Review

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A REVIEW on PRIMARY ENERGY RATIO VALUES of GAS ENGINE DRIVEN HEAT PUMP SYSTEMS

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ABSTRACT: This study reviews the primary energy ratio values of gas engine driven heat pump systems in order to compare gas engine driven heat pump systems among themselves or with heat pump systems using different energy sources in terms of efficiency values. A comprehensive literature review of studies investigating primary energy rates of gas-driven heat pump systems have been presented. The primary energy ratios obtained in the studies on gas-engine driven heat pump systems were determined and tabulated. In addition, waste heat recovery rates in these systems were also investigated. Studies in the relevant field are grouped as experimental and theoretical. Additionally, the differences in the examined system structures are stated and primary energy ratios are presented. Primary energy rates of systems with and without heat recovery were examined. There is no compilation study on the subject in the literature. The calculation methodology used and the obtained values for calculating the primary energy rates of gas-driven heat pumps are presented. Thus, the energy efficiency and environmental evaluations of the examined systems are presented in the light of the literature. In addition, which refrigerants were used in the studies conducted in the literature are presented. Recommendations are provided on choosing alternative and sustainable refrigerants.
Keywords: Gas engine driven heat pump; Primary energy ratio; Waste heat recovery; non-ecological refrigerant substitution strategy, sustainability

1. INTRODUCTION

Heat pumps are one of the alternative energy systems for energy supply applications (heating, cooling, hot water supply, etc.). Heat pumps are systems whose main purpose is to transfer heat from a low-temperature source to a high-temperature medium, using mechanical work. Among heat pumps, gas engine driven heat pump systems use the gas engine to generate mechanical work and drive the heat pump system. In these systems, energy performance criteria are obtained by comparing the energy output to the amount of energy consumed to operate the system. One of these values, the primary energy ratio index, is used to compare the efficiency values of heat pumps using different energy sources. The primary energy ratio is defined as the ratio of useful energy output (heating or cooling) to primary energy input. Heat pumps (HPs) can be used for both heating and cooling of a space. They are much more economical than using two separate systems. In other words, a heat pump system can be used as a heater in the winter and as a cooler in the summer. Heat pumps are not only used for space heating and cooling. These systems are also used for chilling different materials, producing hot water and preheating feed water [1, 2].

Heating-cooling in motor vehicles (especially electric vehicles) can be defined as a new field of application [3,4]. Beside this, desalination, drying (industrial products, clothing products and especially farm products), geothermal heating - cooling and cogeneration systems also stand out as an important application area. [5–10].
Heat pumps can be classified according to the type of energy source they have used. These are electrical heat pumps, hybrid source heat pumps, geothermal heat pumps, solar assisted heat pumps and gas engine driven heat pumps [11–15].

Among heat pumps, gas-engine driven heat pump (GEHP) systems use the gas engine to generate mechanical work and drive the heat pump system. These GEHP systems can be positioned nearest to the location where energy is required. Thus, the energy conversion is carried out in the location where energy is required (on-site production) instead of the central power plant. As a result, higher energy efficiency values are gained. Other advantages of on-site production are the reduction of transmission costs and the minimization of energy losses in the transmission process. In addition, the use of waste heat that can be recovered from gas engines in these systems is another important advantage [16–18].

In GEHP systems, although the gas engines thermal efficiency (30- 45%) is not very high, these heat pumps become much more efficient with the recovery of waste heat in the system (approximately 80% of the total waste heat). The recovery of waste heat generated during the operation of the gas engine in GEHP systems significantly increases their energy efficiency. Furthermore, this increase also benefits the reduction of carbon dioxide emissions and the struggle against global warming. There are two different types of waste heat that can be recovered in GEHP systems. One of them is the waste heat obtained from the cylinder jacket of the engine and the other is the waste heat obtained from the exhaust gases [19–21].

GEHP systems, another advantage is that the speed of the gas engine, which is the power source, can be controlled. Determining the optimum engine speed provides that the system operates more stable and more efficiently. In addition, the use of control strategies in these systems significantly increases the performance values [14, 22, 23].

Natural gas, propane, LPG and LFG are used as primary energy sources in GEHP systems. Among these primary energy sources, natural gas is cheaper and has lower operating costs. Therefore, it is preferred economically [19, 24–26].

GEHP systems contributes to national economies and societies to increase their welfare levels by combating climate change, providing energy supply security, increasing energy efficiency and reducing environmental pollution.

In this study, the primary energy ratios (PER) obtained in studies on GEHP systems, which is the main purpose, were determined and examined. Besides that, an evaluation was made on the rates of waste heat recovery in GEHP systems and the substitution strategy of non-ecological refrigerants used in GEHP systems. Additionally, the comparison of GEHP systems with conventional electrical heat pump (EHP) systems, the energy efficiency indexes commonly used in heat pump systems, and the calculation of PER1 and PER2 values for GEHP systems are also included in the study.

2. GAS ENGINE DRIVEN HEAT PUMP

Heat pump technologies are widely used for energy supply due to their superior performance. GEHP systems are devices that use the gas engine to generate mechanical work and drive the heat pump system [18].

A gas engine driven heat pump system consists of 5 main parts: evaporator (internal heat exchanger), compressor, condenser (external heat exchanger), expansion valve and gas engine for heating season. The schematic diagram of the working principle (heating mode- cooling mode) of a GEHP system is given in Figure 1.

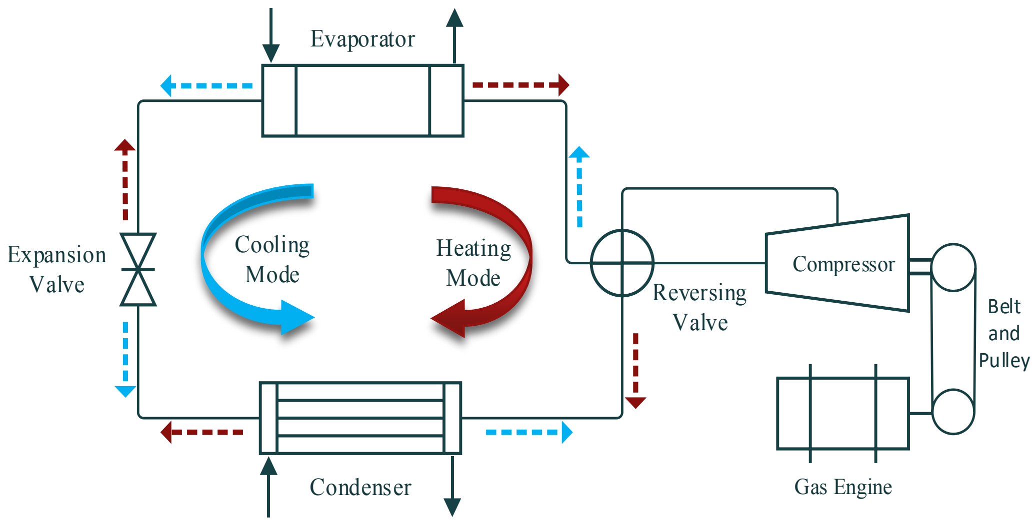

Figure 1. Working principle of a gas engine driven heat pump system

Recovery of waste heat in GEHP systems increases system efficiencies. These waste heats is recovered from the engine cylinder jacket and exhaust gases. The schematic diagram of a GEHP system with a waste heat recovery system is shown in Figure 2.

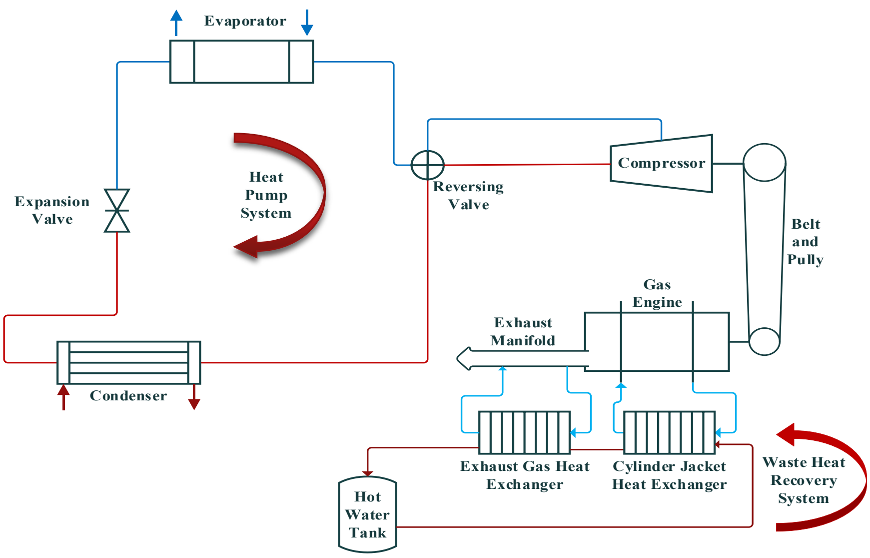

Figure 2. Schematic diagram of a GEHP system with a waste heat recovery system

2.1. Comparison Of Gas Engine Driven Heat Pumps and Conventional Electrical Heat Pumps

Compared to EHP systems, GEHP systems are preferred because of their high efficiency values. One of the most important factors affecting these comparison results is the energy production processes. A conventional EHP system working with energy obtained from fossil fuels experiences electrical losses in the process until it reaches the end user. The first of these losses occurs with the direct release of waste heat to nature, which arises during the conversion of fossil fuels into electrical energy in a central power generation facility. The second is the losses that occur along the transmission line of this converted electrical energy. After these losses, the electrical energy reaches the engine of the EHP system and the operation of the heat pump is provided by this engine drive. These losses are shown in Figure 3. If gas motor is used instead of electric motor in heat pumps, it is seen in Figure 4 that the losses in energy conversion and energy transmission processes are eliminated. In other words, since the energy conversion is done very close to the heat pump, the number of energy conversions has decreased, the transmission cost and the losses in the transmission process have been eliminated. In addition, the recovery of waste heat generated during the operation of the gas engine significantly have been increased their energy efficiency. To acquire the same total usable heat, the conventional EHP system must be supplied with more than 3 times the energy input of the GEHP system (Figure 4). This demonstrates that the energy efficiency of the GEHP system is 3 times higher. This increase in energy efficiency also benefits the reduction of carbon dioxide emissions and the struggle against global warming [16, 17, 21].

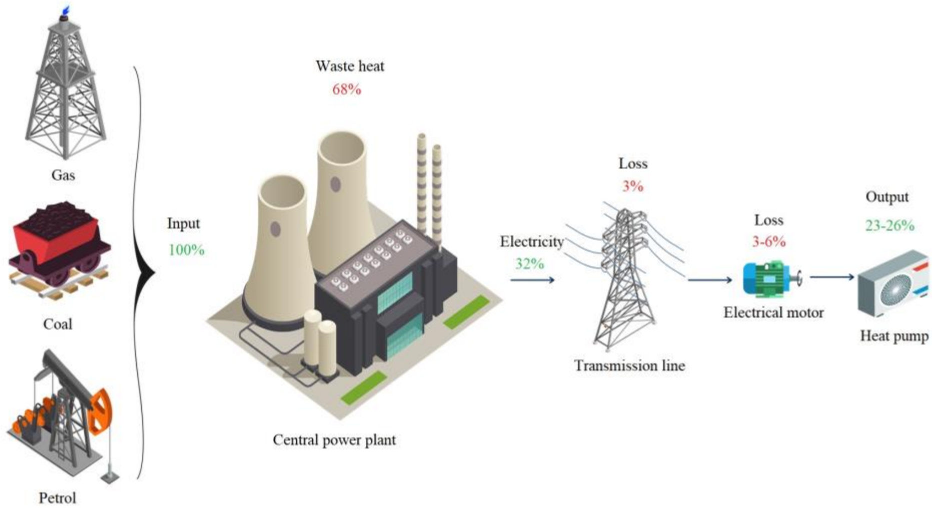

Figure 3. Losses in energy conversion and energy transmission processes [16].

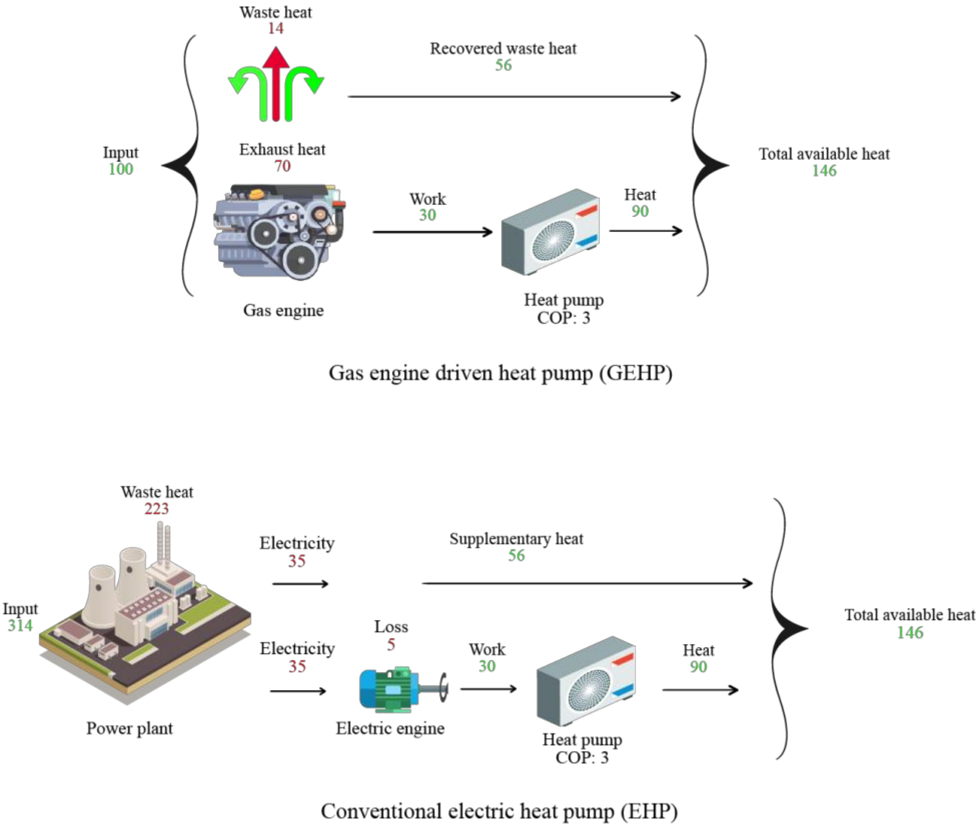

Figure 4. Energy conversion processes of GEHP and conventional EHP systems [16].

2.2. Energy Efficiency Indexes for Heat Pump Systems

Energy efficiency values in heat pump systems are obtained by comparing the energy output to the amount of energy consumed to operate the system. Higher energy efficiency values indicates that heat pump systems operate more efficiently. Therefore, determination of energy efficiency values is very important for heat pump systems [1, 20].

According to Dincer and Rosen [20], the most commonly used energy efficiency indices are as follows:

COP (Coefficient of performance): COP is the most widely used efficiency index in heat pump systems. In heat pump systems, COP is expressed as the ratio of the heating energy output to the electric energy input the system.

$$COP = \frac{Heating\ energy\ output}{Electric\ energy\ input} \tag{1}$$

EER (Energy Efficiency Ratio): EER is an index used to determine the efficiencies of the refrigeration cycles of heat pump systems. EER is expressed as the ratio of the cooling energy output to the electric energy input the system.

$$EER = \frac{Cooling\ energy\ output}{Electric\ energy\ input} \tag{2}$$

HSPF (Heating Season Performance Factor): HSPF is used to determine the seasonal performance of heating cycles in heat pump systems. HSPF can be described as the average

COP for heating systems. HSPF is expressed as the ratio of the seasonal heating energy output to the seasonal electric energy input the system.

$$HSPF = \frac{Seasonal\ heating\ energy\ output}{Seasonal\ Electric\ energy\ input} \quad (3)$$

SEER (Seasonal Energy Efficiency Ratio): SEER is used to determine the seasonal performance of cooling cycles in heat pump systems. SEER is expressed as the ratio of the seasonal cooling energy output to the seasonal electric energy input the system.

$$SEER = \frac{Seasonal\ coaling\ energy\ output}{Seasonal\ electric\ energy\ input} \quad (4)$$

PER (Primary Energy Ratio): Heat pump systems can be operated using different energy sources. The PER index is used to compare the efficiencies values of heat pumps using different energy sources. PER is defined as the ratio of useful energy output (heating or cooling) to primary energy input.

$$PER = \frac{Useful\ energy\ output}{Primary\ energy\ input}$$
(5)

The relationship between PER and COP values is as follows:

$$PER = \eta . COP \quad (6)$$

The efficiency value at which the primary energy input is converted into compressor shaft work is expressed by η. In the case where electricity is produced in a central power plant, the η value of the electrically powered compressor can drop to 25%. On the other hand, the η value of gas engine driven heat pumps can go up to 75%. These η values show the importance of PER for gas-engine driven heat pumps.

2.3. Data Reduction of Primary Energy Ratio with Heat Recovery and Primary Energy Ratio without Heat Recovery for a Gas Engine Driven Heat Pump

Data for a gas engine driven heat pump system shown in Fig.2 providing heating and hot water supply are as follows:

The primary energy ratio with heat recovery (PER_1) and primary energy ratio without heat recovery (PER_2) for a gas engine driven heat pump can be calculated in Equation (7- 8):

$$PER_1 = \frac{Q_h + Q_{whr}}{Q_{pec}} \quad (7)$$

$$PER_2 = \frac{Q_h}{Q_{pec}} \quad (8)$$

where Q_h is the useful heating energy output; Q_{whr} is the waste heat energy output recovered from engine cylinder liner and exhaust gases; Q_{pec} is the primary energy consumption of the gas engine.

The Q_h is obtained as follows:

$$Q_h = c_{p,w} \,.\, m_w \,.\, (T_{con,out} - T_{con,in}) \quad (9)$$

where $c_{p,w}$ is the specific heat of water, m_w is the mass flow rate of water, $T_{con,out}$ and $T_{con,in}$ are the outlet and inlet water temperature of condenser, respectively.

The Q_{whr} is obtained as follows:

$$Q_{whr} = Q_{cj} + Q_{eg} \quad (10)$$

$$Q_{cj} = c_{p,w} \,.\, m_w \,.\, (T_{cj,out} - T_{cj,in}) \quad (11)$$

$$Q_{eg} = c_{p,w} \,.\, m_w \,.\, (T_{eg,out} - T_{eg,in}) \quad (12)$$

where Q_{cj} is the waste heat energy recovered from engine cylinder liner, Q_{eg} is the waste heat energy recovered from exhaust gases.

The Q_{pec} is obtained as follows:

$$Q_{pec} = V_{gas} \,.\, LHV \quad (13)$$

where V_{gas} is the volume flow rate of gas, LHV is the gas low heating value.

3. STUDIES ON GAS ENGINE DRIVEN HEAT PUMP SYSTEM

3.1. Investigation of Primary Energy Ratio Values of Gas Engine Driven Heat Pump Systems

PER index is used to compare the efficiencies values of heat pumps using different energy sources. The PER values obtained in GEHP systems enable the efficiency values to be compared with heat pump systems using different primary energy sources. The studies on GEHP systems and the PER values obtained in these studies are as follows:

Elgendy and Schmidt [27], carried out an experimental study for the cooling mode without using an engine heat recovery system. It was stated that the increase in the evaporator water inlet temperature increased the PER values, while the increase in the ambient air temperature and engine speed decreased the PER values. The maximum PER value obtained in the study is approximately 2. Sanaye et al. [28] performed a study on the dynamic modeling of a system in cooling mode. These modeling results were compared with the experimental results While the PER value of the system was 1.015 in the experimental results, it was 1.087 in the modeling results. Elgendy and Schmidt [29] evaluated two different waste heat recovery modes comparatively. In the first of these modes, the recovered waste heat was transferred to the refrigerant circuit. In the second mode, it was transferred to the hot water circuit. The maximum PER values were determined as 1.83, 1.25 when the recovered waste heat was transferred to the hot water circuit and to the refrigerant circuit, respectively. In addition, in this study, it was emphasized that the engine speed should be optimized in order to obtain maximum PER values.

X. Wu et al. [30], was studied an air to water GEHP system using R134a/R152a mixed refrigerant. The maximum PER value acquired in this study was 1.69. The PER values of the system increased with the increase of the evaporator water inlet flow and temperature.

Furthermore, for higher PER values, it was stated that the engine speed should be optimized by evaluating the dynamic and economic characteristics of the gas engine. The schematic diagram of this system is given in Figure 5.

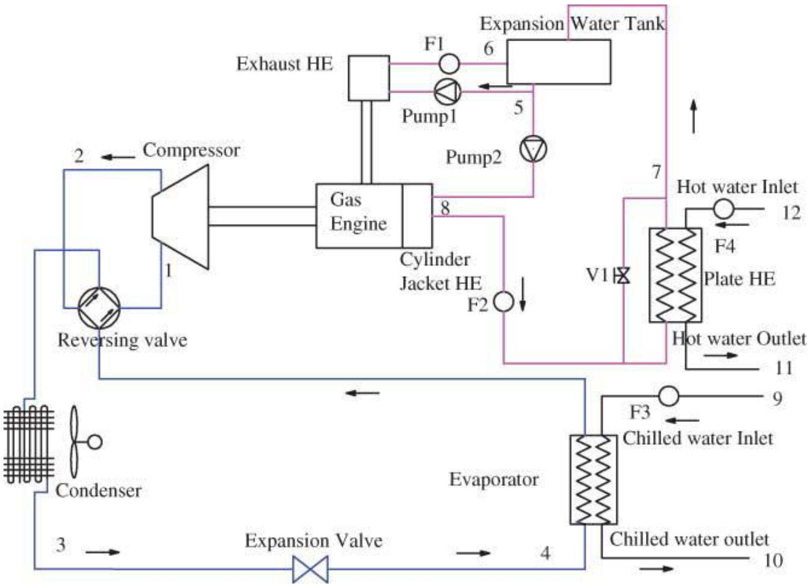

Figure 5. Schematic diagram of the GEHP system using mixed refrigerant [30]

Hao et al. [31] designed a new hybrid air conditioning system by using solar energy and gas engine heat pump systems together. According to the results obtained, the PER values of the hybrid system were between 1.55 and 1.96. The PER values of the system were found between 1.42-1.51 when operated with GEHP only, and between 1.13-1.51 when operated only with solar heat pump. As a result, when the PER values were examined, it was seen that the efficiency of the hybrid system is higher. Liu et al. [32] operated the Rankine cycle with the waste heat of a GEHP system in studies. In their study, they ran the Rankine cycle with the waste heat of a GEHP system. This hybrid energy system can provide heating, cooling, hot water and electrical energy. The minimum PER value had obtained in their study was 1.21. Besides, they stated that the fuel inlet values of this hybrid system are less than GEHP and EHP systems. Less primary energy input indicates higher PER values will be achieved. Jiang et al. [33] conducted a modeling study on the hybrid power gas engine heat pump (HPGEHP) system. In their study, they compared the PER values of HPGEHP systems with GEHP systems. They determined that the PER values of the HPGEHP system were higher than the GEHP system at low, medium and high engine speed values. H. Liu et al. [34] experimentally investigated the cooling performance of a GEHP system with an evaporative condenser. They found that the PER values of the evaporative condenser system were 28.1% higher when compared to the conventional air-cooled condenser system. Compared to GHEP systems with air-cooled condensers, they determine that evaporative condenser systems have higher primary energy savings and CO_2 emission savings. In addition, they have stated in their studies that GEHP systems are more efficient in primary energy savings and CO_2 emission savings than EHP systems. The schematic diagram of this system is given in Figure 6.

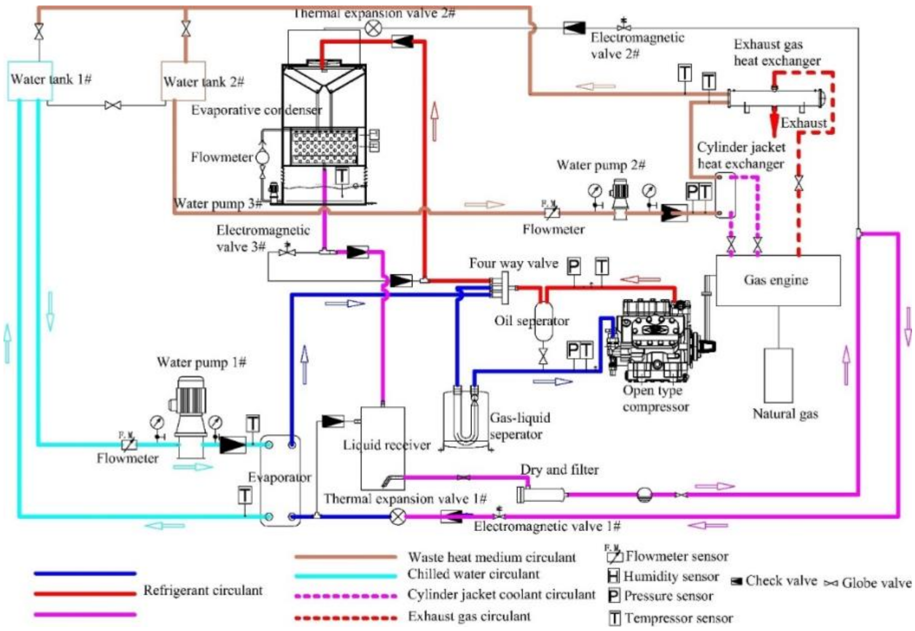

Figure 6. Schematic diagram of the GEHP system with evaporative condenser [34]

J. Wu and Ma [25] have designed a biogas engine driven heat pump system using landfill gas (LFG) fuel. The maximum PER value of 1.4 was obtained for this system. Wan et al. [35] have determined the average PER values of the HPGEHP system at low and high compressor speeds were higher than that of the GEHP system, and lower at medium compressor speeds. F.-G. Liu et al. [36] experimentally performed performance evaluations of a GEHP system for heating and domestic hot water supply. The PER values of the system decreased with increasing gas engine speed and increased with increasing condenser water inlet temperature and ambient air temperature. As a result of the experiments, they determined that the PER values of the system were between 1.23 and 1.48. F. Liu et al. [37] have designed a parallel gas engine compression-absorption heat pump (GECAHP) system. The total heating capacity and PER values of this system are 6% and 5% higher, respectively, than GEHP systems. The maximum primary energy ratio of the GECAHP system is above 1.5. Hu et al. [26] have developed a simulation model for a GEHP system with waste heat recovery. The maximum PER value of this system as 1.72. Qiang and Zhao [38] comparatively analyzed the energy storage gas-engine driven heat pump (ESGEHP) system and the GEHP system. They indicated average PER values of ESGEHP and GEHP systems to be 1.74 and 1.40, respectively. Q. Zhang et al. [39] have specified the annual primary energy rates (APER) of the ESGEHP system were 6.11%, 19.11% and 34.83% higher, respectively, in the heating, cooling and transition seasons compared to the GEHP system. F.-G. Liu et al. [40] have evaluated the performance of a GEHP system for cooling and hot water supply in their study. The PER values of the heat recovery system are between 1.14 and 1.45. The schematic diagram of this system is given in Figure 7. F. Liu et al. [41] have worked on the modeling of a series GECAHP system. The PER value they have obtained for this system is between 1.0 and 1.1.

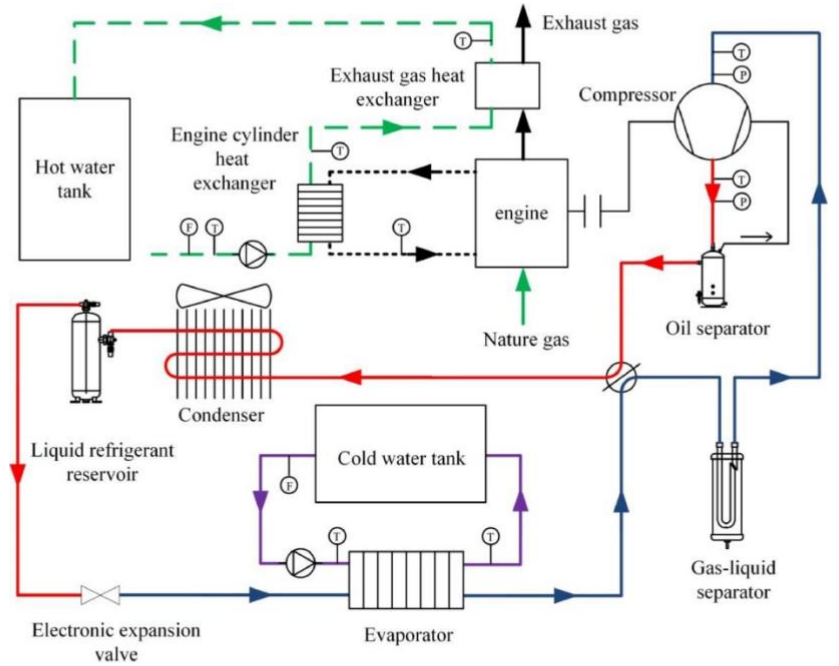

Figure 7. Schematic diagram of the GEHP system supplying combined cooling and hot water supply [40]

Q. Zhang et al. [42] investigated the applicability of GEHP systems with energy storage systems in heating and cooling processes of different building types (residence, hotel, office and university). The schematic diagram of the working principle of this energy storage gas-engine driven heat pump (ESGHP) system is shown in Figure 8. They stated that the annual primary energy rate (APER) of ESGHP systems is approximately 21.4% (residential), 35.2% (hotel), 23% (office), and 26.6% (university) higher than conventional GEHP systems. ESGHP systems can be used in different building types due to their more stable operation, higher PER and more suitable performance characteristics than conventional GHEP systems. X.Ma et al. [43] found that the average PER value of the hybrid power gas engine driven heat pump (HPGEHP) system was 12.1% higher than the GEHP system. The schematic diagram of this HPGEHP system is given in Figure 9.

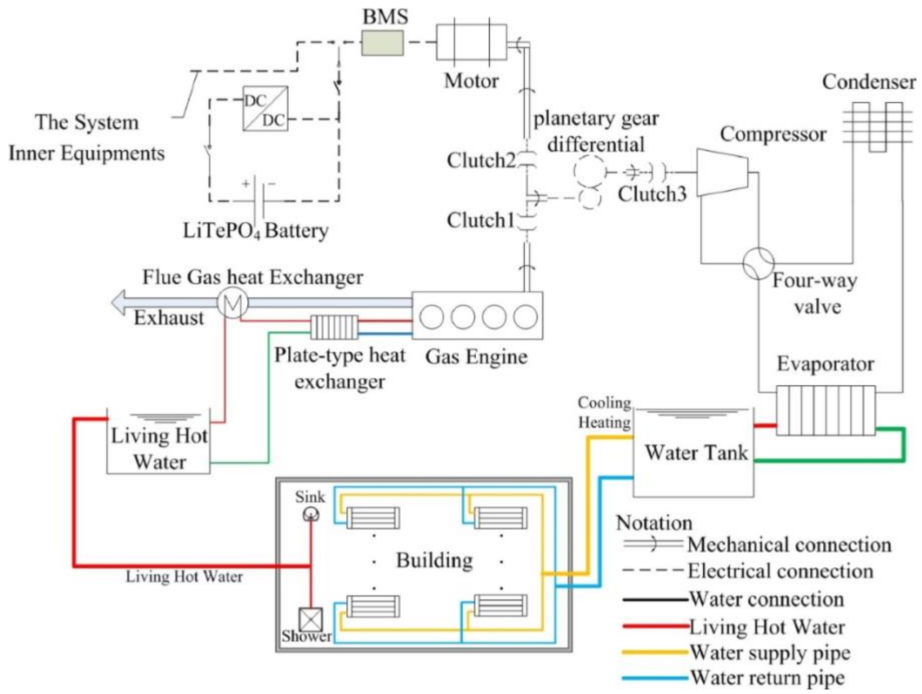

Figure 8. Schematic diagram of the working principle of ESGHP systems [42]

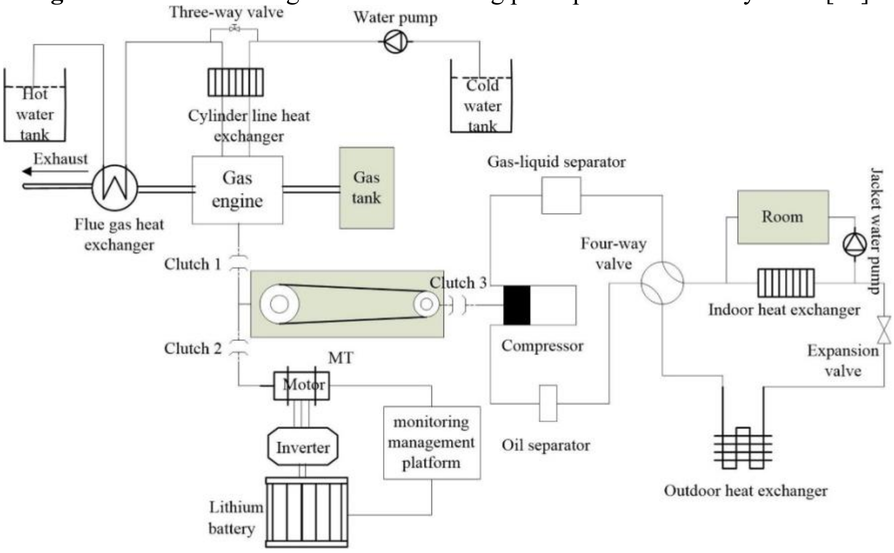

Figure 9. Schematic diagram of the HPGEHP system [43].

W. Zhang et al. [44] experimentally investigated the performance of a GEHP system for space heating and cooling. They determined that the PER value obtained in the cooling mode in summer conditions of the system is lower than the PER values obtained in the heating mode in winter conditions. Jia et al. [14] (2020), conducted experimental analysis of a new GEHP system that could provide cooling and hot water supply. The average PER_1 (with waste heat recovery) and PER_2 (without waste heat recovery) values of the system under all operating conditions are 1.57 and 0.96, respectively. It was observed that PER_1 and PER_2 values decreased with increasing engine speed and air temperature, and increased with increasing evaporator inlet water temperature. Tian et al. [18] have investigated the cooling performance of the system to determine the stability and efficiency of the GEHP system. They found that PER_1 (with waste heat recovery) values were higher than PER_2 (without waste heat recovery) values. A water source gas engine driven heat pump (WSGEHP) is used in the system. This WSGEHP system experiment set is shown in Figure10.

Figure 10. WSGEHP system experiment set [18]

Z.Ma et al. [45] comparatively were investigated the heating performances of a water source GEHP system for R152a (low global warming potential) and R134a refrigerants. The PER value of the system using R134a is 1.46, while the PER value of the system using R152a is 1.60. R.

Zhang et al. [46] have proposed a new waste heat utilization mode for GEHP systems to contribute to the development of clean heating technology. They have designed a water source GEHP system that uses waste heat in auxiliary heating mode. The PER value of this system is 1.67. In addition, when this waste heat is given to the domestic hot water, the PER value of 1.52 was determined. Studies on GEHP systems and obtained PER values are given in Table 1 with reunited.

Table 1. Studies on GEHP systems and PER values obtained in these studies

		Study Type		System Type			
#	**Investigators (Year)**	**Experimental**	**Theoretical**	**Heating**	**Cooling**	**Hot Water**	**Primary Energy Ratio Values**
1.	Elgendy and Schmidt [47]	√			√		▪ PER_{max}: ~2
2.	Sanaye et al. [48]	√	√		√		▪ PER: 1.015 (For experimental study) ▪ PER: 1.087 (For theoretical study)
3.	Elgendy and Schmidt [29]	√		√		√	▪ PER_{max}: 1.25 (For mode 1) ▪ PER_{max}: 1.83 (For mode 2)
4.	X. Wu et al. [49]	√			√		▪ PER_{max}: 1.69
5.	H. Liu et al. [32]	√	√		√		▪ PER_{min}: 1.21
6.	Hao et al. [50]		√	√			▪ PER: 1.55- 1.96 (For hybrid system) ▪ PER: 1.42- 1.51 (For GEHP system) ▪ PER: 1.13- 1.51 (For SEHP system)
7.	Jiang et al. [51]	√	√	√			▪ PER_{HPGEHP}> PER_{GEHP} (For different engine speed) ▪ PER_{max}: 1.2 (For HPGEHP system)
8.	H. Liu et al. [52]	√			√		▪ PER: 1.55 (For evaporative condenser) ▪ PER: 1.21 (For air-cooled condenser)
9.	J. Wu and Ma [25]	√		√			▪ PER_{max}: 1.4
10.	Wan et al. [53]	√		√			▪ PER_{HPGEHP}> PER_{GEHP} (For low engine speed) ▪ PER_{GEHP}> PER_{HPGEHP} (For medium engine speed) ▪ PER_{HPGEHP}> PER_{GEHP} (For high engine speed)
11.	F.-G. Liu et al. [54]	√		√		√	▪ PER: 1.23 – 1.48
12.	Q. Zhang et al. [55]	√	√	√	√		▪ $APER_{ESGEHP}$> $APER_{GEHP}$ (For heating season) ▪ $APER_{ESGEHP}$> $APER_{GEHP}$ (For cooling season) ▪ $APER_{ESGEHP}$> $APER_{GEHP}$ (For transitional season)
13.	Qiang and Zhao [56]	√	√		√		▪ PER_{avg}: 1.74 (For ESGEHP system) ▪ PER_{avg}: 1.40 (For GEHP system)
14.	Hu et al. [26]	√	√	√			▪ PER_{max}: 1.72
15.	F. Liu et al. [57]		√	√			▪ PER_{max}: 1.53 (For GECAHP system) ▪ PER_{max}: 1.47 (For GEHP system)
16.	Q. Zhang et al. [58]	√	√	√	√		▪ PER_{ESGEHP}> PER_{GEHP} (For all working conditions)
17.	F.-G. Liu et al. [59]	√			√	√	▪ PER_1: 1.14 - 1.45 ▪ PER_2: 0.61 - 0.81
18.	F. Liu et al. [60]		√	√			▪ PER: 1.0 – 1.1 (For GECAHP system)
19.	X. Ma et al. [43]		√	√	√		▪ PER_{avg}: 1.058 (For HPGEHP system) ▪ PER_{avg}: 0.85 (For GEHP system)
20.	W. Zhang et al. [61]	√		√	√		▪ $PER_{heating}$> $PER_{cooling}$

21.	Tian et al. [18]	√		√		▪ PER_1: 2.63 PER_2: 0.92 (1200 rpm) ▪ PER_1: 2.40 PER_2: 0.81 (1400 rpm) ▪ PER_1: 2.17 PER_2: 0.72 (1600 rpm)
22.	Jia et al. [14]	√		√	√	▪ PER_1: 1.57 ▪ PER_2: 0.96
23.	Z. Ma et al. [62]	√	√			▪ PER: 1.60 (For R152a refrigerant) ▪ PER: 1.46 (For R134a refrigerant)
24.	R. Zhang et al. [46]	√	√		√	▪ PER: 1.52 (For mode 1) ▪ PER: 1.67 (For mode 2)

$^*PER_1$: Primary energy ratio with heat recovery **$^*PER_2$**: Primary energy ratio without heat recovery

3.2. Waste Heat Recovery in Gas Engine Driven Heat Pump Systems

In gas-engine driven heat pump systems, energy efficiency values can be increased by recovering the waste heat generated when the gas engine is running. In order for GEHP systems to have higher PER values, waste heat recovery rates should be increased. In this context, Hepbasli et al. [17] have prepared a review article on the applications of GEHP systems in residential and industrial areas. They determined that the waste heat recovery rates of the systems in their studies were approximately 30% of the total heating capacity. This study was taken as a reference to compare the waste heat recovery rates in our study.

Elgendy et al. [47] experimentally investigated the performance characteristics in combined heating and cooling mode. They stated that 50.1% of the total energy input was recovered. Elgendy et al. [63] have conducted experimental studies for hot water supply. They stated that the waste heat recovery values decreased with the increase in the condenser water inlet temperature, and the waste heat recovery values increased with the increase in the ambient air temperature and engine speed. Elgendy and Schmidt [29] have proposed two different waste heat recovery modes. The recovered waste heat was transferred to the refrigerant circuit and the hot water circuit separately. These waste heat recovery modes were compared with each other. According to the results, the PER value obtained in the case where the recovered waste heat is transferred to the hot water circuit is 46.4% higher than in the other case. Liu et al. [32] designed a hybrid energy supply system by combining the organic Rankine cycle, which is a promising energy conversion technology in the field of low-grade waste heat utilization, with a GEHP system. In their study, they determined that the waste heat energy value recovered from the gas engine is more than 55% of the gas engine energy consumption value. In addition, they emphasized that while the recovered waste heat value remained almost constant in the evaporator water inlet temperature changes, the recovered waste heat value increased with the increase in gas engine speed. The schematic diagram of the system used in the study is given in Figure 11.

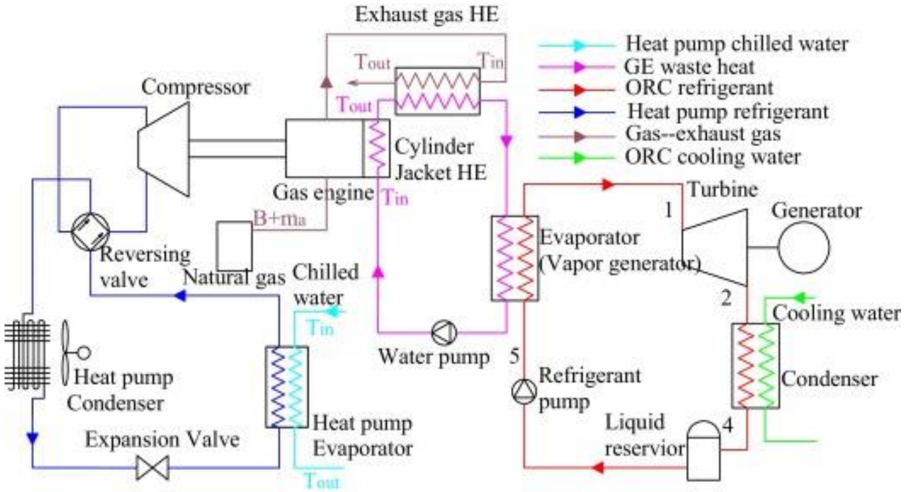

Figure 11. Schematic diagram of the hybrid system consisting of GEHP and ORC system [32]

W. Zhang et al. [64] experimentally investigated the performance characteristics of a heat recovery GEHP system. In their study, they stated that the recovered engine waste heat composes 40-50% of the total heat capacity. H. Liu et al. [52] experimentally investigated the cooling performance of a GEHP system with an evaporative condenser. They determined that the waste heat energy value recovered from the gas engine is more than 55% of the gas engine energy consumption value. J. Wu and Ma [25] stated that in biogas engine driven heat pump systems, recovering the waste heat of the engine cylinder jacket and exhaust gas will increase the heating capacity of the system. F.-G. Liu et al. [54] experimentally have evaluated the performance of a GEHP system providing heating and domestic hot water supply. In this study, heating energy obtained from heat recovery constitutes 35-45% of the total heating capacity of the system. In addition, the water temperatures obtained by heat recovery are between 40 °C and 60 °C. As a result of these values, it has been determined that the system can meet domestic hot water demands. The schematic diagram of the system used in the study is given in Figure 12.

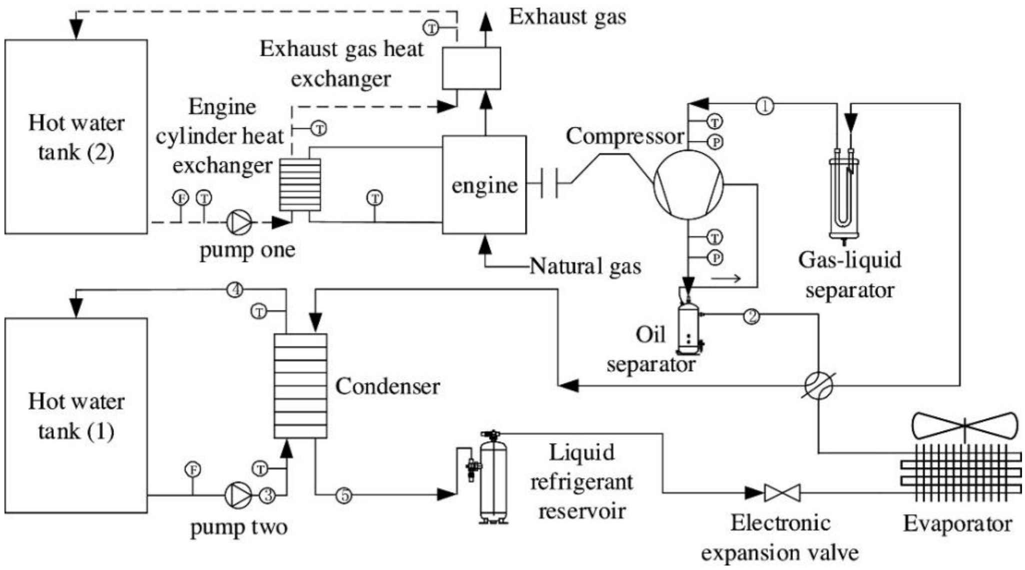

Figure 12. Schematic diagram of the GEHP system schematic diagram [54]

F.-G. Liu et al. [59] have evaluated the performance of a GEHP system for cooling and hot water supply. In this study, the effects of evaporator water inlet temperature, ambient air temperature and gas engine speed on system performance were investigated. For these three parameters, PER_1 values were higher than PER_2 values. Average hot water outlet temperatures between 40.7 °C and 61.7 °C were obtained under the operating conditions of the GEHP system. W. Zhang et al. [61] stated that the use of heat recovery systems in GEHP systems, whether in heating mode or cooling mode, is of great importance in increasing the energy use efficiency of the system. Jia et al. [14] conducted an experimental analysis of a new GEHP system that could provide cooling and hot water supply. The average PER_1 value for all operating conditions in the GEHP system is 63.5% higher than the average PER_2 value. R. Zhang et al. [46] have proposed a new waste heat utilization mode for GEHP systems to contribute to the development of clean heating technology. They have designed a WSGEHP system that uses waste heat in auxiliary heating mode. The schematic diagram of this system is given in Figure 13. In the WSGEHP system, waste heat recovery accounts for 32.2-36.5% of the total heat capacity. In addition, a new index that can be used to measure the energy efficiency of the WSGHP system, "waste heat ratio (R)," was presented in the study. With the increase in the waste heat rate of the WSGHP system, the advantage of saving energy will decrease. In other words, the lower the waste heat rate, the more beneficial the operation of the system will be. For this reason, they also stated that the waste heat ratio is an index that can be used to measure the energy efficiency of WSGHP systems. In addition, they stated in their study that GEHP systems have higher primary energy savings and CO_2 emission savings than EHP systems.

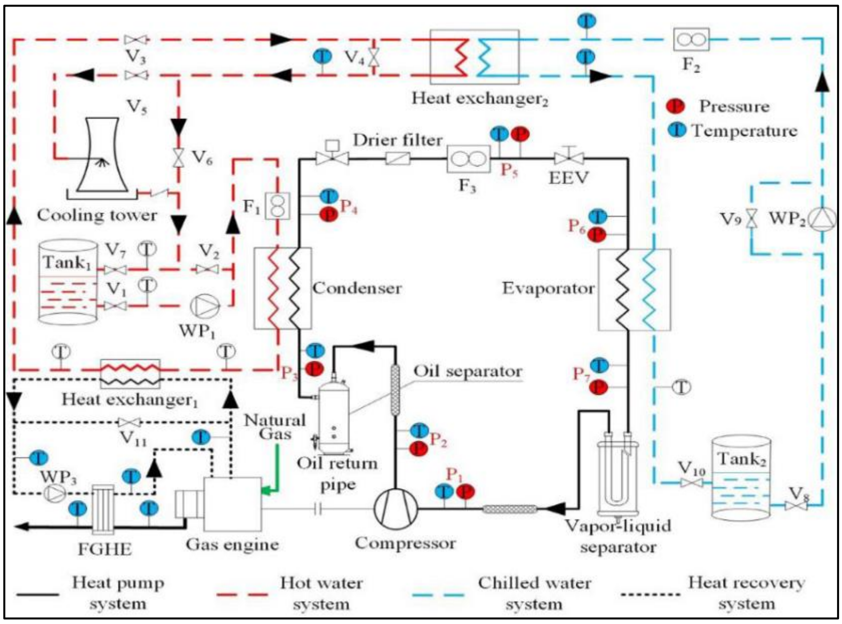

Figure 13. Schematic diagram of the WSGHP system [46]

3.3. An Evaluation on the Non-Ecological Refrigerants Substitution Strategy in Gas Engine Driven Heat Pump Systems

The use of non-ecological refrigerants in energy systems causes to an increase in greenhouse gas emission values and depletion of the ozone layer. These factors also cause an increase in global warming. Therefore, it is very important to use ecological refrigerants in energy systems [65].

In this context, the studies on gas-engine driven heat pump systems according to the refrigerant types used are as follows:

Eustace [66] have designed a high temperature GEHP system for use in three different industrial processes. In this system, R114 refrigerant was used. X. Wu et al. [49] have conducted a study on performance evaluations of an air-to-water GEHP system using a mixture of R134a/R152a as refrigerant. Z. Ma et al. [62] comparatively investigated the heating performances of a water source GEHP system for R134a and R152a.

Except for the studies given above, R22, R134a, R410A and R407C refrigerants were used in studies on GEHP systems. In this context, the refrigerants used in the studies on gas-engine driven heat pump systems (Table 2) have been determined. These determined refrigerants will be evaluated according to their environmental characteristics (Table 3), the change in refrigerant trends used in energy systems (Figure 14) and the usage restrictions of refrigerants (Table 4).

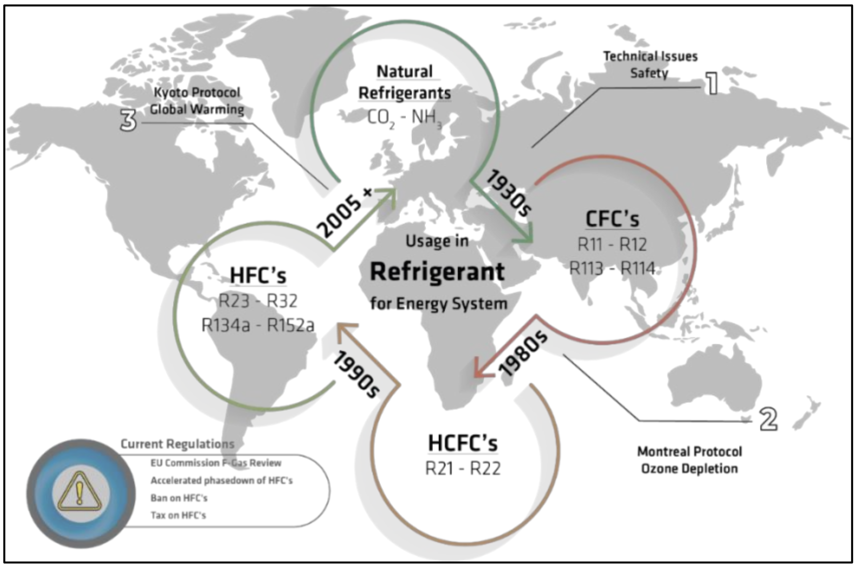

Figure 14. Changes in the refrigerant trends used in energy systems by years [67]

The environmental characteristics of these refrigerants are classified in Table 3. In order to make this classification more meaningful, restriction and prohibition criteria for refrigerants are given in Table 4.

Table 2. Studies according to the types of refrigerants used in GEHP systems

R22	R134a	R410A	R407C
Burg and Lohstrater [68]	Y.-L. Li et al. [69]	Elgendy and Schmidt [47]	R. R. Zhang et al. [70]
Howe et al. [71]	Z. Xu and Yang [72]	Elgendy et al. [73]	Sanaye et al. [74]
Jiang et al. [51]	Chen et al. [75]	Elgendy et al. [76]	Sanaye and Chahartaghi [28]
Wan et al. [53]	Z. Yang et al. [78]	Elgendy et al. [79]	Sanaye and Chahartaghi [80]
X. Ma et al. [43]	X. Zhang et al. [81]	Elgendy and Schmidt [82]	Gungor et al. [83]
X. Xu et al. [84]	H. Liu et al. [85]	Kamal et al. [86]	Sanaye et al. [48]
	Hao et al. [85]	Lv et al. [87]	Sanaye and Asgari [88]
	Ji et al. [89]	Tian et al. [90]	Gungor, Hepbasli et al. [91]
	J. Wu and Ma [25]	Y. Hu et al. [92]	Gungor, Tsatsaronis et al. [94]
	Dong et al. [95]	Y. Hu et al. [96]	W. Zhang et al. [97]
	F.-G. Liu et al. [54]	Y. Hu et al [98]	W. Zhang et al. [61]
	F. Liu et al. [57]		
	F.-G. Liu et al. [59]		
	F. Liu et al. [60]		
	Q. Zhang et al. [58]		
	Jia et al. [14]		
	Tian et al. [18]		
	Liu et al. [99]		

Table 3. Environmental characteristics of refrigerants used in gas-engine driven heat pumps [81, 94]

Refrigerants	Group	ODP	GWP (CO_2=1)	Atmospheric Lifetime (years)	Safety Code
R114	CFC	0.7-1.0	6900	130-220	
R22	HCFC	0.055	1900	11.8	A1
R134a	HFC	0	1600	14-15.6	A1
R152a	HFC	0	140	1.5-8	A2
R410A	Near azeotropic mixture	0	1890	-	A1
R407C	Zeotropic mixture	0	1610	-	A1
R134a/R152a	Mixture	0	907.6	-	-

Table 4. Restrictions and prohibitions for refrigerants [101]

ODP (R11=1)	Montreal Protocol	GWP (CO_2=1)	EU F-Gas 2
Zero	No restriction	Low (<150)	No controls
Medium	Subject to consumption phase down	Medium (150-2500)	Some supply restrictions and new equipment use bans
High	100% global production and consumption ban	High (2500)	Substantial supply and use restrictions and new equipment bans

The ODP values of the refrigerants in the studies on GEHP systems are zero or very close to zero. In these systems, the use of refrigerants with lower GWP values has gained importance. In this context, studies have been carried out using refrigerants with lower GWP values in GEHP systems. These studies are as follows:

X. Wu et al. [49] used R134a/R152a mixed refrigerant with medium global warming potential (GWP) value and zero ozone depletion potential (ODP) value from R134a and R22 refrigerants. The performance evaluation of the GEHP system was carried out experimentally in cooling mode as a result of this study, the maximum PER values of the air-to-water GEHP system using R134a/R152a were determined as 1.69. As a result of this study, the maximum PER value of the air-to-water GEHP system using R134a/R152a mixture refrigerant was determined as 1.69. They also stated that this refrigerant can be used safely in GEHP systems. Z. Ma et al. [62] separately tested R134a and low GWP R152a refrigerants in heating mode in a GEHP system. It has been determined that the use of R152a refrigerant, which has a low GWP value, instead of R134a can achieve better heating performance and PER values in GEHP systems, as well as significant environmental benefits. The PER value of the system according to the refrigerant used is 1.46 and 1.60 for R134a and R152a, respectively. The schematic diagram of this study is given in Figure15.

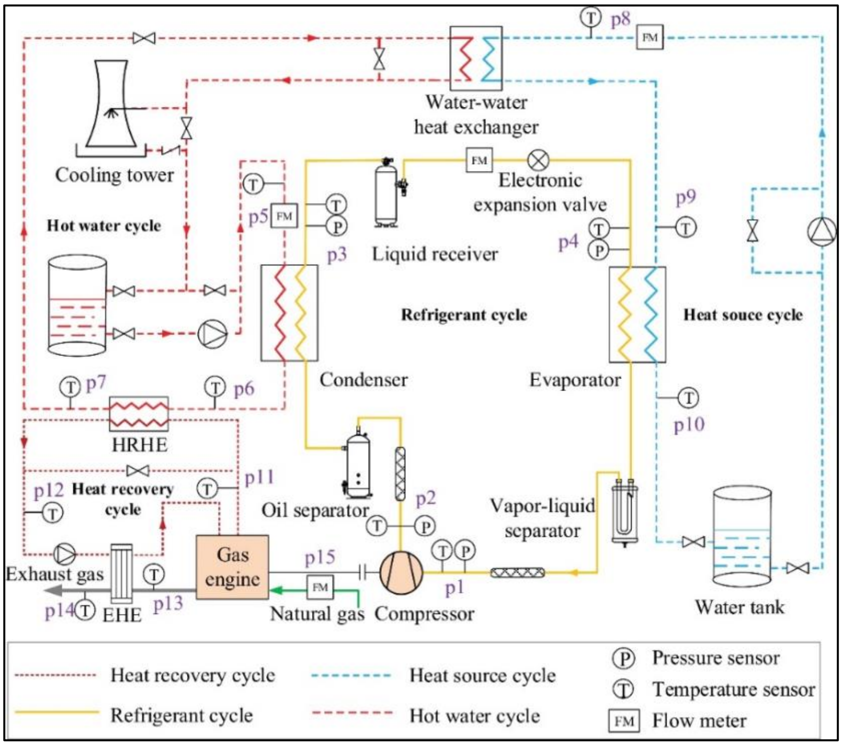

Figure 15. Schematic diagram of the GEHP system where R134a and R152a refrigerants are tested separately [62]

4. CONCLUSIONS

Results of the study are summarized below:

1) Knowing the PER values of GEHP systems allows GEHP systems to be compared with heat pump systems using different energy sources. In order to make these comparisons, PER values ranging from 0.61 to 2.63 (including PER_1 and PER_2) in different studies on GEHP systems are presented in tables.
2) In the studies on GEHP systems, the effects of waste heat recovery on the PER value were evaluated by comparing the PER_1 (with waste heat recovery system) and PER_2 (without waste heat recovery system) values for the same systems. In comparative studies, PER_1 values were higher than PER_2 values. This shows that waste heat recovery increases the PER values of the systems.
3) In GEHP systems, waste heat recovery rates have a direct contribution on system performance. Hepbasli et al. [17] in their study examining the applications of GEHP systems in residential and industrial areas, stated that this rate constitutes approximately 30% of the total heating capacity. In our study, it was determined that the waste heat recovery rates in GEHP systems vary between 32.2-50% of the total heating capacity for different studies. These values show that waste heat recovery rates have increased in GEHP systems. This increase in waste heat recovery rates has increased the PER values of GEHP systems.
4) In studies on GEHP systems, it has been determined that R114, R22, R134a, R152a, R410A, R407C and R134a/R152a mixture are used as refrigerants. The ODP values of

the refrigerants used in studies on GEHP systems are zero or very close to zero. However, in most of these studies, refrigerants with medium GWP values were used. The number of studies conducted with refrigerants with low GWP values is very few. Considering the restrictions and prohibitions applied for refrigerants, it is necessary to increase the number of studies with refrigerants with low GWP values. In addition, when the changes in the refrigerant trends used in energy systems are examined, it is predicted that natural refrigerants will be used in future studies on GEHP systems. Using natural refrigerants means substitution the non-ecological refrigerants used in GEHP systems with ecological refrigerants. This is a very important strategy in the struggle against climate change and air pollution, which are among the biggest problems of today's world.

5) The load characteristics and speed ratings of the gas engine are crucial to the performance characteristics of the GEHP system. For this reason, in order to reach higher PER values in studies on GEHP systems, engine speed should be optimized considering the dynamic and economic characteristics of the gas engine.
6) Energy storage systems are able to store this energy when there is more production than energy demand. When there is a production below the energy demand, it can use this stored energy. Thus, it is ensured that the system operates at higher efficiencies values. ESGHP systems show more stable operation, higher primary energy ratio values and more favorable performance characteristics than traditional GHEP systems. As a result, it has been determined that higher PER values will be obtained in the systems if energy storage systems are integrated into the studies on GEHP systems.
7) The GEHP systems used in the studies were compared with the EHP systems. In the comparative results, it is stated that GEHP systems have higher energy savings, and less CO_2 emission values than EHP systems.

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Nomenclature

Abbreviations

APER	*annual primary energy rates*
AVG	*average*
CFC	*chlorofluorocarbon*
COP	*coefficient of performance*
EER	*energy efficiency ratio*
EHP	*electrical heat pump*
ESGEHP	*energy storage gas-engine driven heat pump*
HCFC	*hydrochlorofluorocarbon*
HFC	*hydrofluorocarbon*
HP	*heat pump*
HPGEHP	*hybrid power gas engine driven heat pump*
HSPF	*heating season performance factor*
GECAHP	*gas engine compression-absorption heat pump*
GEHP	*gas engine driven heat pump*
GWP	*global warming potential*
LFG	*landfill gas*
LHV	*lower heating value*
LPG	*liquified petroleum gas*
ODP	*ozone depletion potential*
PER	*primary energy ratio*
SEER	*seasonal energy efficiency ratio*
WSGEHP	*water source gas engine driven heat pump*

Symbols

cp	*specific heat in constant pressure*	*(kj/kg.K)*
eta	*efficiency*	
m	*mass*	
Q	*heat energy*	*(kj)*

T	*temperature*	*(K)*
Vgas	*volume flow rate of gas*	*(m^3)*

indexes

cj	*waste heat energy recovered from engine cylinder liner*
con	*condenser*
eg	*waste heat energy recovered from exhaust gase*
h	*heating*
in	*inlet*
out	*outlet*
pec	*primary energy consumption*
w	*water*
whr	*waste heat energy output recovered*