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A comparative study on electric and gas engine heat pump

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Abstract. The paper compares heat pumps driven by electric motors (EHP) with heat pumps driven by gas engines (GEHP). GEHPs are still a novelty on the Polish HVACR market - therefore, the subject of the study is to indicate whether in Polish climatic conditions their use is profitable. A thorough analysis of the energy consumption of selected devices was carried out due to the consumption of utilities needed for their propulsion and the related costs. This has been done by calculating seasonal efficiency coefficients and using an innovative method of comparative modifiers allowing for unification of the performance of EHP and GEHP pumps. The results obtained include average energy efficiency coefficients, operating costs and payback times. Discussion of the calculation results proved that under certain assumptions GEHP pumps may be competitive with EHP heat pumps due to the possibility of managing waste heat at high temperatures.

1 Introduction

Gas engine driven heat pump (GEHP) is a relatively new technology, the first industrial application get back to 1985. GEHP is mainly used in industry, office buildings, warehouses and hotels. It is because of narrow range of products designed for individual customers. The equipment is dominated by devices with a capacity many times greater than the heat demand of a residential house. On the other hand, heat pumps driven by an electric motor have been used since the 1920s. So there is wide range of capacity comfortable for different customer needs. The share of heat pumps on the market of new detached houses in Poland currently reaches 12.5%.

Heat pumps driven by electric and gas motors operate a left-handed Linde refrigeration cycle. The described devices cooperate with lower and upper heat sources. The lower sources are air, water and soil. In the chemical, food and paper industry - these are high temperature waste heat streams. The upper source can be central heating and/or domestic hot water installations. For central heating, heat pumps can be operated in water, air or direct evaporation systems [1].

2 Technology

2.1 Engines

2.1.1 The electric engine

Modern EHP are equipped with high-performance motors with inverter which controls capacity from 30% to 100%. They are characterized by high energy efficiency, flexibility of work, low starting current, precise temperature control and long compressor life. The efficiency of high power electric motors is above 95%, for motors with small power the efficiency may decrease even up to 80%. It is due to the use of wires with a smaller cross-section and worse electromagnetic field distribution inside the machine.

2.1.2 The gas engine

The gas engine work is based on the Otto cycle. Devices with a power output of less than 60 kW are automotive engines adapted to this technology. More powerful motors are slow-running motors with a long service life specially designed for GEHP demands. The efficiency of the gas engine is much lower (from 30% to 45%), but the possibility of recovering waste heat generated during engine operation gives more efficiency [2, 3]. So, the technology can compete with other heating systems, including EHP.

In his report [4], Gasterra states, that internal combustion engines have an efficiency between 25% and 38%. The efficiency depends on the brand, engine type and power. More powerful engines usually have higher efficiency.

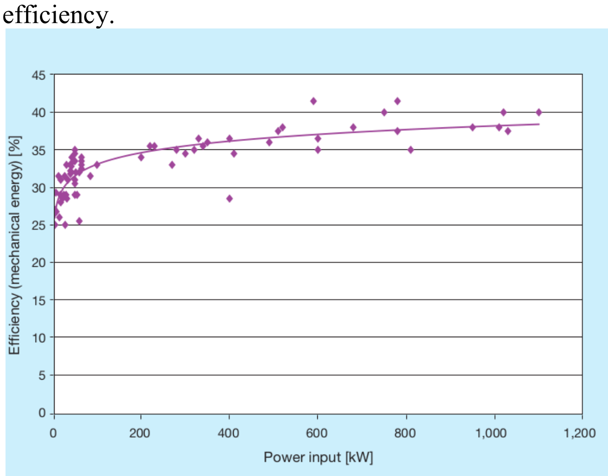

Fig. 1. Gas engine efficiency, Gasterra, 2010, [4]

In combustion engines there are parts the most exposed to wear which are replaceable. The service life of the engines driving heat pump compressors is longer than that of car engines. This is because of a smaller number of starts and stops, which lead to alternate cooling and heating of engine parts [4]. More frequent regular inspections are recommended for large installations or installations with old motors. The current engine generation requires less frequent inspections which include: valve adjustment, spark plug, oil and air filter inspection, fuel-to-air ratio inspection, and compressor measurement on all cylinders.

As far as regular maintenance is concerned, it is advisable to replace the oil filter, spark plugs and belt drive every 10,000 operating hours and to adjust the valves. However, an oil change is advisable every 30,000 operating hours.

New generation engines are equipped with a larger oil collector, modified ignition, special spark plugs and full synthetic oil [4]. For example, the manufacturer Aisin Toyota recommends that filters, spark plugs, V-belts and oil replenishment in the engine will be replaced every 5 years or 10,000 hours worked, while the oil will be replaced every 30,000 hours [5]. Assuming an annual operation of 3,120 hours (12 hours a day, 5 days a week), the inspections may be performed once every 3.2 years.

2.2 Compressors

In the case of heat pumps with power up to 100 kW, scroll compressors are used. In devices above 100 kW screw compressors are used.

2.3 Power system issues

Choosing GEHP instead of EHP leads to a reduction in electricity consumption, what could be important during summer peak demand for air conditioning drive. one favours the country's power system [6]. Then lower fluctuations in demand and lower maximum demand reduce the investment needs in peak and intermediate load power plants.

2.4 Specific applications

In addition to the advantages discussed above, GEHP has an additional benefit over EHP in situations where [7]:

- EHP connection would require a conversion of the voltage switchgear,

- the electricity consumption of the building must be reduced or part of the consumption must be allowed to supply other appliances,

- no possibility of connecting three-phase power supply,

- there is a constant high demand for hot water (swimming pools, spas, hotels, industrial processes),

- in countries where electricity prices significantly exceed gas prices.

3 Energy efficiency

We have 2 basic factors describing energy efficiency of heat pumps: EER and SEER in cooling and heating mode. EER is for examination of energy efficiency of heat pump in specific time, SEER is for whole heating and cooling season (Tab. 1).

Table 1. Conditions for heating and cooling modes of heat pumps

	Heating	Cooling
Outside temperature [°C]	7	35
Inside temperature [°C]	20	27

3.1 EER and SEER

The EER is the ratio of the useful energy output from the appliance to the energy supplied to the appliance to ensure its operation. It is the ratio that can be determined experimentally for a device under strictly defined temperature conditions. It describes the operation of the device in only one measuring point.

Table 2. Definitions of efficiency factor EER

Mode	EHP	GEHP
Heating (EER_{heat})	ratio of heating power to electric power consumed by the electric motor	ratio of heating power to the gas fuel heating power increased by electric power to drive auxiliary equipment
Cooling (EER_{cool})	ratio of cooling power to electric power consumed by the electric motor	ratio of cooling power to the gas fuel heating power increased by electric power to drive auxiliary equipment

Table 3. Examples of nominal EER values for the analysed heat pumps

Mode	EHP	GEHP
Heating (EER_{heat})	4.38	1.49
Cooling (EER_{cool})	4.58	1.18

Here, it is assumed that $SEER_{HEAT}$ and $SEER_{COOL}$ coefficients are not measured coefficients. They are estimated by using EER_{HEAT} and EER_{COOL} respectively, as provided by the manufacturer plus the conditions under which they were calculated.

The method of estimating the $SEER_{HEAT}$ and $SEER_{COOL}$ coefficients for GEHP is described in the European Standard DIN EN 16905 in Chapter 5. For EHP, the $SEER_{HEAT}$ and $SEER_{COOL}$ coefficients can be estimated using EN 14825.

A different way of estimating the above mentioned coefficients is presented below. In his report [7], Zaltash presents method of calculating the EER. It is evaluated for any temperature based on experimental measurements. In this way, it is possible to determine the EER for each temperature reached during the heating and cooling period. So, here SEER is determined as follows:

$$SEER = \sum_i t_i(T_i) \cdot EER_i(T_i) \qquad (1)$$

where t_i is the time of occurrence of T_i temperature and EER_i is the EER calculated on the basis of Table 2.

4 GEHP calculation methodology

The heat pump driven by a gas engine at the Oak Ridge National Heat Pump Laboratory [8] was taken into account for the analyses. Laboratory measurements of the efficiency at 1650, 2000 and 2400 rpm for gas engine revolutions and operating parameters were made. On this basis, a mathematical model of the device operation was prepared.

For the current analyses, GEHP with a heating power of 35 kW was taken into account. Simulated demand for heating power of the building is shown in Fig. 3. On the basis of the calculation model the characteristics of work were built depending on the external temperature assumed from -22°C to +16°C (Fig. 2.).

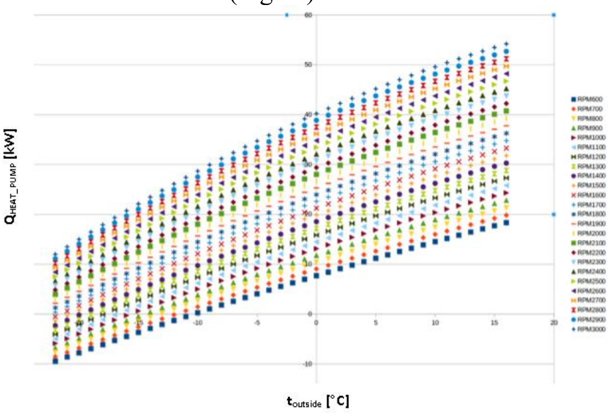

Fig. 2. Performance characteristics of the unit for different motor speeds as a function of outside temperature

Then the maximum and minimum pump capacity at a given temperature was calculated. The graph shows the ranges of smooth regulation of pump operation and building heat load (Fig. 3). The design temperature was assumed to be -10°C.

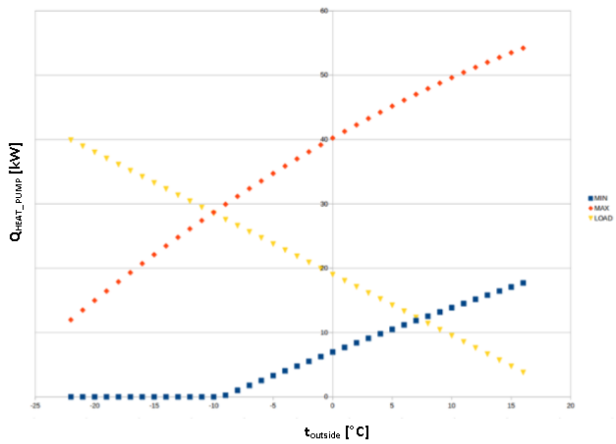

Fig. 3. Minimum and maximum operating range of GEHP taking into account the thermal load of the building

The characteristics of the heat pump indicate that it can operate continuously in the temperature range from -10°C to +7°C. Below -10°C, the GEHP must be supported by another emergency heating system to cover the building's needs.

From +7 to +16°C, the heat pump must be in ON-OFF mode. Operation in this mode is characterised by switching the motor off and in order to adjust the minimum heating capacity of the unit to the current building load. Such operation of the pump has a negative impact on the operation of the motor. Due to the frequency of occurrence of these temperatures in the heating period, an analysis of a system consisting of two heat pumps has been proposed. The diagram of the range of smooth work regulation is presented below.

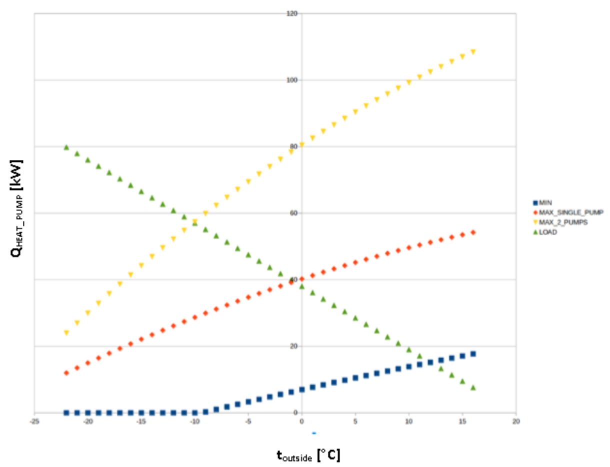

Fig. 4. Minimum and maximum operating range of two pump batteries combined with the heat load of the building in heating mode

The temperature's range of continuous operation of a single pump is from 0° to +11°C, while from -10° to -1°C is the range of simultaneous operation of two pumps. Below -10°C pump operation is supported by a peak heating system, while the range from +12° to +16°C is the operation of one of the pumps in ON-OFF mode.

To simplify further calculations, the thermal load of the building and the values directly related to it are given for continuous operation of one pump.

Further analysis allows us to create a computational model for determining the EER capacity ratio and the SEER seasonal capacity ratio.

The inverse characteristic of the EER_{HEAT} capacity coefficient is shown below (Fig. 5.)

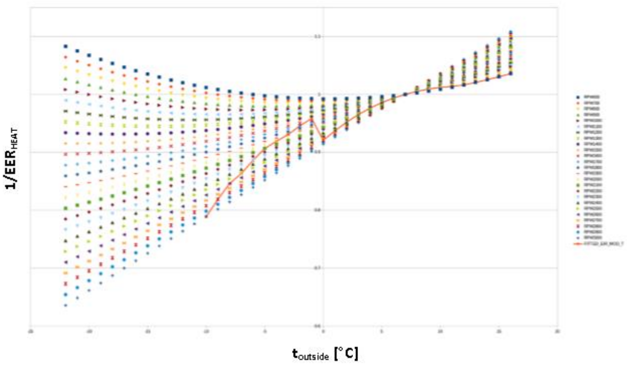

Fig. 5. Inversion of EER_{HEAT} of GEHP in heating mode

After calculating the $SEER_{HEAT}$ of 1.6, it was possible to estimate the total heating cost of a building for one heating period. This cost is 4560 EURO, of which 3,025 EURO was a cost associated with burning gas and 1,535 EURO was a component associated with the purchase of electricity to power auxiliary equipment.

Taking into account the achievable heat output from the cooling of the engine, the $SEER_{HEAT}$ factor has increased to 2.33. This significantly increases the economic benefits of using GEHP during the heating season. The pump is able to heat 1,538 m^3 of water (up to 45°C), which leads to savings of 20,806.85 PLN (approx. 4,624 EURO).

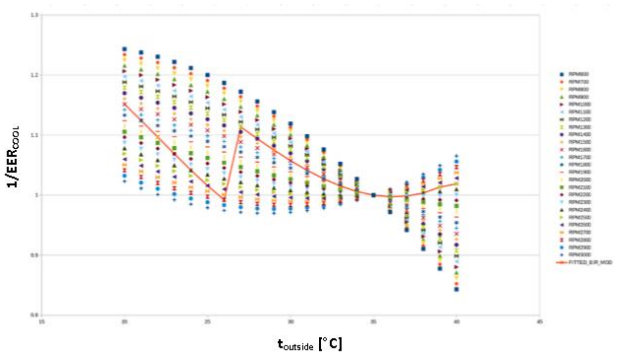

Fig. 6. Inversion of EER_{COOL} of GEHP in cooling mode

The same analysis was done for GEHP used in cooling mode (Fig. 6, 7). The $SEER_{COOL}$ coefficient was determined equals to 1.03. Then the total cost of GEHP work in cooling mode was 2,197 EURO, of which 1,887 EURO was related to the purchase of gas and 310 EURO to the purchase of electricity.

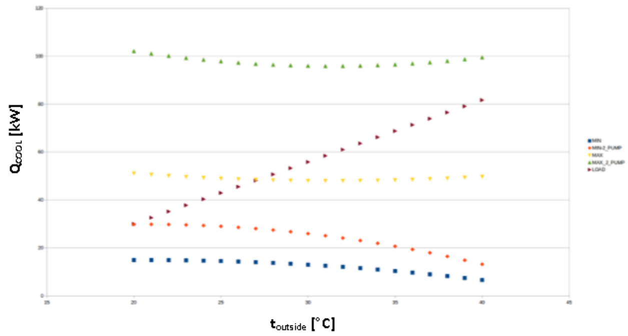

Fig. 7. Minimum and maximum operating range of two pump batteries combined with the heat load of the building in cooling mode

In the range from +24 to +26°C only one GEHP works. From +27 to +40, the need for building cooling can be satisfied by the simultaneous operation of two pumps. Also, as in the case of heating mode, the heat load of the building and the values directly related to it are given in relation to the continuous operation of one pump.

Taking into account the achievable heat from cooling of the engine, the $SEER_{COOL}$ factor has increased to 1.58. In the summer season, the pump is able to heat 809 m^3 of water, which leads to savings of 10,942 PLN or 2,431 EURO.

5 EHP calculation methodology

The following calculations have been made for the available data: heat load of the building in winter (Fig. 8) and summer (Fig. 10), hourly frequency of a given outdoor temperature, data on heat pumps driven by an electric motor. Characteristics of pump operation as a function of temperature were built, coefficients of heating and cooling capacity were determined. The SEER seasonal coefficient for heating and cooling was calculated, which allowed to determine the total cost of use of the pump in winter and summer.

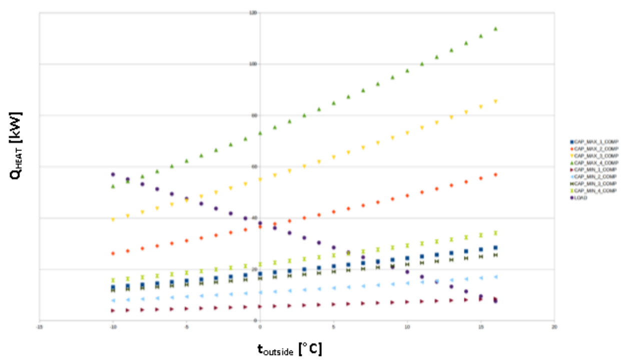

Fig. 8. Minimum and maximum operating range of two EHP heat pump batteries combined with the heat load of the building in heating mode

The power control range of a single compressor is from 30% to 100% of heating power. According to the fact that dual compressor pumps are the subject of analysis, the minimum efficiency is considered to be 15% of the heating power. In the range from +1 to +15°C, one EHP pump will be sufficient. At +16°C, one pump will operate in the ON/OFF mode. In the range from -8 to 0°C both pumps will operate simultaneously, while in the range from -10 to -9°C the operation of EHP pumps will be supported by an additional heating device.

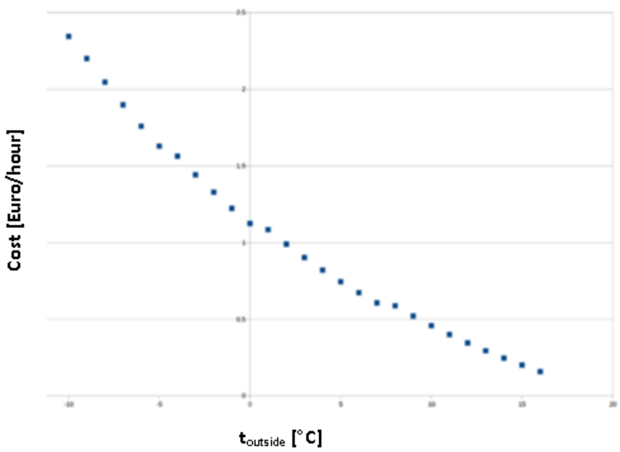

Fig. 9. Cost of EHP operation in the heating period as a function of the outside temperature

The total cost of the heating season was calculated as 4,379 EURO.

Next the cooling mode in summer was considered. The characteristics were built for work of EHP in cooling mode (Fig. 10)

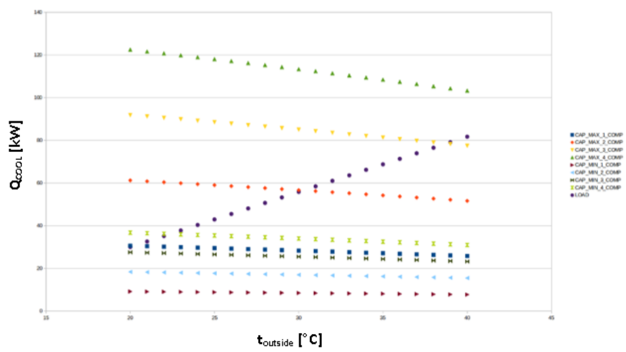

Fig. 10. Minimum and maximum operating range of two EHP heat pump batteries combined with the heat load of the building in cooling mode

The whole cost of exploitation of EHP for summer season was estimated upon partial costs (Fig. 11) as 1,070 EURO ($SEER_{COOL}$ = 4.63)

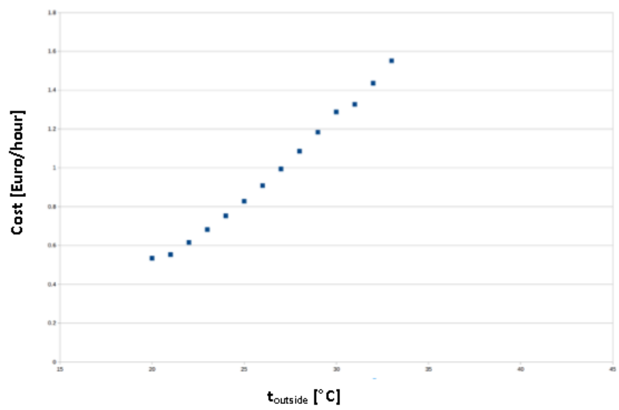

Fig. 11. Cost of EHP operation in the cooling period as a function of the outside temperature

Investment costs were estimated on the basis of available data [9]. Ultimately, the cost of installing GEHP was established as 30,000 EURO while EHP respectively as 25,000 EUR. Taking into account the savings due to the production of domestic hot water (GEHP) the operating costs of GEHP and EHP are estimated over a period of 10 years. This cost for GEHP is 65,500 EUR, compared to 90,200 EUR in case of EHP. Without the production of domestic hot water, GEHP is much worse. The operating costs for this configuration can be estimated as 122,000 EUR (Fig. 12).

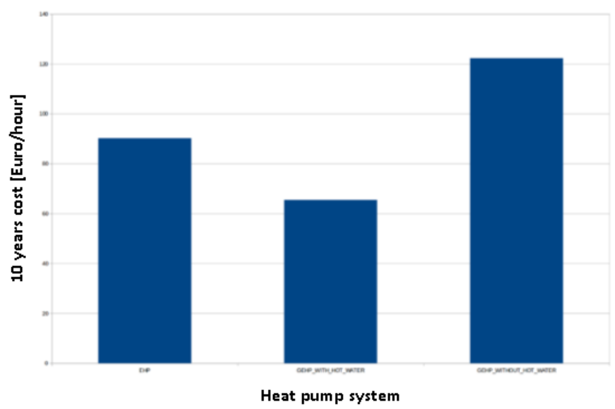

Fig. 12. Comparison of operating costs of GEHP and EHP systems

The operating costs of EHP and GEHP may differ from those estimated below due to annual fluctuations in electricity and gas prices.

6 Conclusions

The paper presents a comparison of the profitability of using heat pumps driven by a gas engine and conventional electric heat pumps. New calculation method of any gas and electric pump operating point allows to present characteristics of efficiency in heating and cooling mode, seasonal efficiency coefficients SEER and total costs of using the devices in heating and cooling season. Next, an economic analysis is made and the projected operating costs of the equipment for 10 years are presented. Conducted analysis allows to draw the following conclusions:

1. GEHP technologies are competitive in comparison with EHP when used in buildings with an energy demand above 30 kW. Usage of GEHP is economically justified in commercial applications because of good ratio of the gas to electricity price. However, still relatively low efficiency of the gas engine must be taken into account.

2. The choice of heat pumps driven by gas engines instead of electric pumps, apart from economic reasons, also leads to a smoothing of the electricity demand peak in the summer season, lower carbon dioxide emissions and higher primary energy utilisation rate.

3. In uncommon applications where the cost of the electrical connection is very high or there is no continuous electricity supply GEHP technology seems to be better choice than EHP.

4. The characteristics of heat pump operation can be reduced to regression curve equations which describe efficiency, energy and waste heat. Therefore, there is a standardized way of representing the work of both technologies.

5. In the scientific literature collected there are coefficients for calculating the regression curves for both electric and gas engine heat pumps. These models are based on experimental measurements in all possible conditions of temperature and heat load.

6. Reliable data on gas consumption, electric current consumption, efficiency and waste heat values are measured experimentally by placing the device tested in a thermostatic chamber. A number of measurements are made according to the ARI 340/360-2004 standard.

7. With experimental data, regression curve coefficients, heat load characteristics of the building and temperature data, it is possible to present operating characteristics of heat pumps and to estimate the costs of heating and cooling of the building using the given technology.

8. From the analysis it can be concluded that taking into account only heating and cooling of the building, electric pumps are almost 1.5 times cheaper solution than gas pumps (during 10 years). On the other hand the analysis considers the use of waste heat from the water cooling of the gas engine. If the gas pump system is adapted to produce domestic hot water, the benefits of it should be included in the analysis. The money savings will represent a significant percentage of the annual costs and will be a decisive item to choose GEHP instead of EHP.

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