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Review

Review of Gas Engine Heat Pumps

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Abstract: In this paper the most promising developments of technology for gas engine-driven heat pumps for the last 15 years are presented. The purpose is to present the latest research studies and changes in this type of device, as well as to help readers to search for publications containing relevant aspects of gas engine heat pumps. Gas engine-driven heat pumps are devices for parallel heating and cooling production based on compressor heat pump technology. However, unlike heat pumps with compressors powered by electric motors, gas engine-driven heat pumps are driven by gas internal combustion engines. The reviewed solutions are an interesting alternative to traditional heating systems, characterized by the higher than 1.0 Performance Energy Ratio which expresses the degree of conversion of the energy contained in the fuel supplied to the device into energy transported to the utility needs. Presented in this review, papers show different solutions for conversion of the energy contained in the fuel into mechanical and thermal energy, and mechanical energy through the shaft system is used to drive the compressor of the heat pump. The presented study shows that, due to the complexity of the system and the wide range of applications, the technology has been subjected to detailed analyses and optimizations during the last 30 years in order to increase the efficiency of devices.

Keywords: heat pumps; cogeneration; renewable energy; gas engine-driven heat pumps

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1. Introduction

Gas-engine heat pumps have been a known technology for many years and are widely used for the heating and cooling of residential and commercial buildings because of their high energy efficiency. A compressive review of this type of device was undertaken in 2007 by Hepbasil et al. [1–3], who describe the history and development of the technology and energy performance as well as the methods used for gas heat pump efficiency. Figure 1 shows the estimated number of research papers indexed in Science Direct and Scopus during last three decades. As can be seen, an overall increase in the number of papers has been observed over the years. Because of the development of technology over recent years, the authors decided to present the scope of the research carried out and the directions of technology development, which include gas heat pumps. Due to the need to diversify energy sources and systems generating heat and cooling energy, heat pumps powered by gas combustion engines are an alternative to conventional sources. In this article, readers will find articles on the latest solutions and systems after 2009, together with a brief overview of their assumptions. During the analyzed period, various research teams focused on research related to improving the efficiency of existing devices available on the market, their work was discussed in the first parts of this article. The rest focused on new technologies and new systems, in which the gas heat pump was a key element. In the second part, the authors briefly describe the design and system news related to gas engine heat pumps (GEHP).

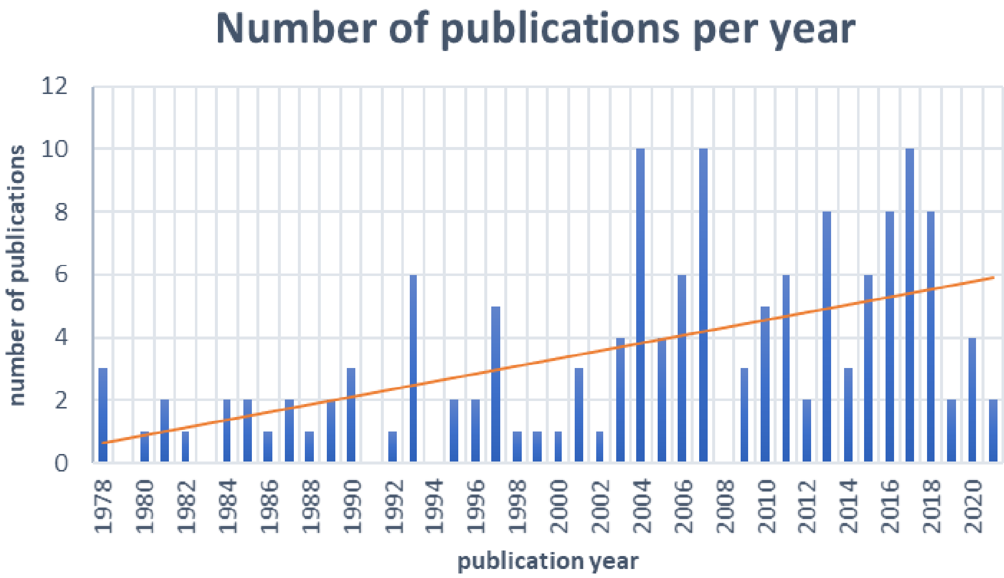

Figure 1. Number of key publications on gas engine heat pumps per year. Resources: Scopus and Science Direct.

Unlike electric motor driven compressor heat pumps, in which the compressor is powered by electricity (electric motor), gas heat pumps are driven by an internal combustion gas engine by transferring mechanical energy to the operation of the compressor. The solution is an alternative to traditional heat systems and is characterized by high overall efficiency that is impossible to obtain using any gas burner or electric heating. The use of natural gas, LPG, syngas or in the near future renewable fuels as an alternative source of power is a solution that is largely due to the vast majority of targeted economic conditions due to the high levelized cost of electricity (LCOE). How does a gas heat pump work and how to develop devices with the highest overall efficiency? The essence of this issue is related to the conversion of the energy contained in the gas fuel into mechanical and thermal energy. Mechanical energy through the shaft gear system is used to drive the compressor of the heat pump system, while thermal energy can be recovered and used in the facility or as waste (energy losses), so the device can distinguish between two main thermodynamic cycles [1]. Figure 2 shows the concept of gas engine-driven heat pumps. The engine is provided with 100 units of energy (for example, the energy contained in the fuel that is gas). This energy is divided into mechanical energy for compressor work and waste heat energy that can be later recovered with the recuperator system. The heat pump system with its main components that are represented in this chamber (compressor, evaporator, condenser, and expansion valve) is responsible for receiving heat energy from outside air. The scheme shows that for a heat pump system we can obtain 140 of heat energy units from 100 primary energy units of the fuel. Due to the complexity of the system and the very wide range of applications, the technology has been subjected to analyses and optimizations during the last 30 years in order to improve the overall efficiency of devices under various conditions as well as their adaptation to market parameters. The presented system can be extended using electrical energy generator in order to produce the most desirable form of energy—electrical energy; however, because of additional complexity this issue is not taken into consideration in this study.

$$COP_{HP} = \frac{HEAT\ ENERGY}{MECHANICAL\ ENERGY} = \frac{140}{35} = 4.$$

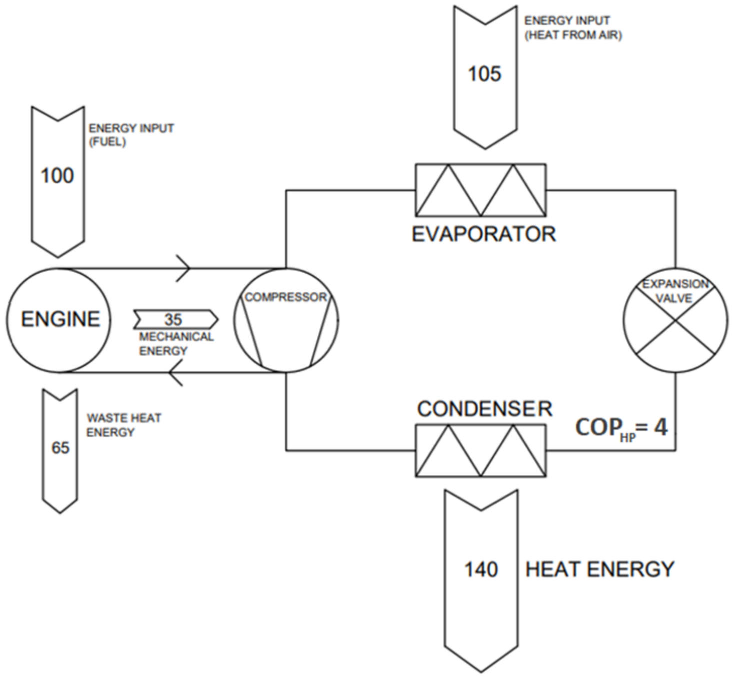

Figure 2. Schematic diagram of gas engine-driven heat pump energy flows.

2. Review of Gas Engine-Driven Heat Pumps Optimization Studies

The success of the device and its popularity on the market are closely related to its effectiveness. Despite the fact that gas engine-driven heat pumps were presented on the market over 30 years ago, they are subject to optimization processes to meet their requirements. The most important factor for measuring the performance of the GEHP is the Performance Energy Ratio (PER). The PER indicator expresses the degree of conversion of the energy contained in the fuel supplied to the device into heat energy transported to the utility needs; the value of the higher (instantaneous, mean or annual) PER indicates that the unit is working more efficiently. The PER index for GEHP is determined on the basis of the EN 16905: 1–5 standard. However, the method of determining the seasonal coefficient of PER is complicated and time consuming. The authors of [4] developed a simplified methodology call IPER (Integrated Primary Ratio) that allows the much faster determination of this coefficient. The analysis showed that the proposed method introduced only a small error of about 3.7% in reference to standard PER methodology.

2.1. Heating Performance

In order to optimize GEHP, typically numerical calculations are carried out [4–6] and most optimized cases are compared with the experimental laboratory or in-situ tests. The GEHP mostly requires modeling for fluid flow and thermal field of the compressor, condenser, expansion valve, evaporator (heat pump system) and internal combustion engine including engine jacket cooling system, exhaust gas heat exchanger and additional heat source [4,5]. When the differences between numerical calculations and experimental results are within the limits of a few percent, the model can be considered for unit development. After the implementation of a reliable numerical model, the entire system can be tested using various control strategies [6] in order to determine the most optimal operating points. The heating energy produced in these devices can come from two different sources with different non-linear dependent rates. The first is an internal combustion engine in which the fuel combustion process takes place and the energy contained is converted into mechanical and thermal energy. Thermal energy can then be collected for operational needs through a heat exchanger from the engine shell as well as the exhaust gas recuperator [7]. Laboratory results show that the heat from engine operation constitutes approximately 1/3 of the total heat produced by the device and which is rated up to 45% [8] of the total heating power of the GEHP system. It has been found that the amount of heat energy generated by the engine is closely related to its rotational speed [9,10]; with increasing temperature, the engine heating efficiency increases and the index PER increases [7–14]. On the other hand, systems should run at low speed if the goal is to save as much fuel as possible. It has to be noted that the rotational speed of the engine has a significant impact on the stability of operation and the efficiency of the entire device, but the gas engine is mostly a non-linear dynamic system, which makes system and speed control a very difficult issue. The characteristics of rotational speed control are described in [15]. In [12], the authors propose a gas engine speed control strategy for the GEHP system. To achieve this main goal, a test bench was developed and an engine speed controller was designed according to the characteristics of the gas engine and the GEHP system. Then, the engine speed controller was applied to the GEHP system; finally, the experimental measurements were carried out under various external and internal conditions as well as the control of the engine speed and anti-interference. The experimental results show that maintaining a constant engine speed without overshoot costs less than 40 s when changing the engine speed setting. In the event of an abnormal change in superheat, the error (accuracy) of the engine speed is controlled to within ±50 rpm. The motor speed control strategy can not only guarantee stable operation but can also ensure high efficiency of the GEHP system. Finally, the performance characteristics of the GEHP are characterized by the heating efficiency and the Primary Energy Factor (PEF). The results indicate that the engine speed is an important factor that significantly influences the performance of GEHP. The heat recovery from engine operation consists of heat received from the engine shell and exhaust gases. Especially in the latter case, it is necessary due to the requirement of cooling the exhaust gases of the device and condensing the moisture therefrom [16] to reduce pollutants entering the atmosphere, in particular CO_2. The vast majority of waste heat is used to heat domestic hot water [17], but with its wider use, e.g., as an auxiliary heater, the efficiency of the system may increase significantly, taking into account that the temperature of the domestic heating water supply is in the range of 40–60 °C. While reducing fluid temperature, for example, up to the temperature required by low-temperature heating, the efficiency of the heat pump system increases [18,19]. The second thermodynamic cycle that generates heat is the heat pump compressor, which is driven by mechanical energy from the engine. The refrigerants used in GEHP are predominantly CFC-based, but they have high Global Warming Potential (GWP). The possibility of replacing the R152a with alternative refrigerant R134a has been investigated in [20,21]. With new fluid, PER increased, depending on conditions, by 2.6–10.4%, 3.5–10.7%, and 5.8–7.3%, which confirms the possibility of using alternative refrigerants with low GWP. There are several ways in which one can increase the efficiency of the system components and improve the PER. For example, in [13] the authors analyzed the temperature increase in the evaporator from 12 °C to 22 °C, the ambient temperature increased from 24.2 °C to 37 °C and the engine rotational speed increased from 1400 to 2000 rpm. The results indicated that the temperature of the evaporator and the engine speed play a substantial role in the characteristics and performance of the system compared to the ambient temperature. The evaluated primary energy ratio was 1.14 and 1.45 with the recovery of waste heat. Similarly, in [8,22] with the heating efficiency of the system for the preparation of domestic hot water, COP and PER increased with increasing temperature of the fluid that supplies the condenser as well as ambient temperature. PER was estimated to be approx. 1.23 to 1.48 under experimental conditions. It has been observed that when the temperature of the supply object increases, the efficiency decreases; however, efficiency increases with increasing water flowrate [11]. Authors have shown that the water temperature can be in the range 35–70 °C [23]. Total heating capacity decreased by 9.3% and heat recovery from the water temperature by 27.7% as the condenser supply changed from 33 °C to 49 °C. Additionally, PER dropped 15.3% when the engine rotation changed from 1300 rpm to 1750 rpm. Furthermore, in [24], the authors conclude that the temperature of the fluid that supplies the evaporator has a significantly greater impact on the efficiency of the system than the ambient temperature and the flowrate of the water in the evaporator. Considering that the heating mode is particularly desirable in periods of low external temperatures, users should pay attention to the freezing of heat exchangers at temperatures below 0 °C. By investigating the most efficient defrost method, the authors showed that the defrost time was the shortest when using the engine waste heat and using a reversible heat pump system [11].

2.2. Combined Heat and Cold

Just like electric compressor heat pumps, GEHP can work in a reversible system, producing cold for domestic or industrial needs. If the system includes heat recovery from the engine operation and the heat pump system works in cooling mode, it can be referred to the combined simultaneous production of heat and cold cogeneration. The authors of [25,26] developed computer numerical models for GEHP systems operating in the mode of simultaneous production of heat and cold. With measurement data and models for both the production of heat alone and for combined heat and cool, control strategies can be developed for possible implementation on the device. For example, in [27] the authors proposed the system of a gas-engine driven heat pump and a water-loop heat pump. To improve the cooling efficiency, the influence of the gas engine and the superheat (T_{sh}) [28] was investigated. With T_{sh} decreasing from 13 °C to 6 °C, the cooling capacity of the system increased significantly and below 6 °C the rate of increase in efficiency gradually decreased. For engine rotational speeds of 1200 rpm, 1400 rpm and 1600 rpm, the optimal T_{sh} of the system was 3.5 °C, 3.8 °C and 4.5 °C. The corresponding system primary energy index was 2.63, 2.40, and 2.17, respectively. The results of the experiments in [29] showed an increase in the cooling capacity with an increase in air velocity in the condenser and a decrease in the ambient air temperature. In [30] the authors investigated the influence of the location of the four-way valve, which is the most widely used solution in GEHP devices operating in reversible heat pump systems for the system performance. The valve should not be close to the inlet of the evaporator because it may reduce heating and cooling efficiency. The proposed solutions with the use of three thermostatic valves ensured a significant improvement in PER of more than 20%. As in the case of heating, increasing the rotational speed of the engine results in a decrease in PER [31]; however, in the case of cooling mode, when there is no need to collect or use the combustion waste heat, this indicator is lower for the cooling season than for the heating season [32]. In Table 1, summaries of studies presented by different research groups with the main focus on performance energy ratio are presented.

2.3. Control Strategies

Key elements include the systems and strategies for controlling individual components in order to keep high system performance [33,34]. Using artificial neural networks and the optimization method, the authors in [35] demonstrated compliance with the thermodynamic model in terms of operating pressure, fuel consumption of the gas engine, outlet water temperature, engine rotational speed, and the system primary energy ratio of the acceptable difference at the level of 5.08%, 5.93%, 5.21%, 2.88% and 6.2%. In [36] the authors described a cascade fuzzy control strategy. Due to GEHP large and variable time constants, it is difficult to perform accurate dynamic modelling and the cascade fuzzy control strategy is an effective solution for such cases. Comparing the performance control strategy with cascade proportional and integral (PI), it can be seen that the cascade fuzzy control strategy produces a better performance, faster response times, and less temperature overshoot. The results presented in [6] indicate that the intelligent control model is very effective in the analysis of the effects of system control and that the steady-state accuracy of the intelligent control scheme is even higher than that of the fuzzy control.

Table 1. Summary of studies and PER efficiency presented by different authors.

Lit	Year	Investigator(s)	Type of Study		Scope of the Study					Others
			Theoretical (Simulation)	Practical (Experimental)	Heating	Cooling	Water Heating	Control Strategy	Efficiency	
[16]	2003	K. Takahata and T. Yokoyama		√	√	√			√	Exhaust heat usage for better COP
[6]	2007	Y. Zhao et al.	√		√			√	√	Results better than fuzzy control
[32]	2009	Z. Xu and Z. Yang		√	√	√				Humidity and temperature area control, PER 1.9
[5]	2010	S. Sanaye and M. Chahartaghi	√		√	√			√	
[23,24,26,31]	2010/11	Elgendy et al.	√	√	√	√	√		√	max PER 2.2
[11]	2013	Z. Yang et al.	√		√		√			PER 1.43
[15]	2013	M. Wang et al.	√					√		
[25]	2013	S. Sanaye et al.	√	√	√				√	
[19]	2014	E. Elgendy and J. Schmidt		√	√		√		√	PER 1.83
[10,14]	2016	N. N. Shah et al.		√	√		√		√	Diesel engine, max PER 1.4
[8,13]	2017/18	F.-G. Liu et al.	√	√	√	√	√		√	max PER 1.55 with gas condenser
[9]	2017	B. Hu et al.	√		√		√			PER 1.52
[12]	2018	M. Wang et al.		√	√			√		
[17]	2020	F-G Liu et al.		√	√	√	√		√	PER 2.34
[20]	2020	Z. Ma et al.		√						Comparison of R134a & R152a
[28]	2020	Z. Tian et al.		√	√	√			√	PER 2.63
[30]	2020	L.-L. Jia et al.		√	√	√			√	PER 1.57

Table 1 contains the most important articles since 2007 dealing with the topic of improving the efficiency of gas heat pumps. Which areas and scope were the subject of research by which individual research teams have been marked. The structure of the table is to simplify the search for relevant information related to the scope of the reader's interest.

3. Applications and Comparisons of Gas Engine-Driven Heat Pumps

GEHP technology meets the needs of most commercial cooling and heating solutions. In [37–39] the authors compared the efficiency of three various devices: an electric heat pump, a water chiller, and a gas heat pump. The papers show that GEHPs are a very interesting direction for space heating, and designers and investors should pay attention to their advantages. They note that CO_2 emissions are comparable to electric compressor heat pumps (for a suitable pure natural gas), which proves the ecological value of these devices. The results showed that economic viability depends primarily on the nature of the customer and the price of gas and cost of electricity. For applications it should be noted that these devices are outdoor units that need to be sited in a suitable place. More than that, units generate noise at the level of 40–80 dB and must be located at an appropriate distance from places of permanent residence of people and properly soundproofed. Gas heat pumps driven by internal combustion engines are used where it is required to provide a sufficiently large amount of heat, due to the fact that these are large units and the vast majority of them are external systems. Large units are, at present, not applicable for single-family houses. However, it should be noted that the heating energy produced by the heat pump system is low/medium temperature heat, therefore the recipient must take into account the need to adapt systems to such output temperatures.

Some examples of GEHP applications presented in this article are summarized in Table 2. The GEHP technology has been developed mainly in East Asia, where it gained great popularity especially in South Korea [35] and Japan [12,40]. There are also solutions dedicated to the industry that requires sufficiently high air temperatures [41], and is widely used in the dried food industry, where maintaining strict conditions [42–45] is required, including dehumidification processes, possibly as a source of air with low temperatures for food storage and air conditioning systems in commercial buildings [46–48] Currently there are many manufacturers that provide devices based on gas engine-driven heat pumps on the global market.

Table 2. Gas engine-driven heat pump application examples.

Lit.	Year	Investigator(s)	Use	Application	Remarks
[38]	2016	L. Pezzola et al.	Commercial	Hotel	NPV for GEHP is 6 years while for EHP 5 years this is because of higher investment costs of GEHP by more than 28%. Due to the greater savings resulting from the use of GEHP, after 20 years, the savings are 75% more compared to EHP.
				Shopping center	In the case of the center, the difference in NPV is the same; it is 10 years for GE, 5 years for GE, also the difference in HP amounts to about 15% on GEHP. It is related to the energy characteristics of the facility. It is not possible to maintain parameters all day in the mall.

Table 2. *Cont.*

Lit.	Year	Investigator(s)	Use	Application	Remarks
[46]	2016	R. Kamal et al.	Commercial	Commercial zone	The GEHP unit was used to provide air conditioning in several thermal zones. The performance was evaluated over a period of 10 months. This study shows how important it is to install the GEHP system fit to the heat energy load of building, because by running your devices at full capacity, you can achieve higher performance. They propose ways to get best efficiency, such as heat production for heat accumulation or energy production.
[42–44]	2011	A. Gungor et al.	Industrial	Technology procedures	Study of plant drying process using GEHP. This paper shows the possibility of the usage of this device for industrial application where maintaining strict environmental parameters is needed with a lot of heat energy demand.
[45]	2011	L. J. Goh et al.	Industrial	Food drying	The main purpose of any drying process is to produce a dry product of the desired quality at maximum and minimum cost. In the article, authors show the range of food products that can be dried and which systems can be used for this including heat pumps such as GEHP. They notice the advantages of the heat pump which reduces the dependence of electricity on fossil fuels such as natural gas.

4. Novel Systems of Gas Engine Heat Pumps

Gas heat pumps are devices composed of many interconnected elements. In this section, among others, hybrid systems or systems with energy storage will be reviewed as examples of cooperation between GEHP and other elements with the aim of obtaining the most effective system.

4.1. Hybrid Gas Engine Heat Pump

A gas engine-driven heat pump is typically applied for heating or both cooling and heating. Due to the waste heat from the gas engine, the heating mode has a higher performance than the cooling mode in these devices. The research groups, striving to obtain the best possible energy, ecological and economic efficiency, subjected the devices to the analysis of a number of systems, including the GEHP. One of them is the hybrid gas engine heat pump (HGEHP) [49,50]. The system has a battery storage as an additional power source for efficient engine operation. The HGEHP (also called later HPGHP) combines hybrid drive technology from both gas engines and electricity (battery), and can be divided into three main categories:

- the hybrid power-driven system;
- the heat pump system;
- the waste heat recovery system.

Figure 3 shows a simplified scheme of a hybrid power, gas-engine driven heat pump where the electric motor works as an alternative energy source, depending on the control strategy and working mode.

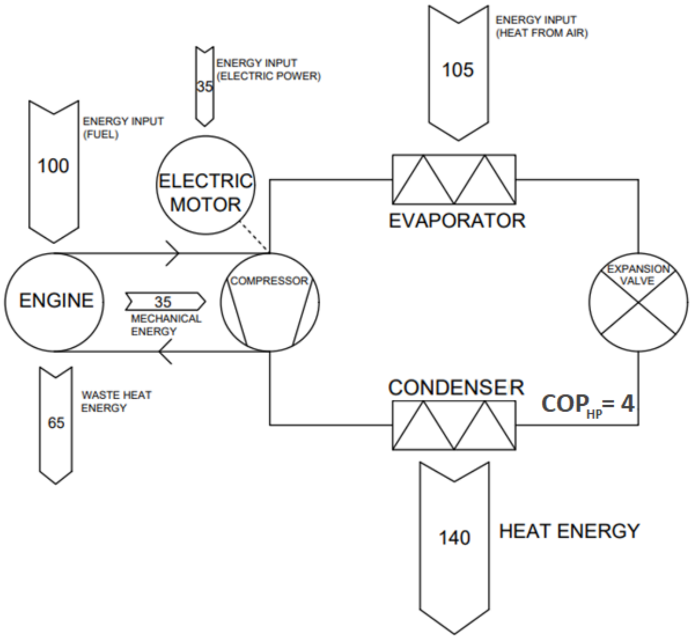

Figure 3. Simplified scheme of hybrid power, gas-engine driven heat pump.

Unlike the GEHP, a hybrid GEHP unit can be driven by an electric motor supplied by battery instead of the gas engine only, so it has two alternative sources of energy. Taking into account the constant changes in external load, it may cause the charging and discharging process to be too frequent, which can have a negative effect on batteries. In the analyzed system, the LiFePO4 battery was used as an additional source of energy and economic performance was estimated [49]. The strategy for energy control was based on the economic criteria in order to distribute power between the gas engine and the electric motor. The authors investigated the impact of selected parameters (fuel consumption, the efficiency of energy conversion, and superior performance of the battery LiFePO4) on the HGEHP system's performance. It also must be noted that the fuel consumption of energy shows that the annual primary energy rate of the mentioned battery was higher than in the other examples. The power used for HGEHP often encounters a temporary power requirement. In [51] the authors showed that, due to switching between different working modes, batteries tend to discharge and charge frequently, which has a negative impact on energy conversion in the system. To increase the economic performance and HPGHP dynamic performance, a logic threshold control strategy to distribute power between the battery and the gas engine has been investigated.

The research on Coefficient of Performance (COP), engine thermal efficiency, heating capacity, energy conversion, fuel consumption, and reclaim of wasted heat has been involved tests, the results of which verify the performance of the LiFePO4 battery in HGEHP. The presented results show that the LiFePO4 battery performs better than the lead-acid battery. On the other hand, in [52] the authors show that the LiFePO4 battery can achieve a better energy saving effect, especially under high-load and low-load conditions. Compared to the GEHP system, the gas conversion efficiency can increase by approximately 7.6% when the logic threshold control strategy is applied in the HPGHP system [53]. The study indicates that the minimum gas consumption of the LiFePO4 battery under low, medium and high load conditions was 12.2%, 1.07% and 6.54% lower than in the case of the HPGHP lead acid battery [49]. To improve the performance of HGEHP, a system in which the heat pump is driven for heating by a gas engine and where an electric motor drives it for cooling, is proposed in [54]. The mathematical model of the HPHP (hybrid power-driven heat pump) system mathematical model is developed, and its performance is compared to that of GEHP and EHP. The PER for HPHP cooling is 28.5–51.2% higher than GEHP and 15.8 to 25.3% higher than EHP for heating. Compared to GEHP and EHP, the hybrid power-driven heat pump system savings ratio is 10.9% better than GEHP and 14.4% better than EHP (tested in Beijing), and 18.5% and 7.3% (tested in Shanghai).

The authors of [55] proposed the optimal torque control strategy for the distribution of power between the gas engine and the battery pack. The parameters of the HPGHP (hybrid power gas engine heat pump) system parameters were simulated in Matlab/Simulink and verified by experimental data. The measurement and simulation results show acceptable compliance, and the maximum difference was 8.9%, 5.9%, 9.5%, 8.2%, respectively for: engine torque, heat recovery, and fuel consumption. The results for HPGHP show the lowest consumption of fuel at 3000 rpm engine speed. The PER for the HPGHP system was approx. 15.9% and 11.4% higher than the respective modes and under the same load. Based on experimental data, the mathematical model of an HPGHP, under the Engine Economic Zone Control Strategy (EEZ-CS) and the Torque Control Strategy (EOT-CS), was established in [56]. These controls were proposed to provide the proper distribution of power for the battery pack and the gas engine. To compare the economics under the two control strategies, the sum of engine gas consumption and the equivalent gas consumption for battery replacement were calculated as an evaluation criterion. The energy for HPGHP under the EOT control strategy is approximately 4% and 25.2% higher than under the EEZ control strategy and GEHP at the same load.

In [57] the authors show that for the baseline control strategy combined with the gas engine optimization control strategy, the fuel-consumed flow changes by 280–340 g per kWh. With an increase in compressor speed, the thermal efficiency of the drive system is maintained between 0.23 and 0.28. The relation between the dynamic load of the compressor and drive system is established in [58] to improve the efficiency of energy conversion. The results of the power system also show that for a GEHP the maximum and minimum thermal efficiencies of the power system are 33% and 22%, respectively. The power system in the HPGHP has maximum and minimum thermal efficiencies of 37% and 27%, respectively [59]. In "Optimization of the waste heat recovery system in hybrid-power gas turbine driven heat pump (HPGHP)" [60], the model of the engine waste-heat reclaim system was developed. The results show that the waste heat recovery rate of the cylinder liner waste heat is higher than that of the exhaust waste heat. The heat exchange surface of the gas heat exchanger is optimized. The results show that when the NTU is around 0.6, the annual net income per unit of flue gas heat recovery is at its maximum; at this point, the economically optimal heat exchange surface is around 1.79 m^2. In [61] the authors established the mathematical model of the HPGHP system to investigate the relations between the load demand for the compressor and the drive system. The simulation results show that the thermal efficiency of the HPGHP system can always be guaranteed above 0.25 and the transmission coefficients are 2.9, 1.8, and 1.4, respectively, in three different load ranges.

To obtain better fuel economy, mathematical models developed to minimize equivalent gas consumption and the power balance principle was established [62]. The results indicated that the gas engine can always operate in the economic zone with a high thermal efficiency above 0.25 under various operating modes. In that work, an economic objective function that included gas consumption and battery loss was used. The overall exploitation costs of GEHP and HPGHP were compared and analyzed. Analyses indicate that the average PER of HPGHP is higher than that of GEHP by approx. 12.1%. The authors used HGEHP as an example of fuel-consumption rate, fuel-consumption flow, fuel-conversion efficiency, and life-cycle assessment to analyze the effects of energy saving and environmental benefits on human health and ecosystem quality. The authors showed in the results that the fuel conversion efficiency of HGHP under various operating conditions is higher than that of conventional GEHP at the same load. The gaseous products are mainly CO_2, and other gases containing carbon or sulfur oxide. That means that the usage of natural gas is effective in reducing pollution gas emissions. Analyses presented in [63] show that HPGHP can provide better environmental benefits than GEHP when it runs for more than 1778 h.

4.2. Gas Engine Heat Pump with Energy Storage

GEHP is a device in which performance and efficiency are closely correlated with variable factors, which include the energy demand of the facility and external conditions, in particular the temperature of the outside air. The lower the outside air temperature, the lower the efficiency of the heat pump. Taking into account the above factors, it is extremely difficult to achieve the best efficiency of the device in periods of the highest demand, especially for heating energy. To obtain the best possible system efficiency, independent of periodic increases and decreases in energy demand by the facilities, the GEHP with energy storage was created. Energy storage is designed to store heat at times of low consumption and low demand, but with optimal operating parameters. Energy stored in this way can be transferred to utility needs. An example of such an analysis can be found in [64–66], where the results showed a reduction in the fuel consumption of the system and an increase in the efficiency of the whole system. The use of energy storage leads to a significant improvement for the entire system [67] by increasing the PER index by even 67.87% for the appropriate operating mode compared to the standard GEHP solution. Figure 4 shows the concept of energy storage; with proper system control, waste heat energy can be stored during low demand and high device efficiency and unload for a better performance and higher economic and ecological benefits.

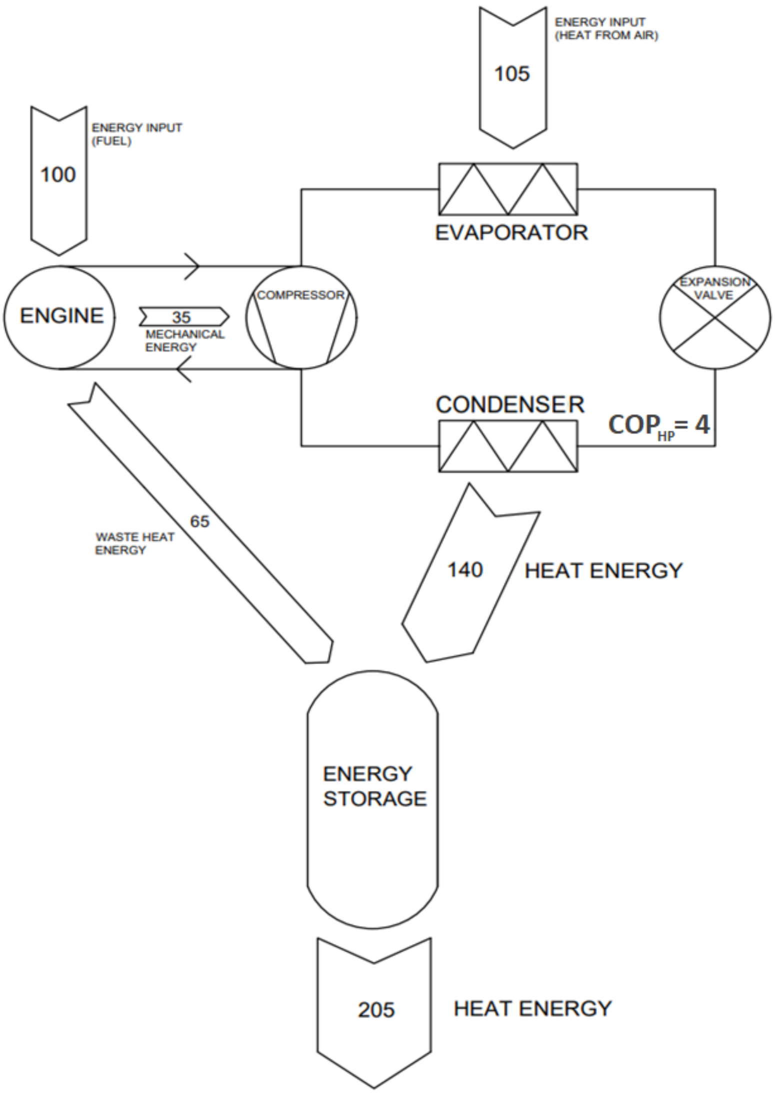

Figure 4. Simplified scheme of gas engine heat pump with energy storage.

4.3. Solar-Assisted Hybrid Power Gas Heat Pump

In order to reduce energy consumption in buildings for heating and cooling, a solar-assisted hybrid power gas heat pump is proposed [68]. The analysis shows that, according to various photovoltaic factors, the use of PV arrays leads to a significant improvement in energy consumption but at the same time causes a significant impact on the environment. Finally, the authors conclude that the environmental return period and the best environmental payback time for the system is 13.4 years with a PV ratio of 40%. To minimize the environmental impact of the system, the influence of the main independent decision variables was used, such as PV ratio transmission mixing and the degree of the ratio. According to [69], the optimal photovoltaic ratio is 40%. The environmental impact potential of the system decreases with the increasing degree of mixing and increases with the increase of transmission ratio. In [70] the authors show the economic profitability of this solution.

4.4. Compression-Absorption Heat Pump for the Para-Ell Gas Engine (GECAHP)

When it comes to natural gas heat pumps, it should be noted that this nomenclature can correspond to two different types of units. This article describes solutions for a device in which the internal combustion engine drives the compressor of the heat pump system, i.e., the so-called vapor-type heat pump or compressor-type heat pump. There is also an absorption heat pump. The combination of these two devices into one system was proposed by the authors of [71–73], where the waste heat from the GEHP vapor type is transferred to the gas pump of the absorption pump. The results showed that the maximum primary energy ratio of the GECAHP system is greater than 1.5. Furthermore, it was shown that by increasing the engine speed from 1500 to 2500 rpm, the heating efficiency increased by 54.5%.

5. Conclusions

The presented review paper shows technology development for gas engine-driven heat pumps over the last 15 years. Since the beginning of the concept of heat pumps powered by internal combustion engines, the willingness to optimize these systems to obtain the lowest energy losses and the highest possible efficiency can be observed. For this purpose, the focus was primarily on the recovery of excess heat from the engine jacket and exhaust gases, which represents approx. 30–45% of the total thermal energy of the device. The presented studies show that engine speed was indicated as one of the most important elements influencing the efficiency of heat generation by GEHP. According to various research studies [6,7,25–30], the range of the optimal operating point is between 1200 and 1800 rpm. Subsequent studies focused on the control strategy in order to obtain the best possible operating parameters of the device, primarily by controlling the engine speed. The main relationship that emerged from all the tests shows that GEHP system efficiency decreases with increasing rotational speed, while power increases at the same time. This means that the ratio of the primary energy consumption to the power of the device increases from a certain point. Most of the authors indicate that determining the optimal operating point is difficult but an important factor for combustion engine gas heat pumps. The presented publications clearly indicated that lowering the outlet fluid temperature (lowering the condensation temperature) rather than the ambient temperature is significant for GEHP performance [34,35]. By lowering the fluid temperature at the outlet, the device can achieve up to 10% of its PER. The common feature of these devices is the need to receive thermal energy and adapt the device to the nature of the facility, both in terms of heating and cooling. It is possible to combine the devices into hybrid systems with energy storage. The aim of such activities and research studies is to obtain the optimized energy production system adapted to the very wide possible group of recipients. Gas-engine-driven heat pumps powered using natural gas, LPG, syngas or in the near future renewable fuels are undoubtedly devices that will be the subject of intensive analysis in the coming years because of the growing interest in heat pumps and the need to diversify their power sources. In summary, gas heat pumps are an interesting alternative to the more popular heating and air conditioning systems. The greatest interest in these devices can be observed in applications for industry and construction with a constant demand for thermal energy throughout the year. Natural gas as a source of primary energy is a solution where there is no possibility of supplying from other sources. The most effective use of this resource will be a research problem for many research groups in the coming years. Therefore, it is expected that new technologies related to gas engine-driven heat pumps and their development will come out; it is also possible that the novelties described in this review will soon find wide application on the commercial market.

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Nomenclature

GEHP	Gas engine heat pump
EHP	Electric heat pump
HGEHP	Hybrid gas engine heat pump
HPHP	Hybrid power-driven heat pump
HPGHP	Hybrid power gas turbine heat pump
GECAHP	Compression-absorption heat pump
PER	Performance energy ratio
PFC	Primary energy factor
LCOE	Levelized cost of electricity
EEZ-CS	Engine economic zone control strategy
EOT-CS	Engine economic zone torque strategy
HPGHP	Hybrid power gas turbine heat pump
CFC	Chlorofluorocarbons refrigerants
LPG	Liquefied petroleum gas
PV	Photovoltaic
NTU	Number of transfer unit
COP	Coefficient of performance
COPHP	Coefficient of performance of heat pump circuit
NPV	Net present value

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