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Technical Feasibility of Exhaust Heat Recovery in Reciprocating Engines: A Case Study on Power Generation Systems

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Abstract

This paper discusses a technical and economic feasibility study of the implementation of an exhaust heat recovery system in a 3.5 MW reciprocating engine-based power generation facility. Indeed, several configuration options for waste heat recovery from exhaust gases and the engine cooling system are pursued through detailed thermodynamic modeling and economic analysis. These results show that the implementation of these heat recovery systems increases the overall efficiency of the engine from an initial value of 40.87% to a maximum of 83.07% in combined scenarios involving the use of exhaust and cooling system heat. An economic analysis indicates that fuel savings and a reduction in operational costs can balance out the initial investment, especially for applications in which there is a need for simultaneous heating and cooling. Other appealing benefits are the environmental ones, up to 30% reduction in greenhouse gas emissions. It looks, too, at the use of CO_2 emissions from the exhaust in greenhouses for cultivation, extending the area to as much as 15.78 hectares. These results confirm that a Combined Heat and Power (CHP) system is the key strategy to be considered in the reciprocating engine in pursuit of energy efficiency at the least cost and with limited environmental damage.

Keywords: Power generation, Environment, Greenhouse, CHP.

1 | Introduction

Energy efficiency and sustainability have gained considerable importance due to the increase in energy demand and the intensification of environmental regulations all over the world. Reciprocating engines, with their versatility and reliability, find extensive applications in both centralized and decentralized power

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generation systems. At the same time, however, these engines have relatively low efficiency, with approximately 55-60% of the input energy being dissipated as waste heat through exhaust gases and cooling systems. The recuperation of this wasted heat is a great opportunity for enhancing efficiency and reducing fuel consumption these days, which is a very crucial goal in reducing greenhouse gas emissions [1]. In this respect, research efforts in recent years have been directed toward the enhancement of heat transfer and improvements in energy storage, thereby cutting consumption of fossil fuel and consequent CO_2 emissions by various methods, including the use of nanofluids and flow pattern optimization [2–8].

As the increase in CO_2 emissions greatly contributes to global warming, the recovery of waste heat relates directly to the climate change mitigation policy. In addition to that, the growth of atmospheric CO_2 concentration, along with other GHGs such as CH_4, N_2O, and SF6, has vastly affected Earth's energy balance with a different set of impacts such as disruption in agriculture, deterioration of forests, dropping levels of groundwater, and disturbances in wildlife ecosystems. One of the ways to improve these issues is to use carbon capture and storage technologies [9].

Among them, the major percentage belongs to CO_2; hence, its reduction is of primary concern in ecological strategies. However, despite its environmental effect, CO_2 finds wide applications in industry: in carbonated beverages, treatment of wastewater, production of dry ice, and oil recovery [10]. Thus, this duality of CO_2 of great value in industry and at the same time destructive to the environment points out that the reduction of its emission and economic usage have to be balanced. In the case of industrial use, however, the CO_2 needs to be cleaned and liquefied to make transportation and utilization effective. Various pretreatment steps include water removal via silica gel towers and gas pressure increase via compressors to about 8 bar in general [11].

Further, this is filtered with activated carbon filters to the high purity required for industrial use, which introduces technical challenges and costs regarding energy consumption in the processing of CO_2 [12]. Issues not unrelated to economic feasibility in recovering heat in power generation systems are the optimization of using CO_2 and minimizing its emissions. Recently, in response to these challenges, some research works have been conducted to explore various methods of capturing and separating CO_2 to reduce the energy consumption rate of such processes. Taousi and Mogharnajad [13], for example, considered the direct separation of atmospheric CO_2 by chemical absorption and simulated the process to optimize energy use. They showed that increasing the number of absorption trays can dramatically raise the recovery rate with much lower energy consumption. Historically, WHR systems have emerged as crucial technologies for increasing energy efficiency in industrial uses and power plants.

First, WHR systems, such as HRSGs, were originally developed for large, baseload power plants [14]. Newer thermodynamic modeling and materials science advances developed more compact and efficient systems that would apply to smaller-scale applications and include the process of internal combustion-external combustion in reciprocating engines. Nowadays, WHR systems are implemented in most industries: chemical processing, food production, etc., bringing some economic and ecological advantages accordingly [1].

Efficient utilization of waste heat has been a focal point in small-scale power generation due to the potential enhancement of system efficiency, reduction of fuel consumption, and lowering of environmental impacts [15]. More importantly, cogeneration systems called Combined Heat and Power (CHP) or Combined Cooling, Heat, and power are viable solutions for maximizing energy utilization in power plants. Extensive studies have been performed to calculate the thermodynamic and economic viability of such systems, very often taking the First Law of Thermodynamics and exergy analysis for the evaluation of benefits related to the innovation.

Small-scale cogeneration systems can offer several benefits to small-scale power plants by recovering the waste heat emissions into the environment that would have been generated otherwise. This will contribute not only to improving the global efficiency of such systems but also to the great reduction of greenhouse gas emissions. Several studies have examined various cogeneration configurations along with their performance for a variety of operational scenarios. For example, Abdollahi made a technical and economic comparison of gas turbine-driven CCHP against a combined cycle power plant and found that CCHP configurations were more efficient and economically viable. Thermodynamic simulations and cost analyses revealed both energy and economic benefits for these systems. Other cogeneration systems integrated with energy storage systems have also fared well in efficiently using energy from different cycles in demand.

For example, Mirlarimi et al. present a Case study investigation of an optimized CCHP system with thermal and electrical energy storage along with auxiliary boilers and absorption cooling. It is shown that energy storage reduces peak demand from the grid, shifts energy storage to off-peak hours, and leads to significant cost savings. Moreover, in the optimization studies on heat recovery within a CHP system, Ebrahimi et al. [16] stated that waste heat recovery from exhaust gases and engine cooling has the potential to increase overall efficiency to almost 56%. Thus, it proves that CHP systems have great potential in the process of improving fuel efficiency with reduced energy consumption. Other works related to design and optimization show valuable contributions towards cogeneration systems. The works involving various heat recovery and fuel optimization methods in different industries by Enteshari et al. and Katouli and Sabzpoushani have emphasized cost-effectiveness in integrating such systems within existing power generation infrastructures.

In particular, the research by Enteshari addressed the technical and economic advantages of the use of recovered heat from power generation cycles to feed absorption chillers for cooling, showing that this approach may significantly save energy and cut costs. On the other hand, Katouli and Sabzpoushani [17] simulated a combined cycle power plant under different fuel conditions. They carried out a comprehensive energy analysis by concluding that natural gas had better performance in comparison with the rest of the fuels concerning both efficiency and power output.

Also, several international studies have highlighted the optimization of cogeneration systems in different applications. Michel Fiedt and Monica Costia [18] presented various cogeneration technologies and made a comparison among them. The result indicated that each cogeneration technology has specific advantages, which manifest under the kind of application and operating conditions. Hence, this points out the need for appropriate selection given maximum energy efficiency and economic return.

Also, local research by Ramazani Aghdash and Mahdavi [19] focused on improving the efficiency of already available power plants by applying cogeneration. This local study conducted on the Shariati Combined Cycle Power Plant in Mashhad showed that large quantities of thermal waste emanating from the turbine exhaust can be recovered and utilized to enhance the efficiency of the plant from 22.75% to 80.61%. This was achieved by cooling the gases exhausted after the heat recovery processes to maximize the extraction of energy from the waste heat. In a similar regard, Tarazali and Fakhar [20] used the Retscreen software to optimize a 2 MW cogeneration plant for a residential complex in Tehran. The various factors analyzed in their study include the consumption of electricity and gas, rate of inflation, and project life, which show the economic viability of the cogeneration system, estimating a payback period of only 4.4 years. From that perspective, Zhang and Wang review thermoelectric materials for the direct conversion of waste heat to electrical energy, which is considered very promising in low-temperature applications. More recently, several studies have quantified the environmental benefits of integrating WHR systems. Wang et al. show that WHR systems can reduce CO_2 emissions by up to 30% in medium-scale power plants. According to Smith and Kumar, other emerging technologies, including supercritical CO_2 cycles and organic Rankine cycles, further enhance the efficiency at a reasonable level in the case of reciprocating engines. Another critical breakthrough for WHR applications has been the integration of solid oxide fuel cells, as was shown in pilot studies by Rivera and Gomes (2023), enabling improvements of efficiencies related to CHP applications by up to 15%.

With the increase in the world's concern about energy efficiency and sustainability, cogeneration systems' design and optimization provide a promising pathway that will lead to much better performance from small-scale power plants. Their tendency to make use of discarded heat, improve the efficiency of the whole system, and decrease greenhouse gas emissions is what makes them attractive for future power generation strategies. The proposed research work is aimed at furthering the literature review to focus not only on innovative ways of waste heat utilization but also on new ways in small-scale power plants and should pursue high plant efficiency with the least environmental impact.

Technical and economic feasibility is studied for the implementation of WHR systems in a 3.5 MW-rated, reciprocating engine-based powerhouse at a governmental facility. Advanced thermodynamic modeling tools are used to simulate several WHR configurations aimed at improving the plant's energy efficiency, reducing fuel consumption, and providing overall better performance. Besides this, the economic analysis is also made based on capital investment, fuel savings, and operational expenditure that are involved in these systems. The results obtained give a detailed understanding of how WHR systems would result in the transformation of energy efficiency in contemporary power plants [19], [1].

2 | Methodology

The approach used in this work relies on comprehensive thermodynamic modeling, making use of the Thermoflow software suite. Indeed, Thermoflow is one of the best-known tools, thanks to the accuracy with which it simulates the operation of power generation systems. An internal combustion engine of 3.5 MW, is considered for the study at hand, which is of widespread industrial use. In this regard, the engine has two major sources of waste heat: the exhaust gases can reach 650°C, while the cooling system of the engine works at much lower temperatures, below 100°C. This modeling concerns the simulation of the two WHR systems in parallel, recovering, on the one hand, heat from exhaust gases and, on the other hand, heat from the engine cooling system. Here a heat exchanger is simulated, which converts high-temperature waste heat coming from the exhaust gas recovery system into steam usable either in industrial processes or for district heating. On the other hand, a low-temperature heat exchanger is simulated in the engine cooling system, which recovers heat for the production of hot water for HVAC applications. They performed the simulations for systems under different load conditions of 50%, 75%, and 100% loads and ambient temperature ranges from -10°C up to 40°C.

The objectives of the simulations have been focused on obtaining the various efficiencies to be yielded by each WHR configuration and their respective enhancements in fuel consumption and CO_2 emissions. Additionally, an economic analysis has been made considering the viability as far as cost returns of the implementation of WHR systems against capital investment in them, maintenance costs, and fuel savings during the system's operational life. The solution in this work used Thermoflow version 23 to carry out a complete thermodynamic and economic analysis. The modular structure allows performing the simulations with great detail using GT-Pro, GT Master, and Thermoflex for the most important components of any power plant: gas turbines, steam turbines, and heat exchangers. The above-mentioned modules will enable an integral approach to optimizing performance and cost-efficiency under a variety of operational conditions. In this respect, solution precision and validity in Thermoflow require deep expertise in power plant systems, further backed by mastery of its modules, which are indispensable for correctly modeling and optimizing energy systems [20].

3 | Case Study Overview

Under this study, a CHP was implemented in one facility under the program that was aimed at raising energy performance and optimizing waste heat utilization. This system has a capacity of electricity generating unit 3457kW, as well as two capacity heat-generating units with a total capacity of 3519kW. The generated electricity is supplied to the national grid through a 20kV line, and the heat obtained is supplied to the building's facilities using hot and steam water lines.

The CHP system uses a natural gas reciprocating engine that utilizes the Otto cycle as a thermodynamic cycle, which, in this case, produces the mechanical energy necessary to turn the crankshaft. The power generated by the engine's rotational force drives a generator, which is mechanically coupled to the engine. Such heat recovery is accomplished in two pathways:

I. Production of steam: hot gases from combustion (up to 4500°C), which are high temperatures, pass through the shell and tube heat exchanger to heat water and turn it into steam. The cooling combustion by-products that are cooled to 1200°C are emitted to the atmosphere thereafter to reduce the loss of waste heat.

II. Hot water supply: heat extracted from the engine body and lubricating oil is used to raise the temperature of water from 45°C to 65°C, with pressure up to 7 bar through a pipe 12 inches in diameter. It provides the facility with hot water while, at the same time, enhancing energy efficiency by reducing the engine cooling requirement.

The CHP system, in turn, efficiently generates 3,482 kW of electricity, 2,830 kg/h of steam (equivalent to 1,846 kW of heat), and 1,673 kW of hot water. With an overall efficiency of 83.4%, this not only meets the total energy requirements of the building complex but feeds about 2.5 MW into the national grid. It maximizes heat recovery for steam generation to support heating and cooling applications, even down to providing absorption chillers, hence being an all-inclusive energy management system. This project case study represents one of the models for energy efficiency in power generation, showing the enormous potential of CHP systems for wider diffusion into similar facilities. *Table 1* summarizes system design and performance parameters, underlining the effectiveness of the system in responding both to the local energy needs and the energy grid at the national level, setting a benchmark for future sustainable energy projects.

Table 1. General specifications of the generator.

Component	Specification
Power output	3,457 kW
Steam production	2,830 kg/h (1,846 kW)
Hot water output	1,673 kW
Overall efficiency	83.4%
Fuel	Natural Gas
Generator model	Deutz Power System TCG 2032 V16
Voltage	11,000 V
Maximum ambient temperature	37°C
Installation year	2007

4|Governing Equations

In reciprocating engines, a considerable amount of energy developed by the combustion of fuel is wasted as heat with the exhaust gases. The recovery of this wasted heat substantially raises the overall efficiency of the system. Thus, the total energy supplied to the engine is divided into useful work output, heat loss through the exhaust gases, and cooling loss. The energy balance equation is given by [21]:

$$Q_{in} = w_{out} + Q_{exhaust} + Q_{cooling}. \tag{1}$$

In *Eq. (1)*, Q_{in} is the total heat input from the fuel, w_{out} is the useful mechanical work produced by the engine, $Q_{exhaust}$ is the heat lost via the exhaust gases and $Q_{cooling}$ is the heat dissipated via the engine's cooling system. This equation provides all the energy transformations occurring in the engine and forms the basis for analyzing the potential of recovering exhaust heat.

Recoverable heat from the exhaust gases $Q_{exhaust}$ is a function of the mass flow rate of the exhaust gases and is calculated as [22]

$$Q_{exhaust} = \dot{m}_{exhaust} \times c_p \times (T_{exhaust} - T_{ambient}). \tag{2}$$

Where m ̇_exhaust represents the mass flow rate of the exhaust gases, c_p represents the specific heat capacity of the exhaust gases, $T_{exhaust}$ is the exhaust gas temperature and $T_{ambient}$ is the ambient temperature. *Eq. (2)* provides an estimate for the total thermal energy availability for recovery that can be converted to useful work.

As the engine is now combined with an integrated exhaust heat recovery system, the efficiency of the complete engine system will increase. Overall efficiency, η_overall, could then be calculated as accounting for engine work output and additional work created from the recovered heat, given by [23]

$$\eta_{overall} = \frac{W_{out} + W_{ORC}}{Q_{in}}. \quad (3)$$

Where, in *Eq. (3)*, W_{out} is the useful mechanical work output from the engine, W_{ORC}, being the additional work developed from the recovered heat via an Organic Rankine Cycle or similar heat recovery technology, and Q_{in} is the total energy input from the fuel.

Waste heat recovery increases the overall efficiency of the system, hence necessitating less fuel consumption and, therefore, better economic performance. Therefore, exergy analysis can be used to develop the quality and usefulness of the energy contained in the exhausted gases. The exergy of the exhausted gases, $Ex_{exhaust}$ exhaust is determined by [24]

$$Ex_{exhaust} = \dot{m}_{exhaust}\left[c_p\left(T_{exhaust} - T_{ambient}\right) - T_{ambient} \times S_{exhaust}\right]. \quad (4)$$

In *Eq. (4)*, $Ex_{exhaust}$ is the exergy of the exhaust gases, and S_exhaust is the specific entropy of the exhaust gases. Exergy analysis provides information on the maximum useful work that can be extracted from the exhaust gases both by the thermal energy and by the entropy losses. This is essential for the optimization of the design of the heat recovery system and also to obtain its maximum efficiency.

5 | Discussion

The efficiency and performance of a power generation system with a reciprocating engine were evaluated in this work, while different possibilities of heat recovery have been explored. The thermodynamic schematic is presented in *Fig. 1*. Mainly, this paper represents the performance of the system in various situations and tries the various means available to optimize energy consumption for better overall efficiency. Each of the scenarios and their outcomes will be discussed in detail below [25].

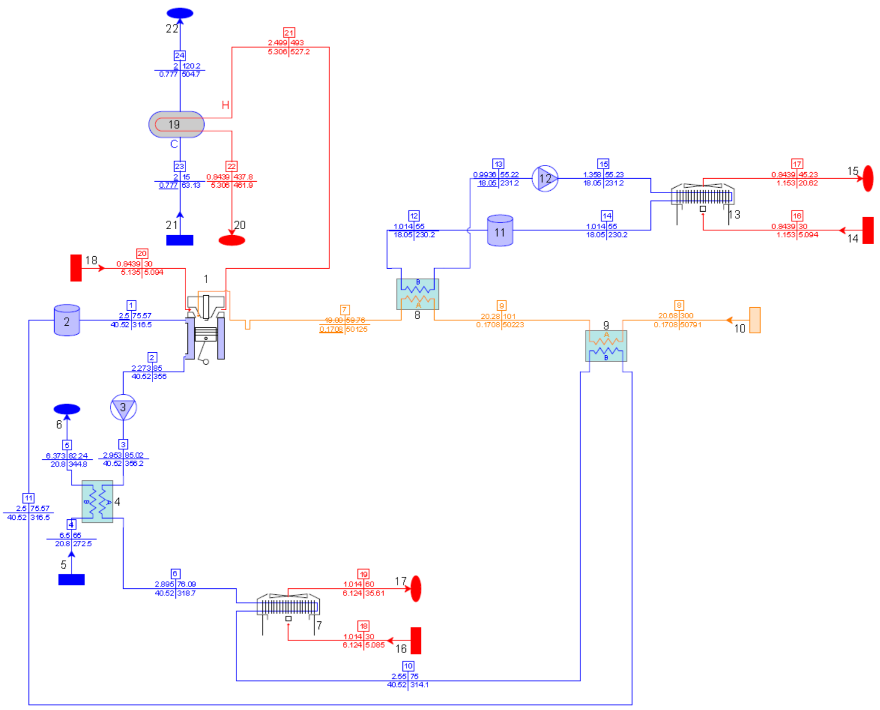

Fig. 1. Thermodynamic cycle schematic of the studied system.

5.1 | Power Generation and Net Energy Input

This system operates on natural gas with a net energy input to the reciprocating engine of 8546 kW. The gross power developed by the engine under this configuration was 3537 Kw, net power output was 3493 kW after deducting internal consumption by auxiliary equipment of 44.37 kW. The all-over efficiency of the system in this configuration works out to be 40.87%, implying heavy energy loss in the form of exhaust gases and cooling.

5.2 | Heat Recovery from Engine Cooling System

The heat absorbed from the engine cooling system is being utilized in this regard to supply the hot water requirements of facilities. In that regard, the temperature of cooling water leaving this system is approximately 85°C, while the cooling water entering this system is about 75.5°C. Correspondingly, the recoverable heat for this section can reach as high as 1503.84 kW, which is attributable to domestic hot water or any other heating applications. This approach reduces energy loss and improves the thermal efficiency of the cycle, at the same time providing an additional source of heat. To this day, the inclusion of this new section boosts the overall efficiency of the entire system to 58.46%.

5.3 | Waste Heat Recovery (Steam Generation)

Exhaust gases at 493°C and thermal power of 2797.32 kW are normally wasted to the ambiance. A heat recovery boiler is therefore used to obtain the steam from these gases. Steam generated at 2 bar and 120°C develops a thermal output of 2102.6 kW. The use of this steam in industrial applications or heating installations raises the general efficiency of the system to 65.47%. This method enhances the efficiency of the system by utilizing the waste heat for a useful energy source.

5.4 | Absorption Chiller for Waste Heat Recovery

In the process, instead of steam generation, heat extracted from the exhaust gases is used to drive an absorption chiller. The absorption chiller runs with a cooling capacity of 1745.4 kW and thus provides cooling using exhaust heat. This method cools the temperature of the exhaust gases down to 130°C. The use of an absorption chiller raises the overall efficiency of the system to 78.89%. It becomes particularly suitable in those areas where cooling is needed, and hence, the percentage of usage of exhaust heat increases accordingly [26]. *Fig. 2* presents a Thermodynamic cycle schematic for cooling generation from exhaust heat.

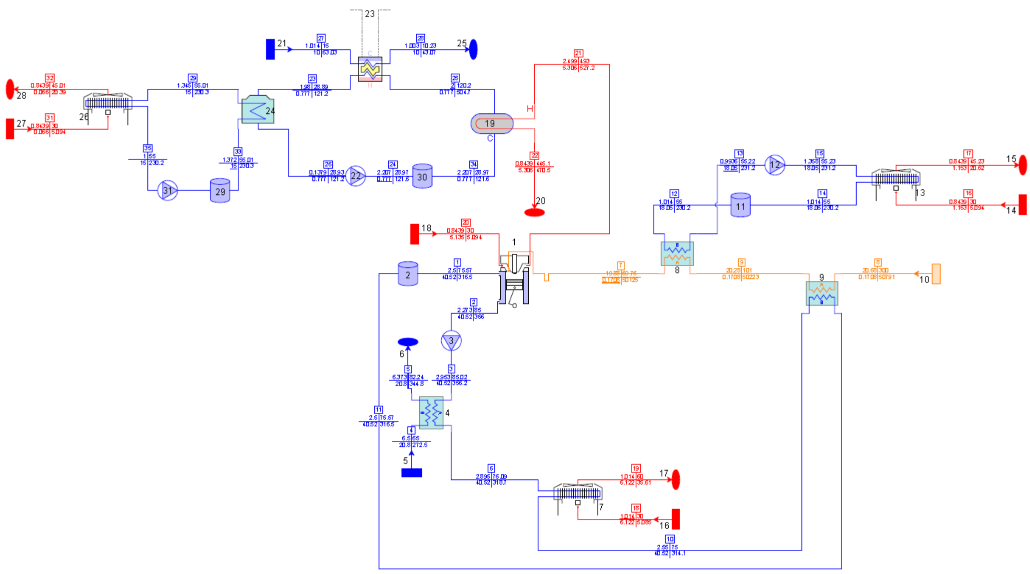

Fig. 2. Thermodynamic cycle schematic for cooling generation from exhaust heat.

5.5 | Combined Heat Recovery from the Engine Cooling System and the Exhaust for Steam Generation

In such a configuration, the system utilizes heat from the engine cooling system for hot water supply and the recovery of exhaust heat using a boiler for steam generation. The heat recovery from the engine cooling system provides 1503.84 kW, and recovery from the exhaust contributes 2102.6 kW, yielding an efficiency of 61.29%. This is quite an effective combination that simultaneously facilitates heating demand from both sources of heat, assuring better overall efficiency of the system.

5.6 | Waste Heat Recovery from Engine Cooling System and Absorption Chiller End

In the last scenario, the system uses the engine cooling system for hot water supply and the absorption chiller for cooling with the assistance of exhaust heat. This allows the overall efficiency of the system to reach 83.07%, which is the highest among all scenarios. Under this configuration, the heating and cooling demands of the system are met by utilizing the excess developed heat most feasibly.

5.7 | Efficiency Comparison Across Different Scenarios

Various schemes of heat recovery and electricity generation were considered to make a proper judgment about the overall efficiency of the system in different scenarios. Each of these has a different impact on the overall efficiency of the system, as highlighted below:

Scenario 1. Electricity generation only-Total efficiency: 40.87%.

Scenario 2. Heat recovery from Engine Cooling-Total efficiency: 58.46%.

Scenario 3. Exhaust heat recovery for steam generation-total efficiency: 65.47%.

Scenario 4. Absorption chiller-total efficiency: 78.89%.

Scenario 5. Combined heat recovery from the cooling system and steam generation: overall efficiency of 61.29%.

Scenario 6. Combined heat recovery from the cooling system and absorption chiller: overall efficiency of 83.07%

The recovered heat from the cooling system is utilized in *Scenarios 5* and *Scenarios 6* for steam generation and an absorption chiller, respectively. Regarding this, the overall efficiency is defined at 61.29% and 83.07% for *Scenarios 5* and *Scenarios 6,* accordingly. This comparison showed that heat recovery from the engine cooling system, together with the absorption chiller, as explained in Scenario 6, would be the most effective system. In this manner, the system can supply a building's all possible heating and cooling needs simultaneously, thus maximizing the heat usage potential of the system [27]. This may result in fuel economy and greater economic viability for the system.

5.8 | Utilization of CO_2 Emissions for Greenhouse Cultivation

Another benefit of the system is that the CO_2 emission from the generated exhaust gases could be used for greenhouse cultivation purposes. It is assumed that the quantity of CO_2 produced in the system can serve nearly 15.78 hectares of greenhouses. This is economically feasible and also friendly to the environment since the exhaust gases are converted to feed the crops inside the greenhouse. It is also possible to use recovered heat to supply heat to greenhouses [28].

6 | Conclusion

This work will also discuss the technical and economic feasibility of waste heat recovery for a 3.5 MW power generation system operated on a reciprocating engine. In the present work, various system configurations for the conversion of the waste heat from exhaust gases and the cooling system of the engine to useful forms are modeled thermodynamically and analyzed economically. Based on the above premises, the conclusions drawn in this work are expressed below.

I. Waste heat recovery for efficiency enhancement: the overall efficiency has increased from 40.87% to an impressive value of 83.07% in the combined case. In this case, both exhaust gases and the engine cooling system were used, while an absorption chiller was applied to maximize recovery of wasted energy. This case gave the maximum efficiency in this work.

II. Economic justification: the economic analysis of heat recovery technologies justifies them as very feasible, in terms of return on fuel savings. Besides, the realization of a potential payback period and operational cost reduction makes these systems financially viable, especially in cases involving the use of process heating and cooling.

III. Some of the other benefits that lie in consonance with environmental concerns are recovered waste heat, which means less fuel consumption and, therefore, reduced greenhouse gas emissions up to as much as 30 percent in some cases. This reduction pertains to the global requirement to reduce environmental impacts and enhance energy efficiency, hence underlining from an environmental point of view the importance of heat recovery technologies.

IV. Greenhouse application: according to the estimates, the CO_2 yield from this system could meet the requirements of approximately 15.78 hectares of greenhouse cultivation. This approach of dual usage increases the economic and ecological value addition for the heat recovery systems; the approach shows the optimal utilization of the exhaust gases to feed crop production in greenhouses.

In general, this work gives evidence that CHP systems applied to the source of power based on internal combustion engines make this process more efficient, less operational-costly, and with less environmental impact.

Author Contributions

Seyedmahmood Kia conceptualized the study, supervised the research process, and led the preparation of the manuscript. Zahra Khodabandeh contributed to the experimental design, data collection, and initial analysis. Amirhossein Barani performed the computational simulations and contributed to the interpretation of results. Fatemeh Aminipour assisted in drafting the manuscript and reviewing the literature. All authors reviewed and approved the final manuscript.

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Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest related to this study or its publication.

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