from natural gas is about 39% lower than the electricity cost of the vapor compression heat pump. The absorption heat pump is a better solution than the compression heat pump because the total financial costs, which include the investment costs and the energy costs over 20 years of operation, are about 9% lower and because the absorption heat pump heats up to an ambient temperature of –20 °C, which is not the case with the vapor compression heat pump.

**Keywords:** absorption heat pump; cooling; heating; thermo-technical system; vapor compression heat pump

## 1 INTRODUCTION

Nowadays, space heating technologies are based on burning fossil fuels such as natural gas, petroleum and coal. The heavy use of fossil fuels has led to environmental pollution and greenhouse gas emissions. With continuous population growth and rising standards, energy consumption is also increasing. Therefore, renewable energy sources such as geothermal energy [1], biomass [2], solar energy [3] and wind power [4] need to be used more. By generating clean energy from renewable sources, green energy buildings [5] can reduce their dependence on fossil fuels, which is crucial for mitigating climate change. Combining gas condensing boilers [6] with renewable energy sources can increase a building's energy independence. When renewable sources are integrated into the system, they can provide a portion of the heating needs, reducing the building's dependence on external energy supplies and increasing resilience during power outages.

Many researchers believe that energy from the air is a reliable and environmentally friendly source of energy suitable for heating future buildings [7].

Heat pump technology using air as a heat source can save high-grade energy and fully utilize low-grade energy. Air absorption heat pumps are economical, environmentally friendly and highly efficient. They have been studied theoretically and experimentally. Li et al. [8] have developed a cogeneration system in conjunction with an absorption heat pump to use solar energy. The proposed model showed good energy saving potential, so that the overall energy and exergy efficiency of the system was increased compared to the basic system, reaching 16,90% and 15,76%, respectively. Dai et al. [9] have theoretically and experimentally investigated an ammonia-water absorption heat pump driven by a parabolic trough collector and using natural gas as the heat source. The coefficient of performance obtained ranged from 1,44 to 1,66 for ambient temperature ranging from 4,31 °C to 11,07 °C. Economic analysis has shown that operating costs can be reduced by 25% if a solar collector is added to the system. Keinath et al. [10] have established a thermodynamic model for gas-fired absorption heat pump water heater. They concluded that this gas-fired absorption heat pump water heater has higher coefficients of performance compared to commercial gas-fired heaters.

Wu et al. [11] have presented a solar absorption heat pump with air as the heat source and exhaust gas recovery. Compared to conventional solar heating systems, the gas-fired system had better performance and produced fewer pollutants. Wu et al. [12] have designed an air-source absorption heat pump for district heating driven by the natural gas and studied its performance. The results show that the system is efficient and COP achieves a value of 1,39 at the evaporation temperature of –10 °C. Lu et al. [13] built and studied a prototype absorption heat pump system using ammonia-water as the working fluid. It utilized heat from exhaust gasses generated from the combustion of natural gas and from the environment. A heating capacity of 30 kW was achieved with COP of 1,66 at an evaporating temperature of 0 °C and the authors concluded that the energy efficiency of the system is higher than that of conventional district heating systems.

In this paper, the energy consumption of the absorption heat pump determined by measurements is analyzed and compared with the energy consumption of a vapor compression heat pump in both the heating and cooling seasons.

## 2 THE PRINCIPLE OF OPERATION OF AN ABSORPTION HEAT PUMP

The working fluids used in heat absorption pumps are binary mixtures, usually ammonia-water ($NH_3$-$H_2O$) and water-lithium bromide ($H_2O$-LiBr). If the absorption heat pump is used for space heating and cooling, the working fluid is ammonia- water. The schematic of the simplest absorption heat pump is shown in Fig. 1. The liquid binary mixture evaporates in the desorber by supplying heat (in this case heat generated by gas combustion) and pure vapor of the participant is formed from the binary ammonia-water mixture, which boils more easily. In this case, ammonia vapor ($NH_3$) is formed.

The ammonia vapor pressure must be high enough to allow the ammonia vapor to condense in the condenser. When the heat pump is in the function of space heating, the heat released in the condenser is transferred to the heating water that heats the space, and when it is in the function of space cooling, the heat is transferred to the air. The condensed ammonia is throttled to a lower pressure in the expansion valve, which lowers the boiling temperature. Lowering the boiling temperature allows the liquid to evaporate at a lower temperature, absorbing heat. The heat absorbed by the ammonia in the evaporator is removed from the air when the heat pump is in the heating function, and it is removed from the chilled water that cools the space when it is in the cooling function. The processes that take place in the condenser, expansion valve and evaporator are similar to the processes that take place in the air to water compression heat pump.

An important difference between the absorption and compression heat pumps is the mode of compression from the evaporator pressure to the condenser pressure. In a compression heat pump, the compression process is performed by a compressor, while in an absorption heat pump, a "thermal compressor" consists of an absorber, a pump, a desorber, and an expansion valve. After the cold ammonia vapor leaves the evaporator, it enters the absorber, where it is absorbed into the water, releasing heat. Then the solution is brought to the condenser pressure by a pump and enters the desorber, where the ammonia evaporates, while the rest of the solution or lean mixture is throttled to the pressure of the evaporator by the expansion valve.

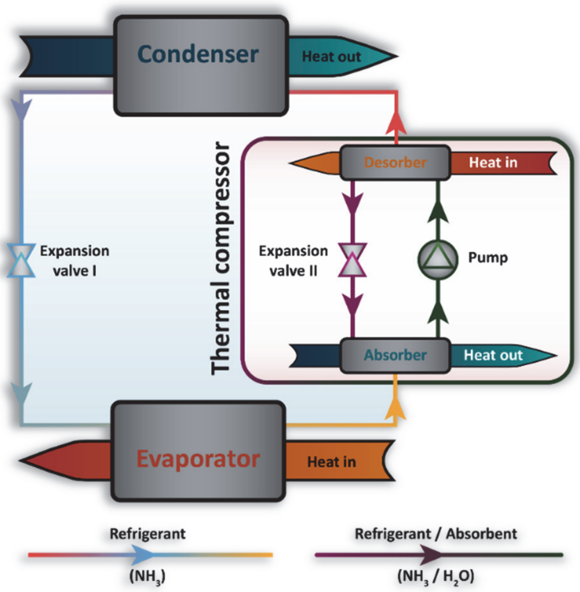


**Figure 1** Scheme of the absorption heat pump

## 3 DESCRIPTION OF THE THERMO-TECHNICAL SYSTEM

For the heating and cooling of the office building with a floor area of 720 m$^2$ in Slavonski Brod, which has three floors, a thermo-technical system was built that uses an air to water absorption heat pump powered by natural gas. The heat pump is installed on a flat part of the roof on the second floor. It consists of three cascade-connected modules that are fully hydraulically and electrically connected on a common steel base.

The heat pump is installed outdoors and takes the air for combustion directly from the surrounding atmosphere, and discharges the combustion products directly into the atmosphere. The heating capacity is 105 kW at an outdoor air temperature of 7 °C, and the cooling capacity is 52,5 kW at an outdoor air temperature of 35 °C. Fan coils were installed to heat and cool all rooms in the building, with water flowing through them, at temperatures of 55/45°C in winter and 7/12°C in summer. The system operates five days a week from 6 am to 3 pm. The heating season lasts from October 15 to April 15, and the cooling season from April 15 to October 15.

Fig. 2 shows the dependence of COP on the outdoor air temperature for different supply temperatures during the heating season for an installed air to water absorption heat pump. It can be seen that the values of COP range from 0,96 to 1,56, which is characteristic for absorption heat pumps. The value of COP increases with the increase of outdoor temperature and the decrease of the supply temperature, which is expected. With a higher outdoor temperature, the pressure in the evaporator increases, which leads to a decrease in the heat energy that must be brought to the desorber and a decrease in the energy consumption of natural gas. Lowering the supply temperature, decreases the pressure in the condenser, which decreases the consumption of heat energy that must be brought to the desorber, resulting in the same effect as when the outdoor temperature increases.The most favorable operating conditions for the heat pump in the heating season are at higher outdoor air temperatures and lower supply temperatures. The diagram shows that the operation of the compression heat pump is possible even at outdoor air temperatures as low as –20 °C.

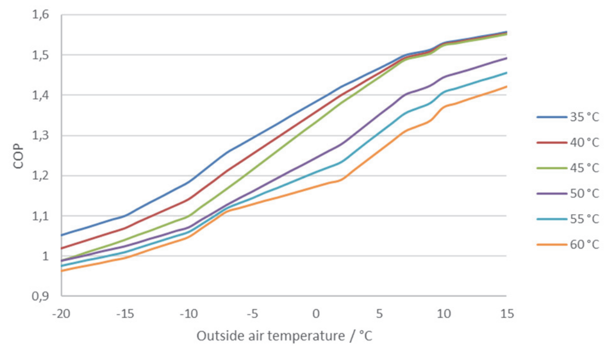


**Figure 2** Dependence of COP on outdoor air temperature for different supply temperatures for the heating regime of the absorption heat pump

Fig. 3 shows the dependence of EER on the outdoor air temperature for different supply temperatures in the cooling season for an installed air to water absorption heat pump. It can be seen that the EER values range from 0,475 to 0,735 depending on the outdoor air temperature and the supply temperature. The EER value decreases with an increase in the outdoor air temperature and a decrease in the supply temperature, which is to be expected. With a higher outdoor air temperature, the pressure in the condenser increases, resulting in an increase in heat energy that must be brought to the desorber and an increase in natural gas energy consumption. Lowering the supply temperature decreases the pressure in the evaporator, which increases the consumption of heat energy that must be brought to the desorber, resulting in the same effect as when the outdoor temperature increases. The most favorable operating conditions for the heat pump in the cooling season are at lower outdoor air temperatures and at higher supply temperatures. It can be seen from the diagram that the supply temperatures 5 °C and 6 °C cannot be achieved at outdoor air temperatures higher than 35 °C.

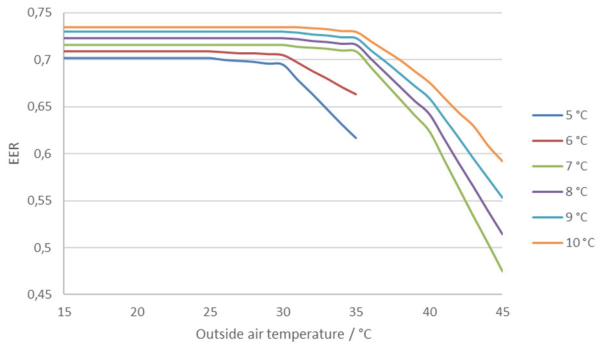


**Figure 3** Dependence of EER on outdoor air temperature for different supply temperatures for the cooling regime of the absorption heat pump

## 4 ENERGY CONSUMPTION ANALYSIS

Tabs. 1 and 2 present measured gas energy consumption data by month for the heating and cooling seasons in the three years for which the measurement was made. Consumption depends on meteorological conditions, i.e. in terms of outdoor air temperature, consumption differs depending on the year and month of measurement.

Based on the measured hourly air temperatures for the city of Slavonski Brod and the heat pump manufacturer's measured data on the coefficient of performance (COP) (Fig. 2.) and energy efficiency ratio (EER) (Fig. 3.), the monthly coefficient of performance and monthly energy efficiency ratio were determined. Tables 3 and 4 show the monthly coefficient of performance for each month of the heating season and the energy efficiency ratio for each month of the cooling season. The parameter on which the ratio depends when the system operates with a constant supply and return temperature during the heating and cooling seasons, is the outdoor temperature. The tables show that the monthly COP ranges from 1,2250, in the colder months, to 1,4056, in the warmer months, while the EER ranges from 0,7126, in the warmer months of the cooling season, to 0,7318 in the colder months of the cooling season.

**Table 1** Gas energy consumption for each month of the heating season / kWh

| | January | February | March | April | October | November | December |
|---|---|---|---|---|---|---|---|
| 2018. | 5444 | 7835 | 6483 | 728 | 1973 | 5379 | 8101 |
| 2019. | 7971 | 6305 | 2954 | 1885 | 2473 | 3818 | 6524 |
| 2020. | 8431 | 5458 | 5021 | 2579 | 2219 | 4509 | 6788 |

**Table 2** Gas energy consumption for each month of the cooling season / kWh

| | April | May | June | July | August | September | October |
|---|---|---|---|---|---|---|---|
| 2018. | 373 | 3203 | 3030 | 2726 | 5734 | 2650 | 208 |
| 2019. | 277 | 1174 | 4736 | 6826 | 6638 | 3647 | 371 |
| 2020. | 430 | 574 | 915 | 6048 | 5752 | 3742 | 250 |

**Table 3** Monthly coefficients of performance of the absorption heat pump for each month of the heating season

| | January | February | March | April | October | November | December |
|---|---|---|---|---|---|---|---|
| 2018. | 1,2925 | 1,2265 | 1,2857 | 1,4056 | 1,3909 | 1,3214 | 1,2440 |
| 2019. | 1,2343 | 1,2977 | 1,3516 | 1,3962 | 1,3762 | 1,3951 | 1,2863 |
| 2020. | 1,2250 | 1,3491 | 1,3355 | 1,3289 | 1,3666 | 1,3458 | 1,2770 |

**Table 4** Monthly energy efficiency ratio of the absorption heat pump for each month of the cooling season

| | April | May | June | July | August | September | October |
|---|---|---|---|---|---|---|---|
| 2018. | 0,7248 | 0,7247 | 0,7181 | 0,7216 | 0,7126 | 0,7214 | 0,7318 |
| 2019. | 0,7242 | 0,7314 | 0,7176 | 0,7194 | 0,7131 | 0,7238 | 0,7266 |
| 2020. | 0,7302 | 0,7301 | 0,7259 | 0,7169 | 0,7190 | 0,7245 | 0,7290 |

Based on the calculated COP and EER and the measured gas energy consumption in the heating and cooling regime, the required energy for heating and cooling the office building is determined, which is important for further analysis of energy consumption if the vapor compression heat pump is installed in the system for space heating and cooling.

**Table 5** Energy required to heat the building for each month of the heating season / kWh

| | January | February | March | April | October | November | December |
|---|---|---|---|---|---|---|---|
| 2018. | 7036 | 9609 | 8335 | 1023 | 2744 | 7108 | 10078 |
| 2019. | 9839 | 8182 | 3993 | 2632 | 3403 | 5327 | 8392 |
| 2020. | 10328 | 7363 | 6706 | 3427 | 3033 | 6068 | 8668 |

**Table 6** Energy required to cool the building for each month of the cooling season / kWh

| | April | May | June | July | August | September | October |
|---|---|---|---|---|---|---|---|
| 2018. | 270 | 2321 | 2176 | 1967 | 4086 | 1912 | 152 |
| 2019. | 201 | 859 | 3399 | 4910 | 4733 | 2640 | 270 |
| 2020. | 314 | 419 | 664 | 4336 | 4135 | 2711 | 182 |

The only device that can replace the absorption heat pump in both heating and cooling mode is the vapor compression heat pump, which uses electricity as an energy source. For the comparison, a vapor compression heat pump was selected that has approximately the same heating capacity as the installed absorption heat pump.

Fig. 4 shows the dependence of COP on the outdoor air temperature for different supply temperatures in heating mode for the selected air to water heat pump. It can be seen that the COP values range from 1 to 4,9 as a function of the outdoor air temperature and the supply temperature. The value of COP increases with the increase of the outdoor temperature and the decrease of the supply temperature, which is expected. When the outdoor temperature is higher, the pressure in the evaporator increases, resulting in a decrease in the compression ratio and a decrease in the energy consumption, i.e. an increase in the thermal energy generated. When the supply temperature decreases, the pressure in the condenser decreases, which decreases the compression ratio, resulting in the same effect as when the outdoor temperature increases. The most favorable operating conditions for the heat pump in the heating season are at higher outdoor air temperatures and lower supply temperatures. The diagram shows that the operation of the vapor compression heat pump is limited to a minimum outdoor air temperature of –15 °C and that at temperatures below –15 °C there are difficulties in the operation of the system.

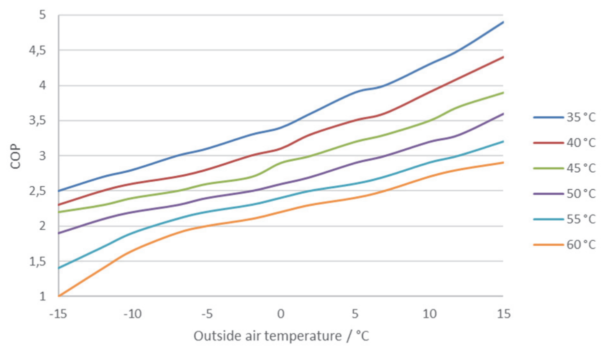


**Figure 4** Dependence of COP on outdoor air temperature for different supply temperatures for the heating regime of the vapor compression heat pump

Fig. 5 shows the dependence of EER on outdoor air temperature for different supply temperatures in the cooling season for the selected air to water heat pump. It can be seen that the EER values range from 1,9 to 5,5 depending on the outdoor air temperature and the supply temperature. The EER value decreases as the outdoor temperature increases and the supply temperature decreases, which is to be expected. When the outdoor air temperature is higher, the pressure in the condenser increases, which results in an increase in the compression ratio and an increase in energy consumption. When the supply air temperature decreases, the pressure in the evaporator decreases, which increases the compression ratio, resulting in the same effect as when the outdoor temperature increases. The most favorable operating conditions for the heat pump in the cooling season are at lower outdoor air temperatures and higher supply temperatures.

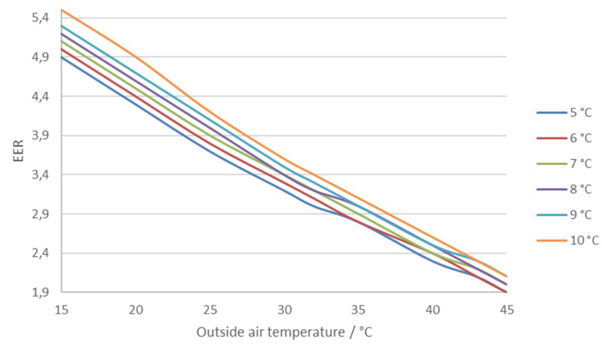


**Figure 5** Dependence of EER on outdoor air temperature for different supply temperatures for the cooling regime of the vapor compression heat pump

The energy consumption of a vapor compression heat pump depends on the COP and EER. The values of COP and EER depend on the outdoor air temperature and the supply temperature which are shown in Figs. 4 and 5 in the same way as in the case of the absorption heat pump. Accordingly, the ways of COP and EER calculation and the electricity consumption are determined in the same way as for the absorption heat pump. Tabs. 9 to 12 show the values of COP and EER and the electricity consumption for each month in the heating season and each month in the cooling season.

**Table 9** Monthly coefficients of performance of the compression heat pump for the months of the heating season

| | January | February | March | April | October | November | December |
|---|---|---|---|---|---|---|---|
| 2018. | 2,4647 | 2,3133 | 2,4608 | 2,7896 | 2,7477 | 2,5514 | 2,3417 |
| 2019. | 2,3409 | 2,4829 | 2,6414 | 2,7632 | 2,6760 | 2,7505 | 2,4630 |
| 2020. | 2,2978 | 2,6134 | 2,5952 | 2,5745 | 2,6810 | 2,5963 | 2,4384 |

**Table 10** Monthly energy efficiency ratio of the compression heat pump for the months of the cooling season

| | April | May | June | July | August | September | October |
|---|---|---|---|---|---|---|---|
| 2018. | 3,9086 | 3,9165 | 3,7361 | 3,8296 | 3,6205 | 3,8265 | 4,1860 |
| 2019. | 3,8981 | 4,1667 | 3,7357 | 3,7780 | 3,6274 | 3,8916 | 3,9732 |
| 2020. | 4,1000 | 4,1015 | 3,9631 | 3,7307 | 3,7607 | 3,9194 | 4,0548 |

**Table 11** Electricity consumption for the months of the heating season / kWh

| | January | February | March | April | October | November | December |
|---|---|---|---|---|---|---|---|
| 2018. | 2855 | 4154 | 3387 | 367 | 999 | 2786 | 4304 |
| 2019. | 4203 | 3295 | 1512 | 952 | 1272 | 1937 | 3407 |
| 2020. | 4495 | 2818 | 2584 | 1331 | 1131 | 2337 | 3555 |

**Table 12** Electricity consumption for the months of the cooling season / kWh

| | April | May | June | July | August | September | October |
|---|---|---|---|---|---|---|---|
| 2018. | 69 | 593 | 582 | 514 | 1129 | 500 | 36 |
| 2019. | 51 | 206 | 910 | 1300 | 1305 | 678 | 68 |
| 2020. | 77 | 102 | 168 | 1162 | 1100 | 692 | 45 |

The comparison of gas and electricity consumption is shown in Figs. 6 and 7. It can be seen that the absorption heat pump consumes 1,88 to 1,98 times more gas energy to heat the building than the compression heat pump. In the cooling season, the consumption ratio is much higher and ranges from 5,08 to 5,72. It can be concluded that the absorption heat pump is more favorable in the heating season than in the cooling season.

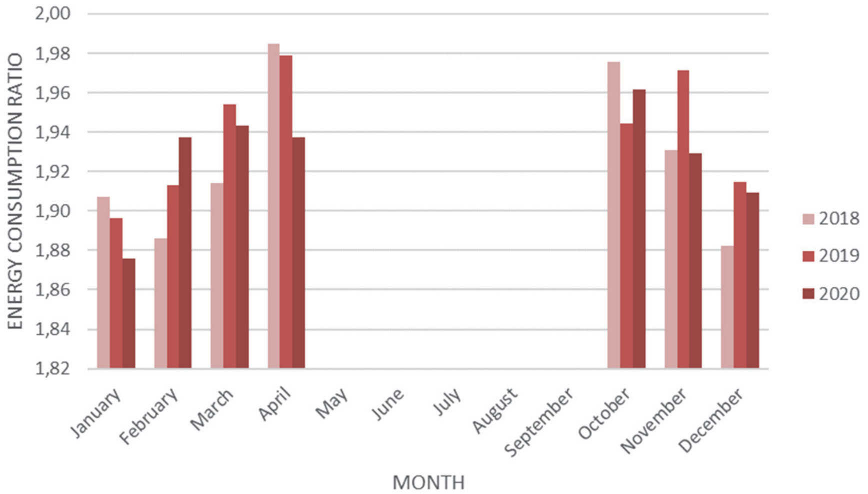


**Figure 6** Representation of the ratio of gas and electricity consumption in the heating season

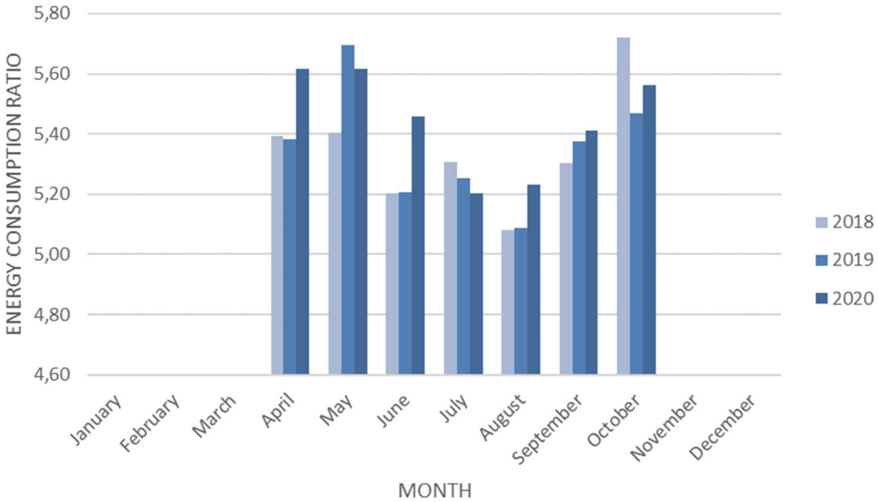


**Figure 7** Representation of the ratio of gas and electricity consumption in the cooling season

## 5 TECHNO-ECONOMIC ANALYSIS

For a complete comparison of absorption and compression heat pumps, a techno-economic analysis is required, in addition to the consumption analysis. For the economic analysis, the prices of the two devices were determined (the prices are from the seller) where the compression heat pump having approximately the same heating capacity as the absorption heat pump installed in the building (the rest of the techno-economic system is modelled with the same influencing parameters for both devices). The absorption heat pump is about 30% more expensive.

Since a 3-year period was considered in the energy consumption analysis, the gas consumption of the absorption heat pump and the electricity consumption of the compression heat pump were averaged for the economic analysis. In accordance with the average energy consumption and the energy price, the annual energy costs are determined, which in the case of the absorption heat pump are lower than the energy costs of the compression heat pump by about 39 %.

If the prices of the devices and the annual energy costs for both devices are compared, it can be concluded that the higher investment costs of a system with an absorption heat pump pay off in lower energy costs over a period of 11 years. The lifetime of such systems is at least 20 years. Therefore, the overall conclusion is that the absorption heat pump is a better device from an economic point of view, since the total investment cost and the energy cost are lower over 20 years. The exact numerical values of the equipment prices, average gas/electricity consumption, energy prices and annual energy costs can be found in Tab. 13.

**Table 13** Economic comparison of absorption heat pump and compression heat pump

| | Absorption heat pump | Compression heat pump |
|---|---|---|
| Device price / € | 43363 | 33330 |
| Average annual gas / electricity consumption / kWh | 54061 | 21655 |
| Energy price / €/kWh | 0,0427 | 0,1485 |
| Annual energy cost / € | 2308 | 3216 |

In terms of functionality (technical function availability of the device), an important advantage of the absorption heat pump over the compression heat pump is that there are no problems with operation at low ambient temperatures, i.e. the absorption heat pump guarantees safe operation at temperatures as low as –20 °C unlike compression heat pump which has a minimum operating temperature of –15 °C.

## 6 CONCLUSION

From the analysis of the consumption of a thermo-technical system with an absorption heat pump it is determined that the absorption heat pump is most efficient in the warmer months of the heating season and the colder months of the cooling season. The only device that can replace the absorption heat pump in both the heating and cooling seasons is the vapor compression heat pump, which uses electricity as an energy source.

From the analysis performed, it can be concluded that the absorption heat pump is more favorable in the heating season than in the cooling season. When considering the whole year, i.e. when both the heating season and the cooling season are taken into account, the absorption heat pump is a more favorable solution in terms of operating costs and operation reliability. The absorption heat pump has higher energy consumption than the compression heat pump and the price of the unit is higher, but the financial cost of natural gas energy is lower than the electricity cost of the compression heat pump. The absorption heat pump is a better solution than the compression heat pump because of the lower total financial cost, which includes the investment cost and the energy cost over a period of 20 years of operation, and because of the operational reliability, since the absorption heat pump heats up to an ambient temperature of –20 °C, which is not the case with the compression heat pump.

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