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# Investigation of Waste Heat Recovery from a 4E Perspective: Performance of Combined Cooling, Heating, and Power Systems with Various Prime Movers for Residential Applications

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*A B S T R A C T*

In this context, a baseline building with an electrical demand of 42 kW has been considered as the consumer. The simultaneous production system incorporates modes of Combined Cooling, Heating, and Power (CCHP), Combined Heat and Power (CHP), Combined Cooling and Power (CCP), and single using four prime movers with gas turbine, steam turbine, Otto, and diesel cycles. The prime movers have been modeled in EES and waste heat of each prime mover investigated. On the other hand, different configurations have been introduced in order to recover the waste heat of each prime mover. The study demonstrates that an increase in operating pressure leads to improved performance in prime movers from an energy perspective, results showed that efficiency improvement in steam turbine, gas turbine, diesel and Otto cycle is 47.7%, 52.5%, 33.7% and 21.1% for CHP mode and for CCHP mode is 50.5%, 55.8%, 35.7% and 22.4% respectively. However, the best efficiency is associaated with the Otto cycle, where the utilization of waste heat recovery can increase efficiency by an average of 40%. Waste heat recovery generates the most significant increase in exergy efficiency in gas turbine and steam turbine cycles is 175% and 306%. Specifically, the average increase in gas turbine cycle exergy efficiency is 1.58 times that of the Otto cycle in CHP mode. Furthermore, the best exergy performance occurs in CCHP mode. Ultimately, the Otto cycle demonstrates the best performance in terms of fuel savings, while the gas turbine cycle is most effective in reducing carbon dioxide emissions.

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**Graphical Abstract**
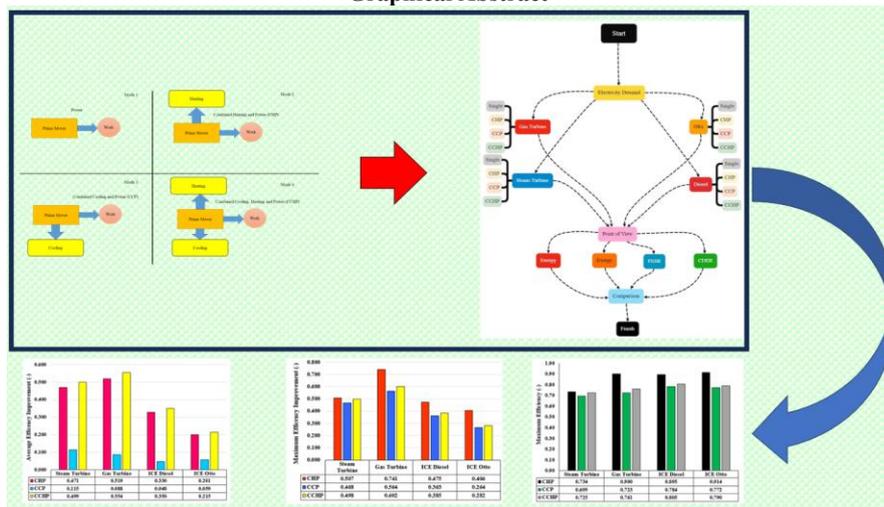


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# 1. INTRODUCTION

There are several ways to decrease fossil fuel consumption, for instance, renewable energy implementation like: solar (1), wave energy (2), hydropower (3), and biomass (4) or considering new technologies (5). However, waste heat recovery is a crucial procedure for improving the efficiency of the prime movers and decreasing fossil fuel consumption. Generally, prime movers like steam turbines, gas turbines, and internal combustion engines consume fuel in the production of mechanical or electrical energy, with a valuable amount of energy being wasted in the form of heat.

CHP and CCHP (Combined cooling, heating, and power) systems capture that wasted heat and put it to applicable use (6). Rather than being allowed to go to waste, such systems make use of it for heating and cooling purposes in addition to generating power. This form of smart reuse alone can bump energy efficiency from a common 30-40% range up to 80% or higher. It's a very practical and realistic way of making energy production so much more effective (7).

The integration of waste heat utilization brings several advantages: reduced fuel consumption, lower GHG emissions, and economic savings. In this respect, it enhances energy resilience and contributes toward worldwide decarbonization. Steam turbine-, gas turbine-, and internal combustion engine-based cogeneration systems demonstrate unique advantages based on their diverse operating characteristics and fuel flexibilities. Each technology has its enabling opportunities and challenges that will make the technologies suitable for different scales and applications (8). On the other hand, it is worth mentioning that climate could be important for assessing the heating demand of residential areas (9).

Readers are encouraged to learn about insights and details that surround these cogeneration systems for a better understanding of their potential to enhance energy sustainability and performance.

### Steam Turbine

Using steam turbines for generating power was conventional for decades. On the other hand steam turbine waste heat is significant and there should be a mechanism to recover waste heat from steam turbines. Some scenarios have been proposed to recover waste heat from stea, and turbines. However, the practical one is using this heat for combined heat and power cogeneration systems, in this regard, the following studies have been investigated. Lowe (10) proposed a CHP system for recovering waste heat of a steam turbine, he studied the thermodynamic basis for low-temperature operation in Combined Heat and Power (CHP) systems, suggesting that CHP functions like a conventional steam cycle plus a virtual heat pump. Urošević et al. (11) studied analyzing the power loss coefficient of steam turbines in cogeneration systems, particularly extraction-condensing turbines and combined cycles. Cerri et al. (12) present a methodology for creating steam cycle simulators for Combined Heat and Power (CHP) plants. The models are validated with real CHP data, showing good capability in estimating component deterioration and accurately reflecting plant operations. Pantaleo (13) compared the energy performance and profitability of various biomass-CHP configurations, thermodynamic simulations, and cost assessments to identify optimal configurations for residential, tertiary, and industrial users within the Italian energy policy context, highlighting key technical and economic factors. Kim and Yoon (14) presented bladeless jet propulsion micro-steam turbines for micro Combined Heat and Power (CHP) systems, designed to utilize low-grade heat sources. Theoretical and experimental studies show an electrical output of 1.5 kW and a turbine efficiency of 6.3% at a pressure ratio of 4. Tatarinova and Suvorov (15) presented computational models for cogeneration steam turbines, focusing on their physical principles and thermal schemes. The paper includes verification examples and discusses using these models to enhance CHP plant efficiency under real conditions. Peng et al. (16) analyzed a CCHP system integrating a solid oxide fuel cell, steam turbine, concentrating solar collector, and absorption chiller. The system uses exhaust gases from the fuel cell to power the chiller and evaluates performance in three Iranian cities. Chahartaghi et al. (17) evaluated a new CCHP system that uses waste heat to enhance efficiency. The system includes a steam boiler, steam turbine, heat exchanger, and absorption chiller. Results show a 24.91% reduction in carbon dioxide emissions, 15.83% in fuel consumption, and 35.34% in operating costs compared to conventional systems, with a tri-generation efficiency of 82.46%. Based on the Wang et al (18) conducted research, optimization could be a great way to enhance the performance of cogeneration systems. This research optimizes a renovated CHP plant using high back-pressure (HBP) and low pressure turbine zero power output LZPO units. The Adaptive Mutation Particle Swarm Optimization (AMPSO) method achieved energy efficiencies of 87.1% for HBP and 88.2% for LZPO. The optimization could increase renewable energy use by 0.191 billion kWh, saving 0.069 million tons of coal and reducing $CO_2$ emissions by 0.181 million tons. LZPO is better for renewable energy, while HBP is preferred for coal savings.

### Gas Turbine

Gas turbine follows the Brayton cycle for generating power, this cycle compressor, combustion chamber, and gas turbine for delivering work. In this cycle a great portion of input heat is wasted, therefore it is crucial to implement a combined heat and power system to enhance the efficiency of the cycle, the following studies have been done to investigate the mentioned issue. Kong et al.

(19) presented a micro-CCHP system, fueled by natural gas or LPG, that achieved >70% overall efficiency, producing 12 kW of electricity, 9 kW of cooling, and 28 kW of heating. A silica gel-water adsorption chiller demonstrated a COP > 0.3 at 13°C evaporation. Kong et al. (20) offered an optimal CCHP energy management, using a linear programming model, which shows that gas turbine operation isn't always cost-effective, depending on load and electricity-to-gas cost ratio. Ghaebi et al. (21) studied a CCHP system's performance and cost are analyzed using energy, exergy, and thermoeconomic methods, investigating the influence of key operating parameters. Wang et al. (22) compare Brayton and recuperative cycle CCHP systems for a northern China vacation village, analyzing the effects of boiler outlet temperature, efficiency, and load ratios on energy and exergy performance in winter. Findings aid in CCHP system design and selection. Sun et al. (23) proposed a multi-objective evaluation index (MEI) model for gas turbine-based CCHP systems (gas turbine + HRSG + LiBr absorption chiller), optimizing component capacity and providing design guidance. Jinying et al. (24) optimize CCHP system operation in office buildings using the simplex method, targeting minimal energy consumption, costs, and $CO_2$ emissions in winter and summer. Winter strategies varied based on goals, often favoring heating-deciding power modes, while summer performance differed, with the traditional system outperforming in energy efficiency.

Hajabdollahi (25) optimized a CCHP-ORC system design using a Real Parameter Genetic Algorithm to identify the best prime mover (gas engine, diesel engine, or gas turbine) based on load demands. Key findings show higher annual benefits at elevated heating loads, with gas turbines preferred for lower electrical and higher heating demands, while diesel engines perform better in high-load scenarios..

A novel CCHP system using cascaded heat recovery from a gas turbine achieves 31.7% natural gas savings compared to separate systems. Flexible cooling-to-power ratios (1.28-3.32) meet variable demands, with economic analysis showing practical benefits (26). Yang et al. (27) proposed a gas turbine-based CCHP system integrated with Compressed Air Energy Storage (CAES) and solar thermal energy (S-CAES) to improve efficiency during partial load operation. A case study in a South China hotel indicated that optimizing the S-CAES system could achieve a power capacity of 435 kW and improve energy efficiency by 1.015%. Moghimi et al. (28) evaluated a new CCHP cycle that integrates Brayton and Rankine cycles, using a 4E analysis. Key design parameters were optimized, revealing a 7% increase in exergy efficiency and a 12% increase in energy efficiency for the CCHP cycle. Aghaei and Saray (29) proposed a CCHP system with a gas turbine and boiler for a dairy factory, optimizing it through three methods. Results show that

the base design requires a high air compressor pressure ratio (RP) of 14.79, but optimization reduces RP to about 6, indicating that an air pre-heater is unnecessary and should be removed. Nondy and Gogoi (30) evaluated two CCHP systems using a recuperative gas turbine. One system features a steam turbine with a recuperative-regenerative organic Rankine cycle, while the other uses a condensing steam turbine. Optimization improves efficiencies slightly, reducing total costs by 9% and 5.3%. Also in the next year, they present a CCHP system that generates chilled water, process heat, and electricity using an intercooler-recuperative gas turbine cycle and an absorption cooling system. The system achieves a net power output of 30 MW and energy and exergy efficiencies of 83.79% and 50.60%, respectively (31). Du and Guo (32) studied a CCHP system that integrates a gas turbine cycle, compressed air energy storage (CAES), and other technologies. CAES enhances waste heat recovery and load regulation. The CCHP system achieves a payback period of 2.44 years, with energy efficiency at 75.99% and greenhouse gas emissions at 0.313 $kgCO_2e/kWh$, significantly outperforming other systems, especially at low loads.

**Internal Combustion Engine**

Internal combustion engines (ICE) have vast applications in industry. The increasing efficiency of the internal combustion engine was always interesting. There are many ways to recover the waste heat of ICE. Using CHP and CCHP systems for waste heat recovery could be a way to tackle the problems caused by the law efficiency of ICE. Mancarella and Chicco (33) demonstrated the trigeneration $CO_2$ emission reduction (TCO₂ER) indicator's effectiveness in assessing GHG reductions from cogeneration and trigeneration systems. It shows that these systems can significantly lower emissions, particularly in fossil fuel-dependent countries. Cho et al. (34) introduced a model for power generation and heat recovery from reciprocating internal combustion engines (ICEs) for CHP simulations. Unlike conventional methods, this model provides performance and efficiency maps for various engine capacities without experimental data, aiding in CHP design. Balli et al. (35) research results indicated that the energy efficiency of the trigeneration system is 58.97%, while the exergy efficiency is 36.13%. The PURPA efficiency is 45.7%, and the equivalent electrical efficiency stands at 48.53%. Meybodi and Behnia (36) investigated the efficiency of CHP systems in the context of potential carbon taxes. It presents an optimal sizing approach for internal combustion engines in medium-scale CHP systems and uses Net Annual Cost (NAC) as a decision criterion across three operational modes: one-way connection, two-way connection, and heat demand following. A case study identifies the optimal powers for gas and diesel engines in each mode while assessing sensitivity to factors like electricity price. Feidt and Costea (37)

compared various CHP system configurations—Vapor Turbine, Gas Turbine, Internal Combustion Engine, and External Combustion Engine—focusing on optimizing exergy under constraints such as heat demand and system limitations. The study reveals that incorporating these constraints significantly affects system design and efficiency, with a sensitivity analysis highlighting key parameter influences. Jannelli et al. (38) evaluated a small CCHP system using a 20 kW Lombardini diesel engine and a water-LiBr absorption chiller, producing hot water from engine cooling heat and chilled water from exhaust gases. Key performance metrics include the energy utilization factor (EUF) for efficiency, the exergy utilization factor (ExUF) for energy quality assessment, and trigeneration primary energy saving (TPES) for energy savings.

Abbasi et al. (39) evaluated a CHP system for a university in Shahrood, using a natural gas internal combustion engine (ICE) from 200 kW to 1,800 kW. An evaluation factor indicator (EFI) is introduced for selecting the ideal engine, with lower EFI values indicating better options. Results show that a 1,200 kW engine has the lowest EFI, and the corresponding CHP system is economically viable, with a return on investment surpassing the interest rate. Abbasi et al. (40) designed a CCHP system for a residential complex in Iran, analyzing various configurations of gas engines, diesel engines, and gas turbines. The optimal scenario, combining a gas engine and diesel engine, achieves 87% energy efficiency, 62.8% exergy efficiency, and an 80% reduction in operating costs, with payback periods of 6.3 years (with interest) and 1.36 years (without). Sheykhi et al. (41) proposed a CCHP system using a gas internal combustion engine (IC) called EF7. A numerical model analyzes the impact of engine parameters on fuel consumption. Results show that minimum specific fuel consumption occurs with combustion starting 20° before top dead center (TDC) for power and cooling, and 50° before TDC for heating. These findings facilitate the design of efficient IC-based CCHP systems that reduce fuel use and pollutants. Mirzaee et al. (42) evaluate a cogeneration system through nine configurations to enhance distributed generation efficiency and reduce the energy crisis. Modeled in EES software, the system includes a gas turbine, chillers, and heat exchangers. Configuration 5, featuring two series absorption chillers, achieves optimum performance for combined electricity and cooling generation with a utility fuel ratio (UFR) of 45325.50 kJ/kg. Scenario 7 is optimal for electricity and heating generation, with a UFR of 39541.90 kJ/kg. Scenarios 1 and 6 have the highest $CO_2$ emissions at 88.18 kg/s. Miar Naeimi et al. (43) optimized the CCHP system in the Qom by integrating solar energy and a gas turbine. Key results from multi-objective optimization show improvements of 3% in exergy efficiency, 15% in total exergy cost, and 10% in environmental impacts for

cooling mode; and 11%, 12%, and 32% improvements, respectively, for heating mode. The analysis was conducted using TRNSYS software. Ghamari et al. (44) designs a CCHP and freshwater system using two desalination methods: multi-effect desalination with thermal vapor compression (MED-TVC) and reverse osmosis (RO). It serves a hotel in Iran using gas turbines and diesel engines as Prime Movers (PMs). The genetic algorithm (GA) optimizes system parameters to minimize annual costs. Results show that diesel engines outperform gas turbines in all modes. Specifically, CCHP + RO (without and with fouling) and CCHP + MED-TVC with diesel engines reduce costs by 9.66%, 1.80%, and 11.68%, respectively, compared to gas turbines. Yao et al. (45) integrated compressed air energy storage (CAES) into a renewable energy-assisted CCHP system to enhance grid stability and efficiency. During charging, compression heat is converted to syngas, which is used for extra power generation during discharging. A 4E (Energy, Exergy, Economic, Environmental) analysis investigates the effects of key design parameters, and a multi-objective optimization aims to maximize efficiency and economic returns while minimizing environmental impact. Results show the system can supply 7.96 MWh of power, 5.34 MWh of heat, and 1.26 MWh of cooling, with an exergy efficiency of 45.14%. After optimization, $CO_2$ emissions decrease by 3.06 kg/MWh, raising exergy efficiency to 47.84%. Wang et al. (46) proposed a solar hybrid CCHP system and optimizes the choice of Prime Movers (PMs) and solar collectors using a genetic algorithm. A case study on a hotel in Shanghai shows that a larger PM and 90 solar collectors save 61.61% of primary energy. Solar and waste heat meet all thermal needs in summer, but an auxiliary boiler is required in colder seasons. The system reduces $CO_2$ emissions by 856.2 tons annually, with a payback period of 3.01 to 3.56 years, depending on fuel prices. Jia and Paul (47) presented a CCHP system using biomass gasification, integrating an internal combustion engine (ICE), a Stirling engine, and an absorption chiller. Key findings include a 14% increase in CCHP output power due to the Stirling engine's recovery of syngas's high-temperature potential and an ICE thermal efficiency of 39% at 5000 rpm. Approximately 50% of total exergy destruction originates from the ICE.

This paper presents a comprehensive analysis of the 4E framework (Energy, Exergy, Economic, and Environmental) in the context of waste heat recovery from various prime movers, specifically within CCHP, CHP, and CCP systems. The novelty of this paper lies in the following key contributions: Integrated performance evaluation: Unlike previous studies that typically focus on individual aspects of energy or exergy efficiency, this research provides a holistic evaluation of how operational pressure affects all four dimensions (4E) of performance across a spectrum of prime movers,

including gas turbines, steam turbines, Otto, and diesel cycles. Comparative insight across prime movers: This study offers a unique comparative analysis that highlights the distinctive advantages and limitations of each prime mover in recycling waste heat, thus addressing critical knowledge gaps. Groundbreaking findings on waste heat recovery: The research reveals that waste heat recovery significantly influences performance metrics, particularly exergy efficiency in gas turbine and steam turbine cycles. Practical implications for system design: By elucidating how operational pressure improvement can enhance the performance of various prime movers in integrated energy systems.

## 2. SYSTEM MODELLING

The system is designed for residential applications. The primary electrical consumers and their power usages are as follows: the lighting index is 43 W/m², a TV (158 W), a washing machine (345 W), a refrigerator (140 W), a computer (225 W), and an iron (940 W). With a demand factor of 0.76, the electricity required during peak hours totals 42.4 kW (48). To gain a better understanding of the method of modeling the process chart has been shown in Figure 1. Climate, energy prices, and grid structure significantly impact cogeneration feasibility. For instance, regions with high electricity prices and cold climates benefit more from CHP, while hot climates favor CCHP systems. But in this investigation, a building in Tehran has been considered. Residential buildings generally do not require both heating and cooling simultaneously; in simpler terms, the consumer needs cooling in the summer and heating in the winter. To ensure that the system's performance analysis aligns with real-world conditions, this research examines the system in four operating modes, which can be seen in Figure 2.

In Mode 1, the performance of the prime mover is studied from energy, exergy PoV, without any system implemented to utilize the waste heat from the prime mover. In Mode 2, the system is assessed for simultaneous electricity and heat generation. In this mode, a line including water as the working fluid is used to harness the waste heat from the prime mover, and this heat is utilized to provide the heating required for a thermal storage tank, which is suitable for winter when there is a greater need for hot water.

In Mode 3, the waste heat from the prime mover is used to supply the heat required for an absorption chiller generator. Under these conditions, the system not only generates electricity but also provides the cooling needs of the consumer, making this mode suitable for summer operation. Finally, Mode 4 encompasses the simultaneous production of electricity, heat, and cooling. In this operating mode, the system uses waste heat from the prime mover to meet the heating and cooling needs of

the system's users. Therefore, as it is evident, in residential applications, the heating and cooling needs of the consumer vary throughout the year.

**2. 1. Gas Turbine**          In a simple Gas Turbine cycle the following four process happens. 1. Isentropic compression, 2. Isobar heat addition, 3. Isentropic expansion and 4. Isobaric heat rejection. All process should follow the following 1st law of thermodynamic (Figure 3):

$$\sum \dot{m}\left(h + \frac{V^2}{2} + gz\right)_i - \sum \dot{m}\left(h + \frac{V^2}{2} + gz\right)_o + \dot{Q} - \dot{W} = 0 \qquad (1)$$
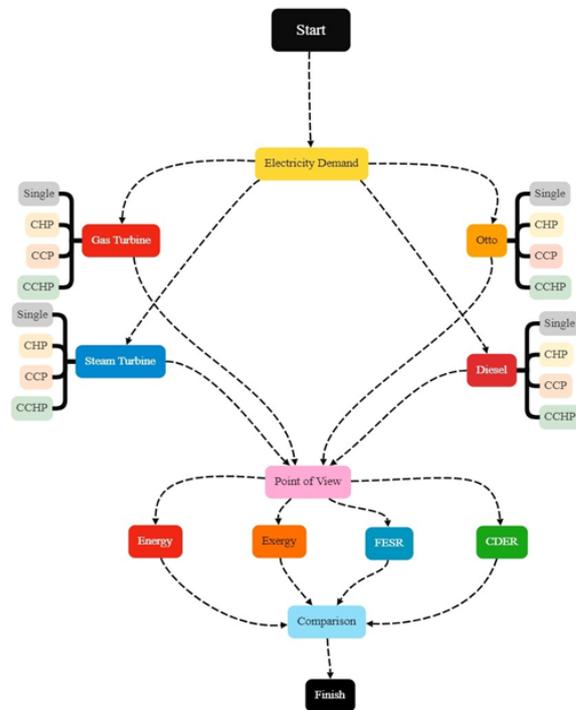


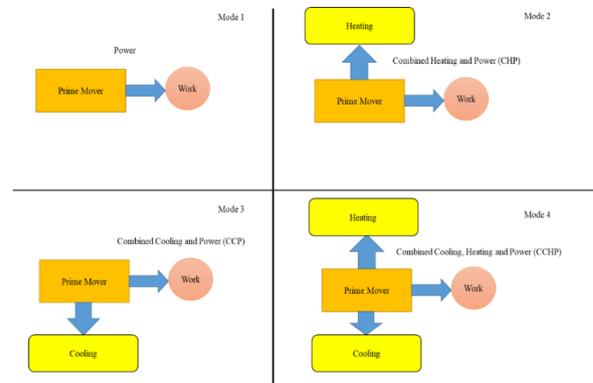**Figure 1.** The system modelling process chart



**Figure  2.** The description of single, CCP, CHP and CCHP modes

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \tag{2}$$

$$\gamma = \frac{c_p}{c_p} \tag{3}$$

## 2. 2. Steam Turbine

In a simple steam turbine power cycle, the 1st law of the thermodynamic and pump work and turbine output work is based on the following equations (Figure 4):

$$\sum \dot{m}(h + \frac{v^2}{2} + gz)_i - \sum \dot{m}\left(h + \frac{v^2}{2} + gz\right)_o + \dot{Q} - \dot{W} = 0 \tag{4}$$

$$\dot{W}_{pump} = v(P_2 - P_1) \tag{5}$$

$$\dot{W}_{turbine} = \dot{m}(\Delta h) \tag{6}$$

## 2. 3. Otto and Diesel Cycle

The air-standard Otto cycle is an idealized model representing a spark-ignition internal combustion engine. The cycle starts with an adiabatic (isentropic) compression of air as the piston moves from the crank-end dead center to the head-end dead center. Heat is then added at constant volume while the piston remains briefly stationary, mimicking the ignition and burning of the fuel-air mixture. The cycle continues with an adiabatic expansion and ends with heat rejection at constant volume as the piston is at the crank-end dead center. On the hand the air-standard Diesel cycle, represents the ideal cycle for the Diesel engine, also known as the compression-ignition engine (49, 50).

**TABLE 1.** gas turbine input parameters

| Parameter | Value | Units | Description |
|---|---|---|---|
| PR | 5 | - | Pressure ratio of the compressor |
| $T_i$ | 297.15 | K | Inlet temperature to the compressor |
| $T_{it}$ | 1200 | K | Turbine inlet temperature |
| $P_a$ | 101.325 | kPa | Ambient pressure |
| $\dot{m}$ | 0.341 | kg/s | Mass flow rate |
| $\eta_c$ | 0.8 | - | Compressor isentropic efficiency |
| $\eta_t$ | 0.8 | - | Turbine isentropic efficiency |
| R | 0.287 | kJ/kg·K | Specific gas constant for air |
| $c_p$ | 1.005 | kJ/kg·K | Specific heat capacity at constant pressure for air |
| $c_v$ | 0.718 | kJ/kg·K | Specific heat capacity at constant volume for air |

**TABLE 2.** Steam turbine input parameters

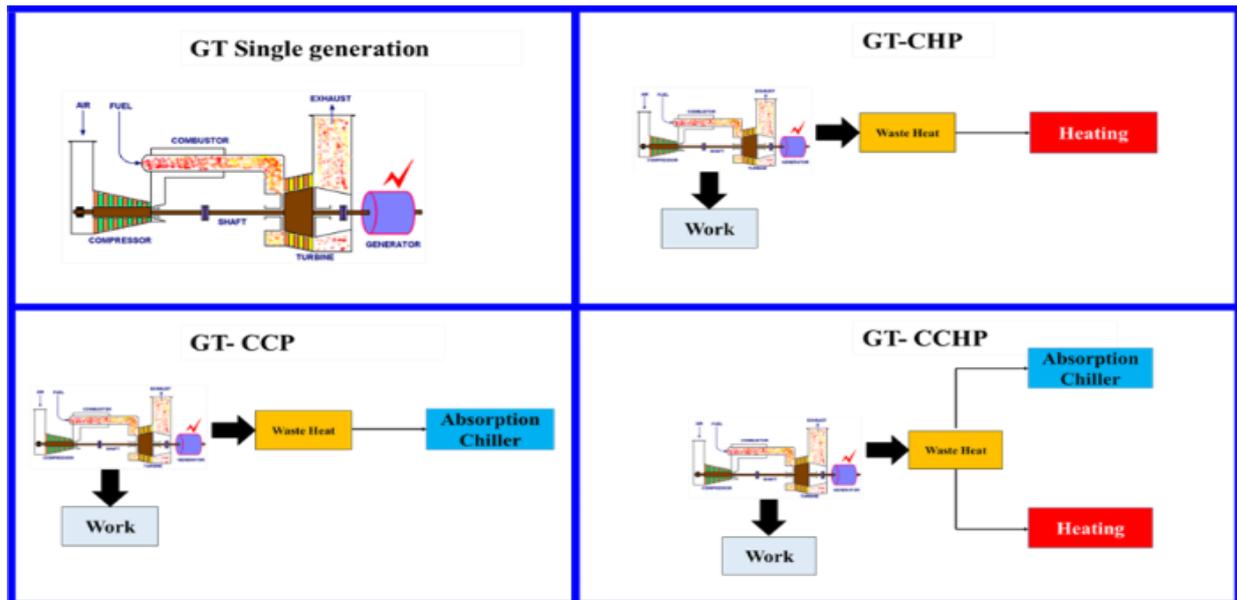| Parameter | Value | Units | Description |
|---|---|---|---|
| $P_b$ | 8 | MPa | Boiler pressure |
| $T_b$ | 550 | °C | Boiler temperature |
| $P_{co}$ | 0.1 | MPa | Condenser pressure |
| $\eta_p$ | 0.85 | - | Pump isentropic efficiency |
| $\eta_t$ | 0.85 | - | Turbine isentropic efficiency |
| $\dot{m}$ | 0.047 | kg/s | Mass flow rate |
| $T_a$ | 25 | °C | Ambient temperature |



**Figure 3.** The description of single, CCP, CHP and CCHP modes for gas turbine
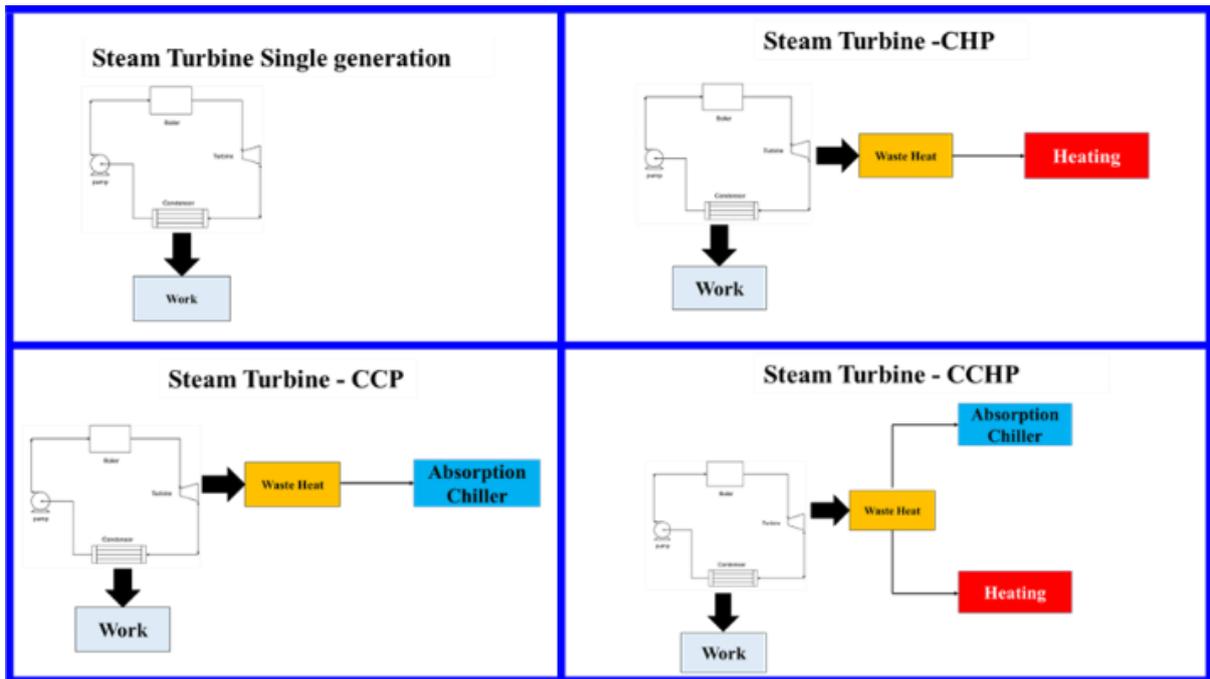
**Figure 4.** The description of single, CCP, CHP and CCHP modes for steam turbine

In this cycle, heat is added to the working fluid at a constant pressure, simulating the fuel injection and combustion in a real engine. During the heat addition, the gas expands, and the heat transfer must be regulated to maintain constant pressure. Similar to the air-standard Otto cycle, the Diesel cycle concludes with a constant-volume heat rejection at the crank-end dead center,

replacing the exhaust and intake processes of an actual engine. Figure 5 shows the operating modes in this study based on ICE engine.

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = \left(\frac{V_1}{V_3}\right)^{\gamma-1} = \frac{T_3}{T_4} \tag{7}$$
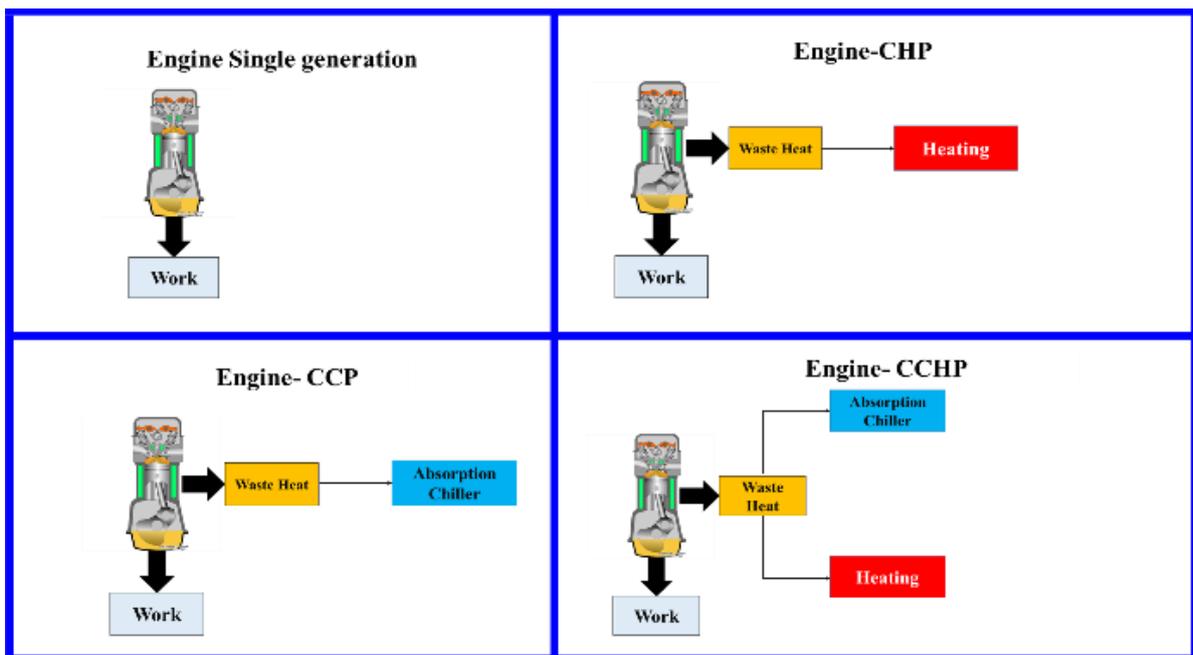


**Figure 5.** The description of single, CCP, CHP and CCHP modes for steam turbine

**TABLE 3.** Otto input parameters

| Parameter | Value | Units | Description |
|-----------|-------|-------|-------------|
| $c_r$ | 8 | - | Compression ratio |
| $T_i$ | 300 | K | Inlet temperature |
| $P_i$ | 101.325 | kPa | Inlet pressure |
| $\dot{m}$ | 0.087 | kg/s | Mass flow rate |
| R | 0.287 | kJ/kg·K | Specific gas constant for air |

**TABLE 4.** Diesel input parameters

| Parameter | Value | Units | Description |
|-----------|-------|-------|-------------|
| $c_r$ | 16 | - | Compression ratio ($V_1/V_2$) |
| $T_i$ | 300 | K | Inlet temperature |
| $P_i$ | 101.325 | kPa | Inlet pressure |
| $\dot{m}$ | 0.1 | kg/s | Mass flow rate |
| R | 0.287 | kJ/kg·K | Specific gas constant for air |

**3. 1. Energy Efficiency**      Energy efficiency is the ratio of useful energy output to the total energy input for a given system. Thus, for cogeneration, energy efficiency can be expressed as (51):

$$\eta_{CHP} = \frac{\dot{W}_{PrimeMover} + \dot{Q}_{HST}}{\dot{m}_{fuel}LHV} \tag{13}$$

$$\eta_{CCP} = \frac{\dot{W}_{fc} + \dot{Q}_e}{\dot{m}_{fuel}LHV} \tag{14}$$

$$\eta_{CCHP} = \frac{\dot{W}_{fc} + \dot{Q}_{HST} + \dot{Q}_e}{\dot{m}_{fuel}LHV} \tag{15}$$

**3. 2. Exergy Efficiency**      Exergy efficiency can be defined as the maximum work output to exergy input as follows:

$$\eta_{ex,CHP} = \frac{\dot{W}_{fc} + \left(1 - \frac{T_{amb}}{T_{heat}}\right)\dot{Q}_{HST}}{[\dot{m}(ex_{in})]_{fuel}} \tag{16}$$

$$\eta_{ex,CCP} = \frac{\dot{W}_{fc} + \left(1 - \frac{T_{cool}}{T_{amb}}\right)\dot{Q}_e}{[\dot{m}(ex_{in})]_{fuel}} \tag{17}$$

$$\eta_{ex,CCHP} = \frac{\dot{W}_{fc} + \left(1 - \frac{T_{cool}}{T_{amb}}\right)\dot{Q}_e + \left(1 - \frac{T_{amb}}{T_{heat}}\right)\dot{Q}_{HST}}{[\dot{m}(ex_{in})]_{fuel}} \tag{18}$$

**3. 3. FESR**      The fuel energy saving ratio has been discussed in this section. For calculating this parameter, it needs to be compared combined system to a conventional energy supply system. In conventional system, the required cooling is provided by the electric chiller, and the required electricity for the building is purchased from the network. Also in this system heating demand is supplied by the hot water generated in the gas-fired boiler.

Fuel-saving could be given as (52):

$$FS = \frac{W_{fc}}{\eta_{con}} + \frac{\dot{Q}_{HST}}{\eta_b} + \frac{\dot{Q}_e}{COP_e} - F_{CCHP} \tag{19}$$

$$FESR = \frac{FS}{\frac{W_{fc}}{\eta_{con}} + \frac{\dot{Q}_{HST}}{\eta_b} + \frac{\dot{Q}_e}{COP_e}} \tag{20}$$

**3. 4. CDER**      In this research, an environmental assessment of the system has been conducted, based on the criterion of the percentage reduction of carbon dioxide emissions. To calculate the percentage reduction in carbon dioxide emissions (CDER) in this combined production system, relationships 21 to 23 can be utilized.

$$CDER = 1 - \frac{CDE_{shp}}{CDE_{cchp}} \tag{21}$$

$$CDE_{shp} = \mu_e E_{grid}^{shp} + \mu_f F_b \tag{22}$$

$$CDE_{cchp} = \mu_e E_{grid}^{cchp} + \mu_f F_{on-site} \tag{23}$$

## 4. RESULTS AND DISCUSSION

To ensure the credibility and reliability of the findings presented in this study, a validation process was conducted based on established thermodynamic principles and experimental data. The methodologies employed for analyzing the performance of various prime movers and the associated waste heat recovery systems were cross-referenced with authoritative thermodynamic reference books, including (53-55). The analysis showed a good agreement between the model results and the reference values.

In the Figure 6 the effect of operating pressure on the work and heat generated by prime mover has been shown. As it can be seen, increasing operating pressure can lead to higher output work from prime mover. However generated heat has unique behavior for each prime mover; for instance, rising operating pressure (or pressure ratio) leads to decreased heat generated by both

**TABLE 5.** Validation of the results (53-55)

|  | Modelling | Reference Value | Relative error (%) |
|--|-----------|-----------------|--------------------|
| $\eta_{GT}$ | 0.2087 | 0.1906 (54) | 9% |
| $\eta_{ST}$ | 0.2511 | Ranges from 20-30% (55) | - |
| $\eta_{Otto}$ | 0.54 | 0.54 (53) | ≥ 1% |
| $\eta_{Diesel}$ | 0.45 | 0.45 (53) | ≥ 1% |

turbines. In the Otto cycle, the pressure rising leads to lower recoverable heat but in the diesel cycle increasing pressure causes higher heat generation based on the operating and reaction mechanisms of these two prime movers.

The effect of operating pressure on the recoverable heat and cooling capacity of the absorption chiller by Gas turbine, Steam turbine, Otto cycle, and diesel cycle has been shown in Figure 7. As it can be seen increasing the operating pressure causes lower recoverable heat for all prime movers except diesel engine. Therefor the cooling system has been considered for two modes, the first mode is CCP and the second one is CCHP; since, all recoverable heat delivers to the generator of the absorption chiller for CCP mode the evaporator has higher capacity in CCP mode instead of CCHP mode. On the other hand as the recoverable heat decreases the evaporator's capacity decreases but the rate of reduction is much lower than the rate of the recoverable heat. Also it is important to note that system in CCHP mode has

lower correlation with recoverable heat and the highest evaporator capacity (for equal power output from the prime mover) belongs to gas turbine for both CHP and CCHP modes.

In Figure 8, the effect of operating pressure on the heat transfer of absorption chiller's components has been shown. As it can be seen by increasing operating pressure the heat transfer rate decreases for all prime movers except diesel engine cycle. When the operating pressure increases the heat generation in gas turbine, steam turbine and Otto cycle decreasing and therefore the heat transfer in absorption chiller reduced, but the heat transfer in chiller of diesel based CCHP system rises, since increasing pressure causes more heat generation in these prime movers and thus the heat transfer in condenser, evaporator and absorber intensified. Also it is worth mentioning that the effect of operating pressure on the heat transfer of chiller components show a linear behavior. On the other hand the heat transfer in absorber
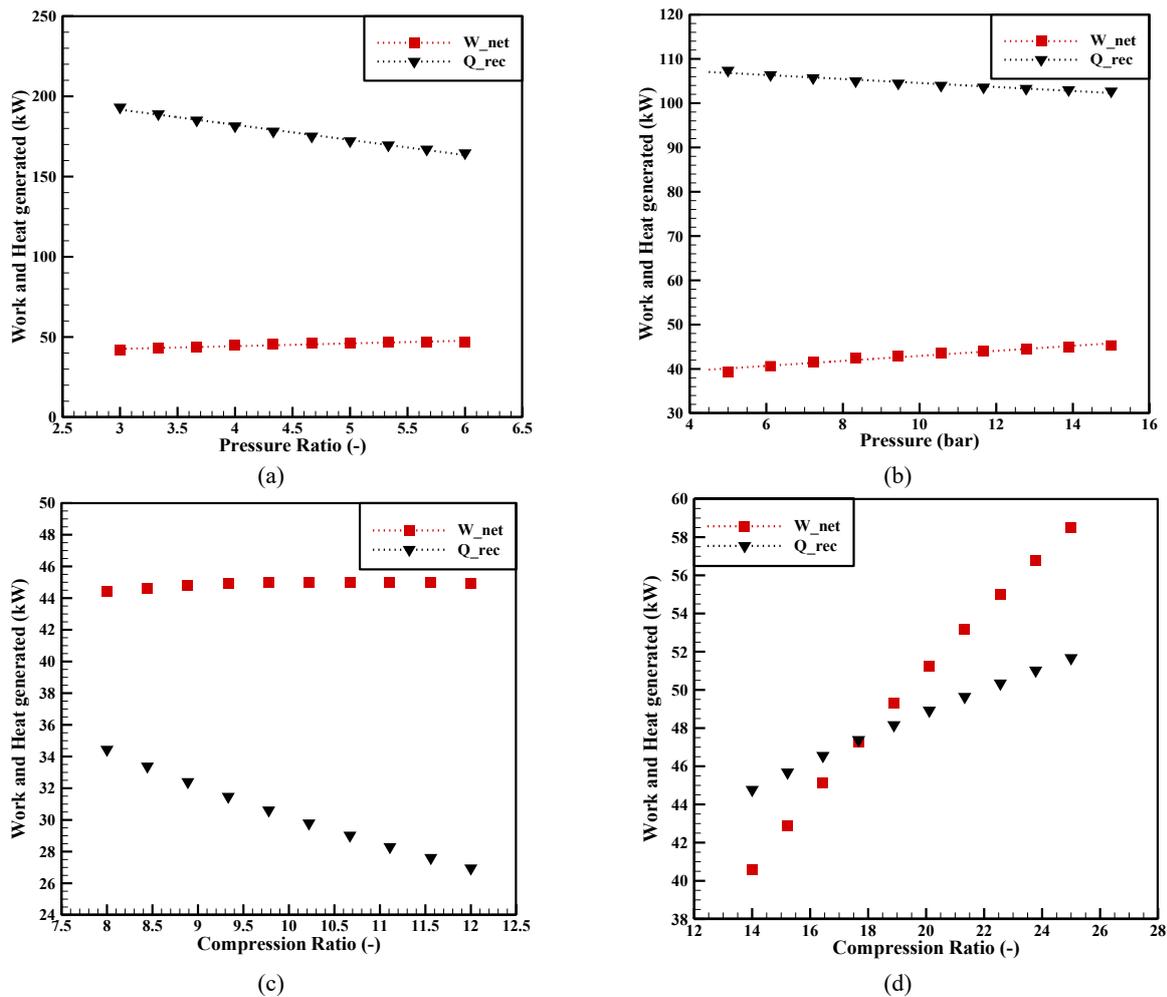


**Figure 6.** the operating pressure impact on the power and heat generated by a)Gas turbine b) Steam turbine c) Otto cycle d) diesel cycle and
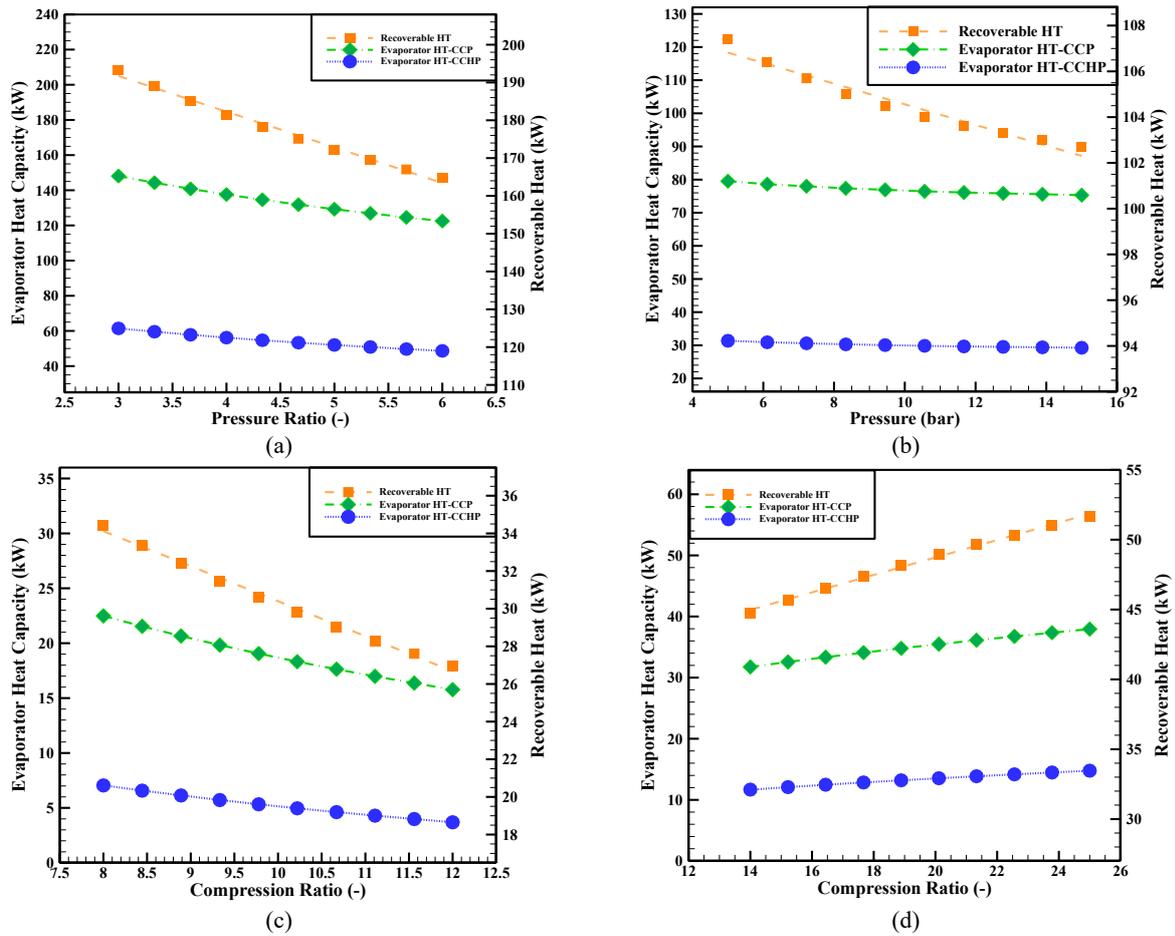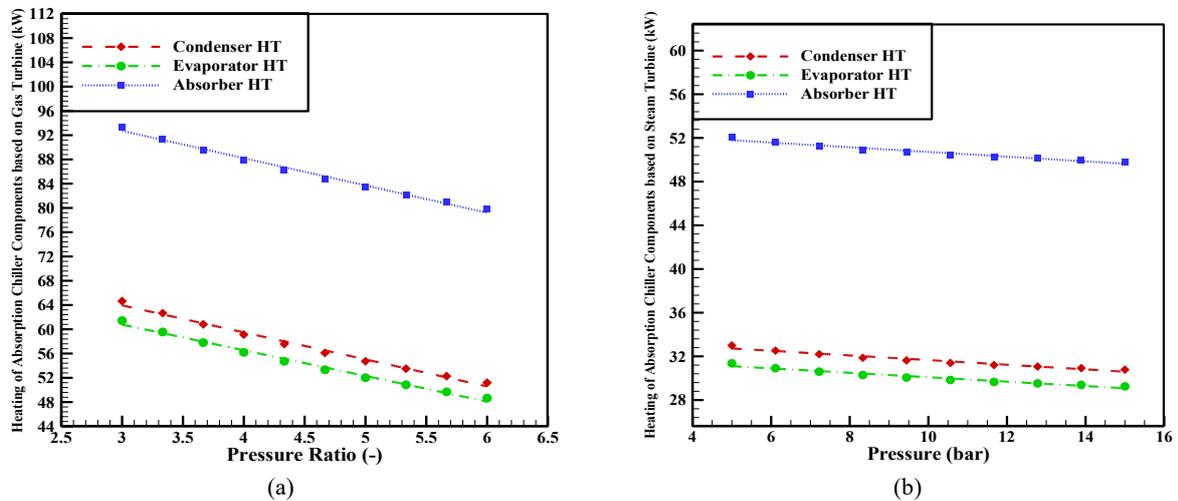
**Figure 7.** the operating pressure impact on the recoverable heat and cooling capacity of the absorption chiller by a) Gas turbine b) Steam turbine c) Otto cycle d) Diesel cycle

is higher than condenser and evaporator based on mixing reaction in absorber. In order to evaluate the performance of the absorption chiller, in Figure 9 the effect of operating pressure on the COP of the absorption chiller by Gas turbine, Steam turbine, Otto cycle, diesel cycle has been shown. The COP of the CCP mode is higher than CCHP and it was expected to see such a behavior.

(c)

(d)
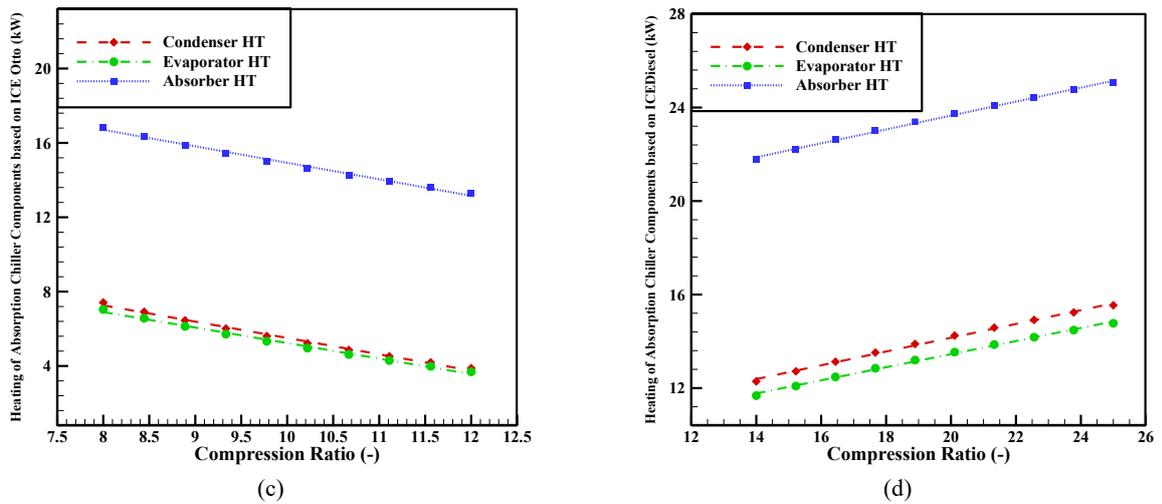
**Figure 8.** the operating pressure impact on the heat transfer of the absorption chiller components by a)Gas turbine b) Steam turbine c) Otto cycle d) Diesel cycle
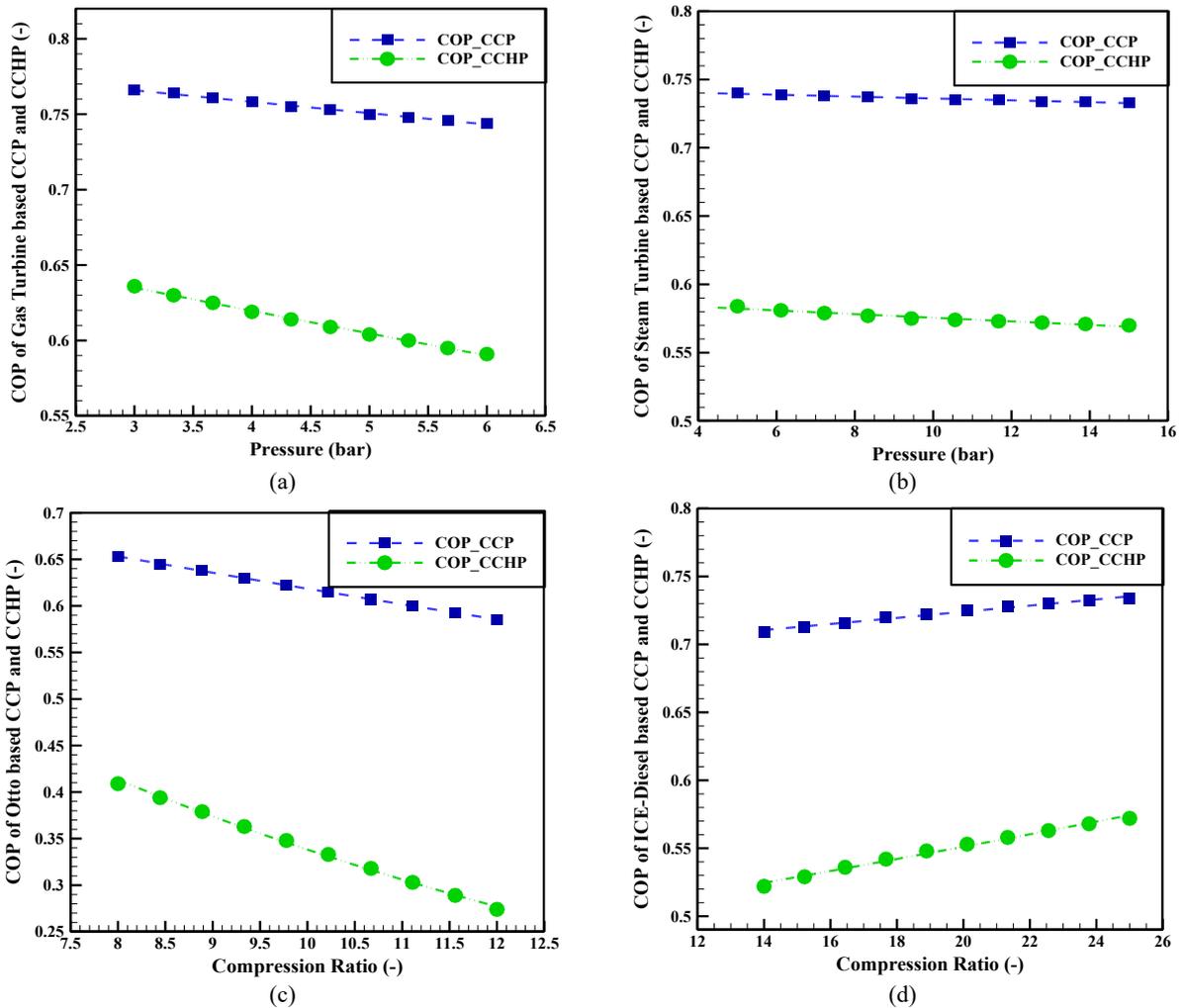


(a)

(b)

(c)

(d)

**Figure 9.** the operating pressure impact on the COP of the absorption chiller by a)Gas turbine b) Steam turbine c) Otto cycle d) diesel cycle

Also the operating pressure doesn't have significant effect on the COP of the steam turbine especially in CCP mode. However if increasing pressure leads to higher recoverable heat the COP rises (Diesel), though the COP decreases by increasing pressure in gas turbine, steam turbine and Otto. The highest performance belongs to gas turbine and the lowest COP is for Otto.

The effect of operating pressure on the efficiency of Gas turbine, Steam turbine, Otto cycle and diesel cycle has been shown in Figure 10. As it was expected increasing the pressure leads to higher performance. However the efficiency range could be an important parameter for considering the performance of the prime movers. The gas turbine range is 16-20%, steam turbine is 23-26%, Otto is 50-57%, diesel is 42-47%. Also the Otto cycle has the highest efficiency and gas turbine has the lowest efficiency. By considering this parameter it can be said that the highest recovering heat is for gas

turbine and therefore the highest COP happens when the prime mover is gas turbine.

In Figure 11 the effect of operating pressure on the efficiency of cogeneration system by Gas turbine, Steam turbine, Otto cycle, diesel cycle has been shown. As it can be seen using waste heat of the prime movers could have significant effect on improving the efficiency of the system. For all prime movers the CHP mode has highest efficiency in comparison with CCHP and CCP mode. Since in CHP mode the waste heat delivers to the user without a complex thermodynamically system such as absorption chiller, therefore the heat loss during process reduced and the efficiency has higher value. On the other hand the highest CHP, CCP and CCHP efficiency belongs to Otto cycle. It is worth mentioning that the pressure have a significant effect on the cogeneration performance of all prime movers except gas turbine and this prime mover shows a smooth behavior against pressure ratio.
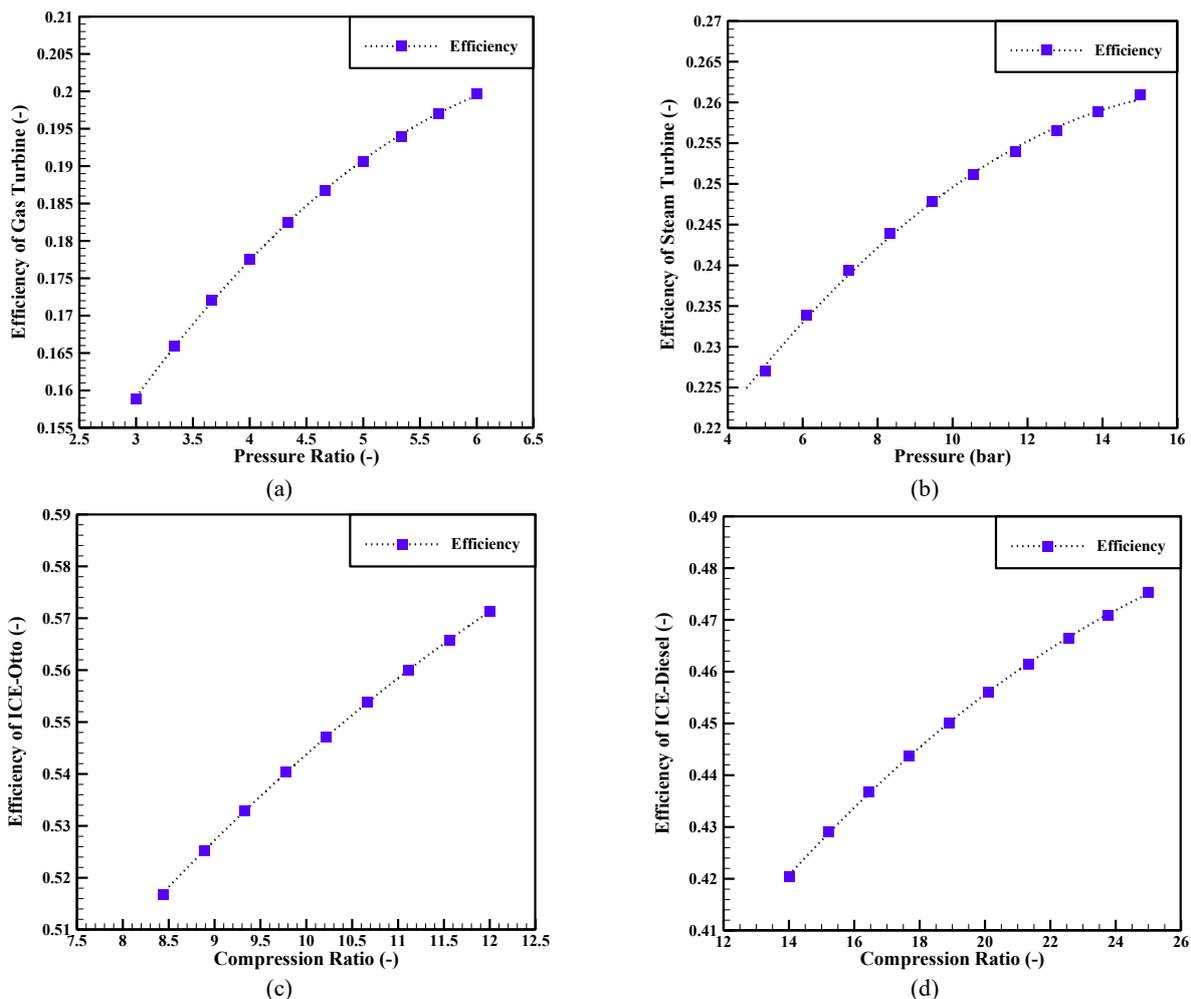


**Figure 10.** the operating pressure impact on the efficiency of a)Gas turbine b) Steam turbine c) Otto cycle d) diesel cycle
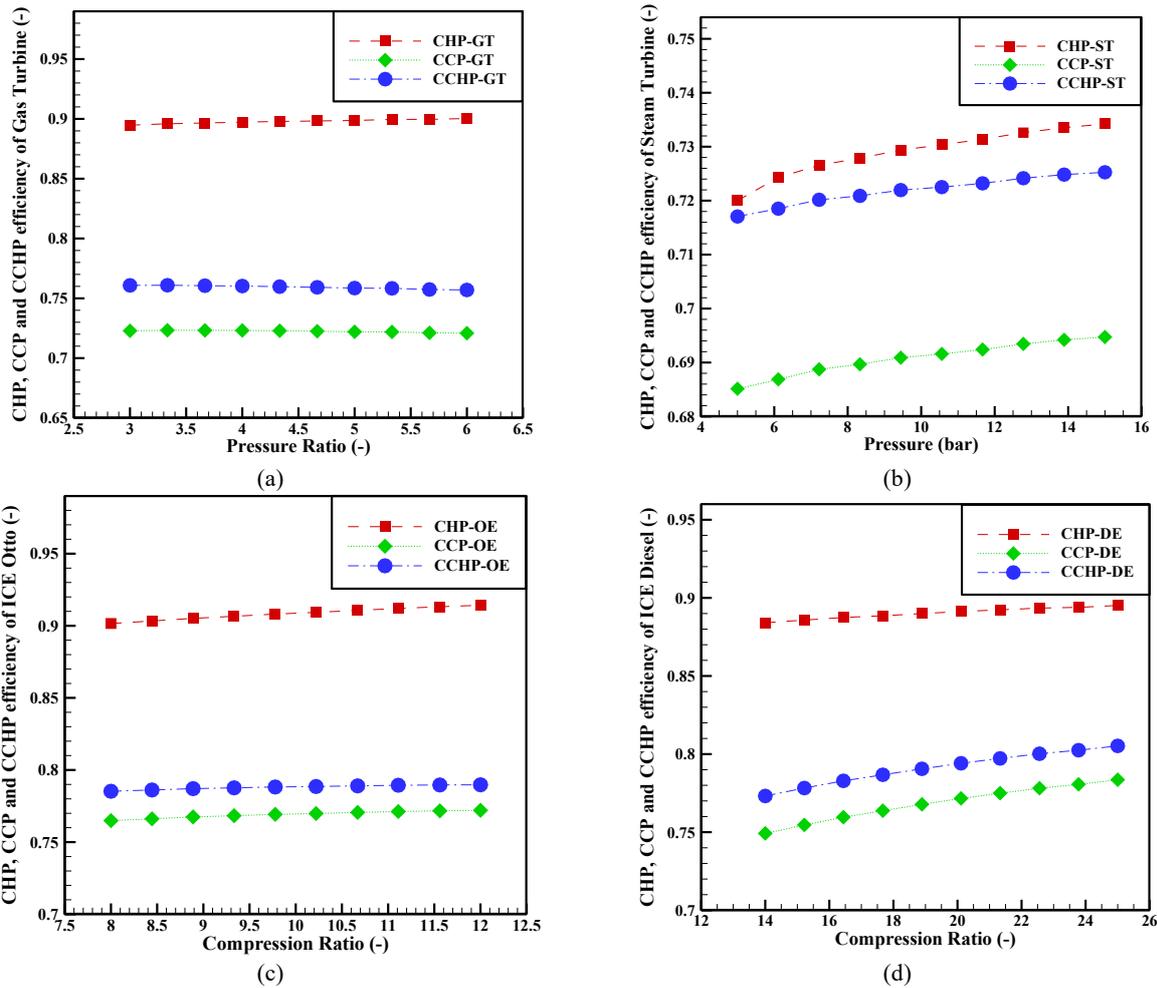
**Figure 11.** the operating pressure impact on the cogeneration efficiency of a) Gas turbine b) Steam turbine c) Otto cycle d) diesel cycle

The effect of operating pressure on the maximum efficiency, average efficiency, maximum improvement of efficiency and average improvement of efficiency has been shown in Figure 12. As it is obvious the highest efficiency of CHP belongs to Otto cycle and the highest CCP efficiency belongs to ICE diesel and the best efficiency of CCHP is for ICE diesel. Also the highest average efficiency for CHP and CCP happens in Otto cycle and the highest average efficiency for CCHP system is for diesel engine. In order to evaluate the effect of waste heat recovery on the efficiency improvement the prime movers maximum and average efficiency has been compared to cogeneration modes. It has been shown that gas turbine experiences the highest efficiency improvement in all three modes of CHP, CCP and CCHP. However in Otto cycle the significant improvement is not considerable.

In Figure 13 effect of operating pressure on the exergy destruction of all prime movers has been shown. In all prime movers operating pressure has a direct relationship with exergy destruction of the prime movers. Also the highest exergy destruction happens in gas turbine. It is important to note that between power cycles which has been considered; gas turbine has higher exergy destruction than steam turbine, Diesel cycle has higher exergy destruction than Otto.

The effect of operating pressure on the exergy destruction of absorption chiller components based on Gas turbine, Steam turbine, Otto cycle, Diesel cycle for CCP (left column) and CCHP (right column) mode has been shown in Figure 14. The exergy destruction inside absorption chiller has a strong relationship with the heat transfer in generator, as it can be seen in CCP mode all recoverable heat feed the generator and the exergy destruction is much higher than CCHP mode. On the other hand, the turbines has highest recoverable heat, therefore the heat load inside the generator is higher than other components and therefore the exergy destruction in turbine based cycle is higher than engine based cycles.
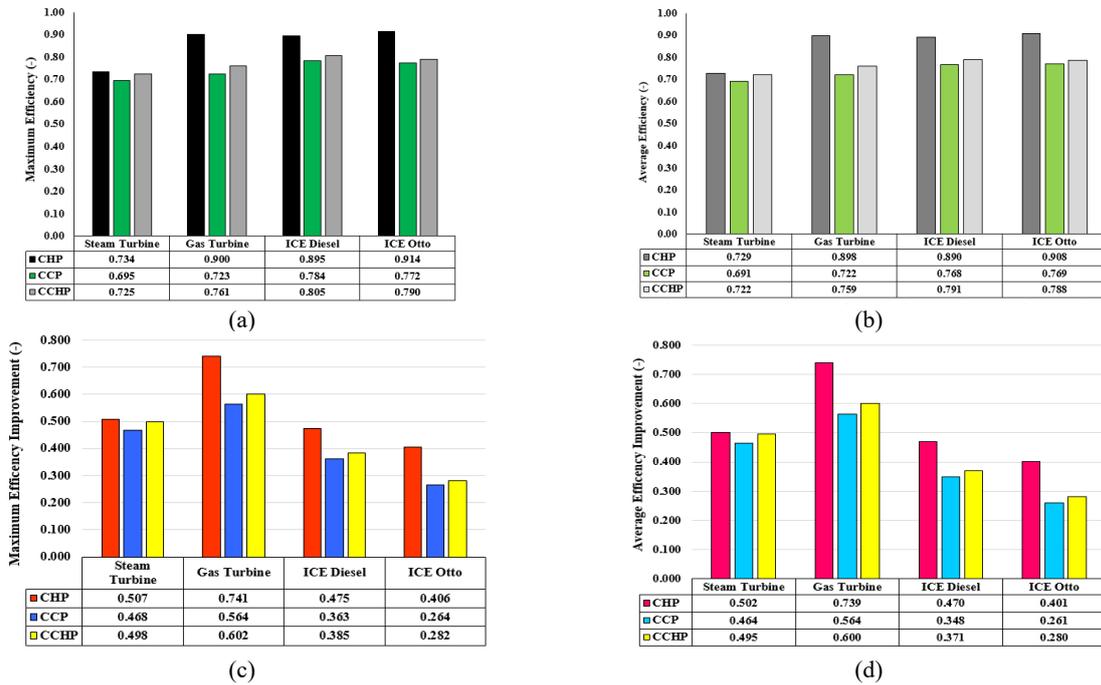
**Figure 12.** the operating pressure impact on the a) maximum efficiency b) average efficiency c) maximum improvement of efficiency and d) average improvement of efficiency
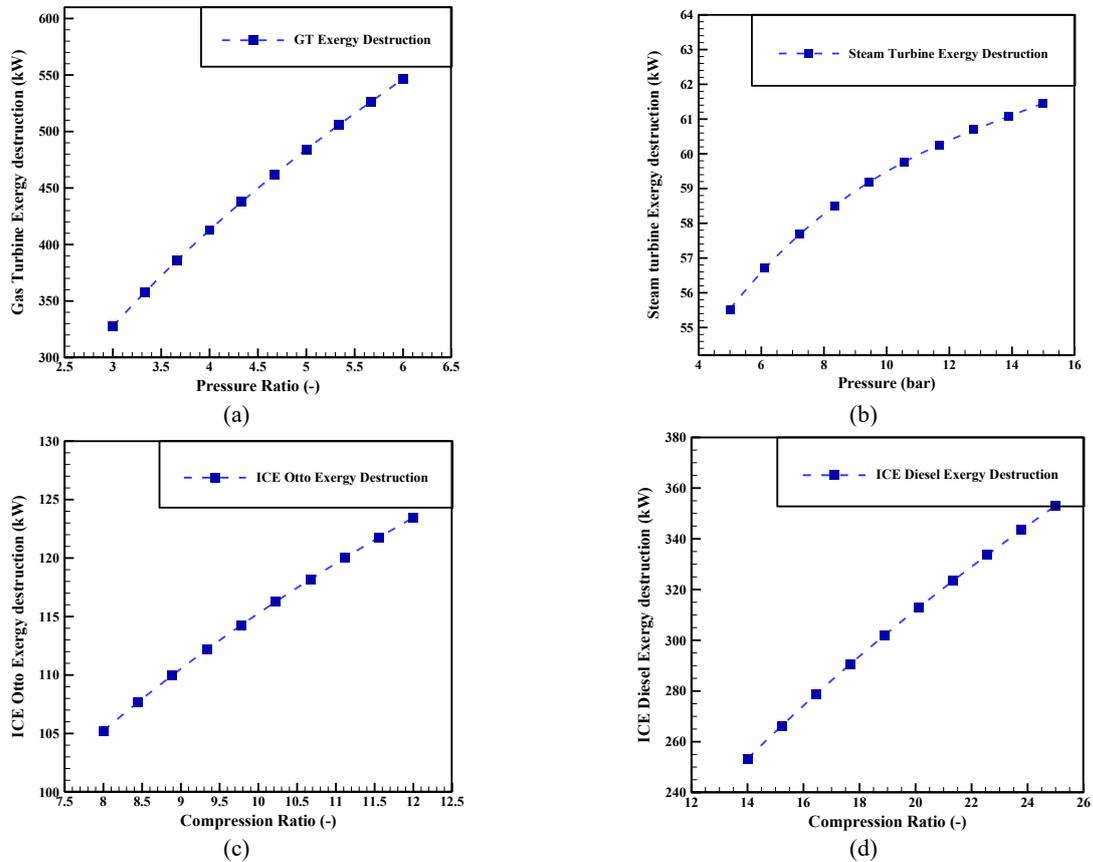


**Figure 13.** the operating pressure impact on the exergy destruction of a) Gas turbine b) Steam turbine c) Otto cycle d) diesel cycle
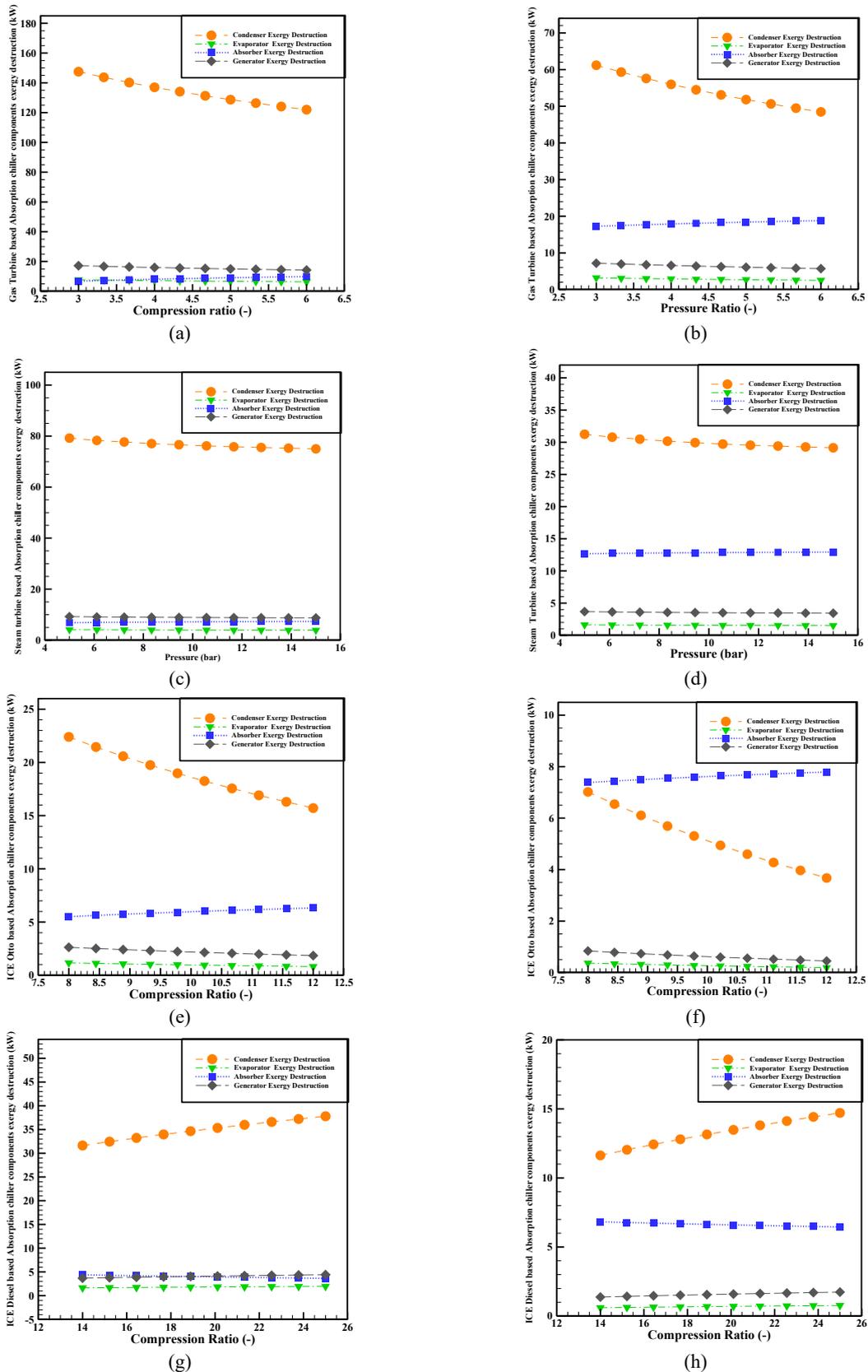
**Figure 14.** the operating pressure impact on the exergy destruction of absorption chiller components based on a,b) Gas turbine c,d) Steam turbine e,f) Otto cycle g,h) diesel cycle for CCP,CCHP mode

In Figure 15 the effect of operating pressure on the COP$_{ex}$ of Gas turbine, Steam turbine, Otto cycle, and diesel cycle has been shown. As it can be seen in all prime mover the exergy coefficient of performance of CCP mode is higher than CCHP mode, because the heat transfer in the generator in CCP mode is higher than CCHP mode. Also it is worth mentioning that the highest COP$_{ex}$ occurs in gas turbine, steam turbine, diesel engine, Otto cycle respectively. On the other hand as it was expected increasing the operating pressure cause increasing COP$_{ex}$ for all prime movers except diesel. The highest exergy coefficient of performance is 0.37 in gas turbine for CCP mode and in CCHP mode the highest is 0.31 for gas turbine.

By increasing the operating pressure, the rate of net power production rises in all prime movers, therefore the operating pressure make a possitive effect on the prime movers efficiency (as show in Figure 16). Also it is crucial to consider that the highest efficiency is for Otto cycle and the lowest exergy efficiency is for gas turbine. It is obviously show that the gas turbine could be a great choice for recovering waste heat and most of the exergy input to the gas turbine has been wasted. However if the increasing slope of the line has been considered the

highest slope belongs to gas turbine and the lowest is for diesel engine. But still when the prime mover works in single mode the valuable exergy has been wasted for all prime movers and recovering could be an impressive choice.

The operating pressure has effect on exergy efficiency of prime movers when the waste heat has been recovered and the cogeneration system could work in CHP, CCP and CCHP mode (Figure 17). As it can be seen the CCP mode for all prime movers has the lowest exergy efficiency because of all recoverable heat of the prime movers deliver to absorption chiller and chiller has many components with exergy destruction, therefore when the CCP mode has been chosen for recovering waste heat of the prime movers, the system doesn't operate as good as CHP and CCHP mode. Also in CCHP mode the system has the highest exergy efficiency but it should note that in CCHP and CHP mode the exergy efficiency doesn't have significant difference. Also operating pressure doesn't have impressive effect on the exergy performance of the cogeneration systems. The highest exergy efficiency of the cogeneration system belongs to Otto cycle and the lowest is for steam turbine.
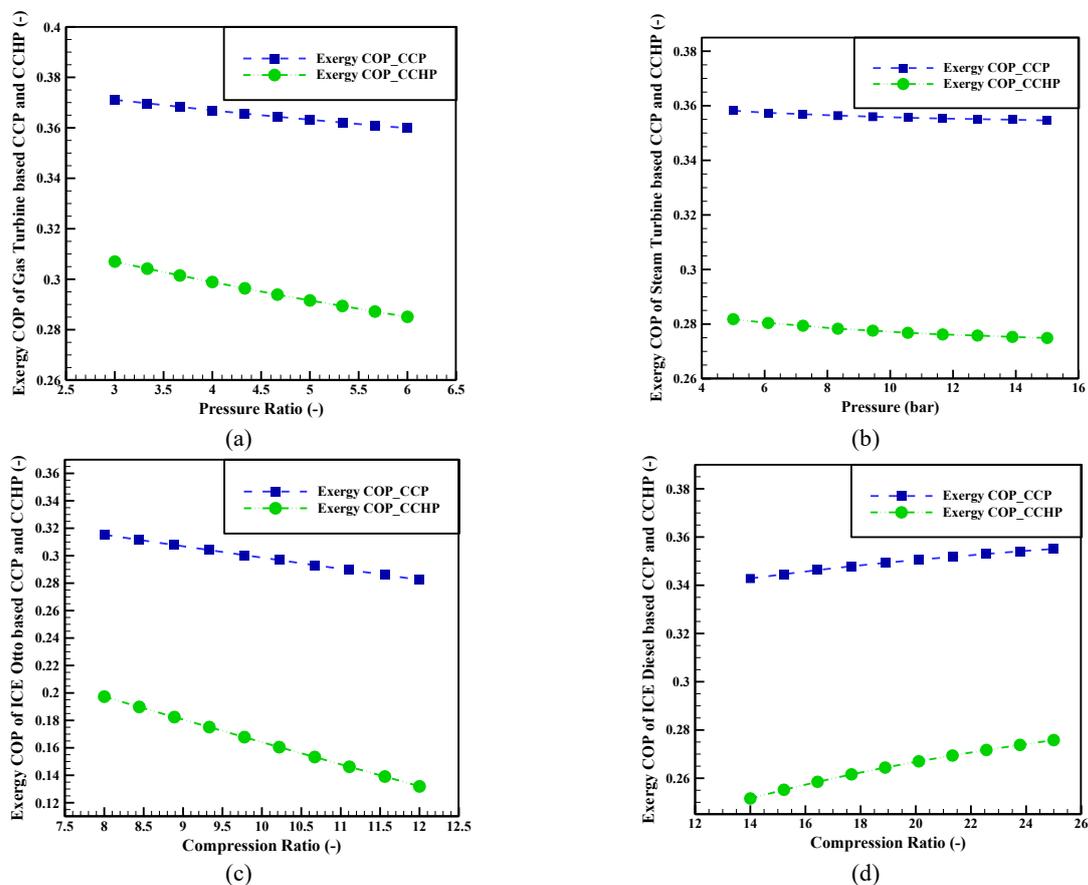
(a)

(b)

(c)

(d)

**Figure 15.** the operating pressure impact on the exergy COP of a) Gas turbine b) Steam turbine c) Otto cycle d) diesel cycle
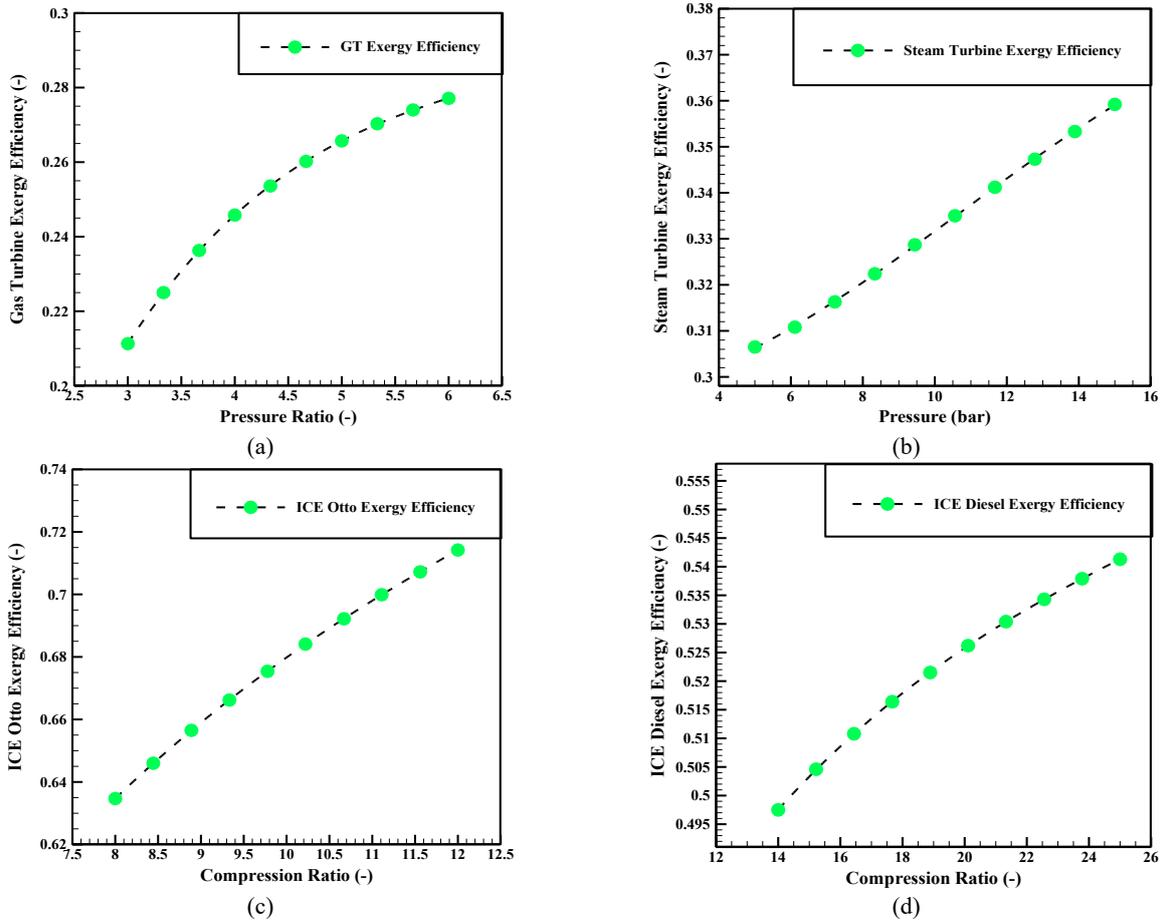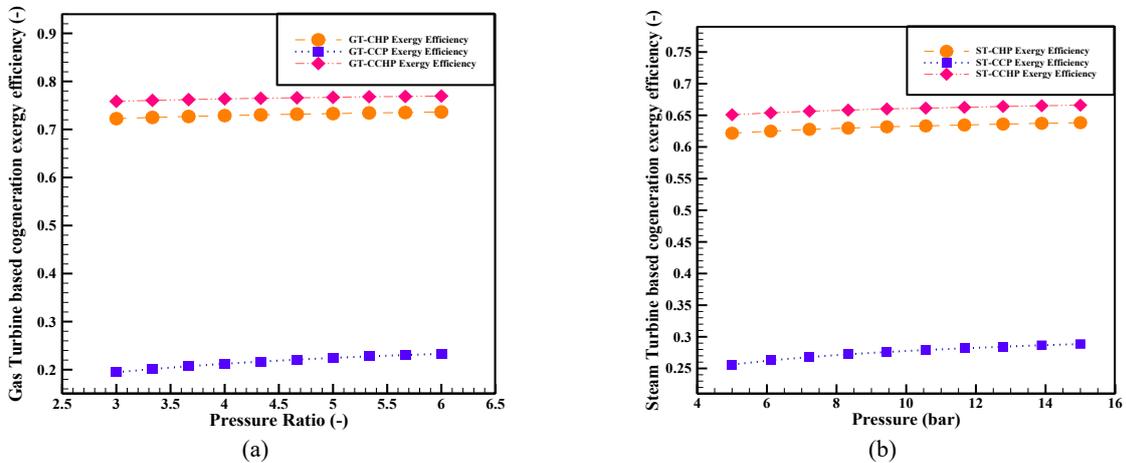
**Figure 16.** the operating pressure impact on the exergy efficiency of a) Gas turbine b) Steam turbine c) Otto cycle d) diesel cycle

The effect of operating pressure on the maximum exergy efficiency, average exergy efficiency, maximum improvement of exergy efficiency and average improvement of exergy efficiency has been shown in Figure 18. As it is obvious the highest exergy efficiency of CHP, CCP and CCHP belongs to Otto cycle. Also the highest average efficiency for CHP, CCP and CCHP happens in Otto cycle. In order to evaluate the effect of waste heat recovery on the efficiency improvement the prime movers maximum and average efficiency has been compared to cogeneration modes. It has been shown that gas turbine experiences the highest efficiency improvement in the modes of CHP, CCHP.
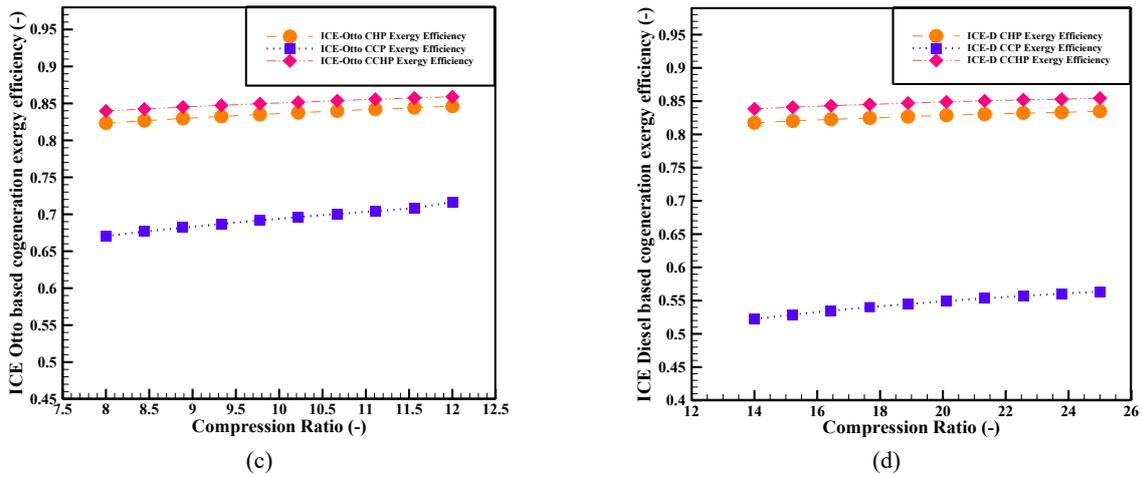
**Figure 17.** the operating pressure impact on the exergy efficiency of a) Gas turbine b) Steam turbine c) Otto cycle d) diesel cycle for CHP,CCP and CCHP mode
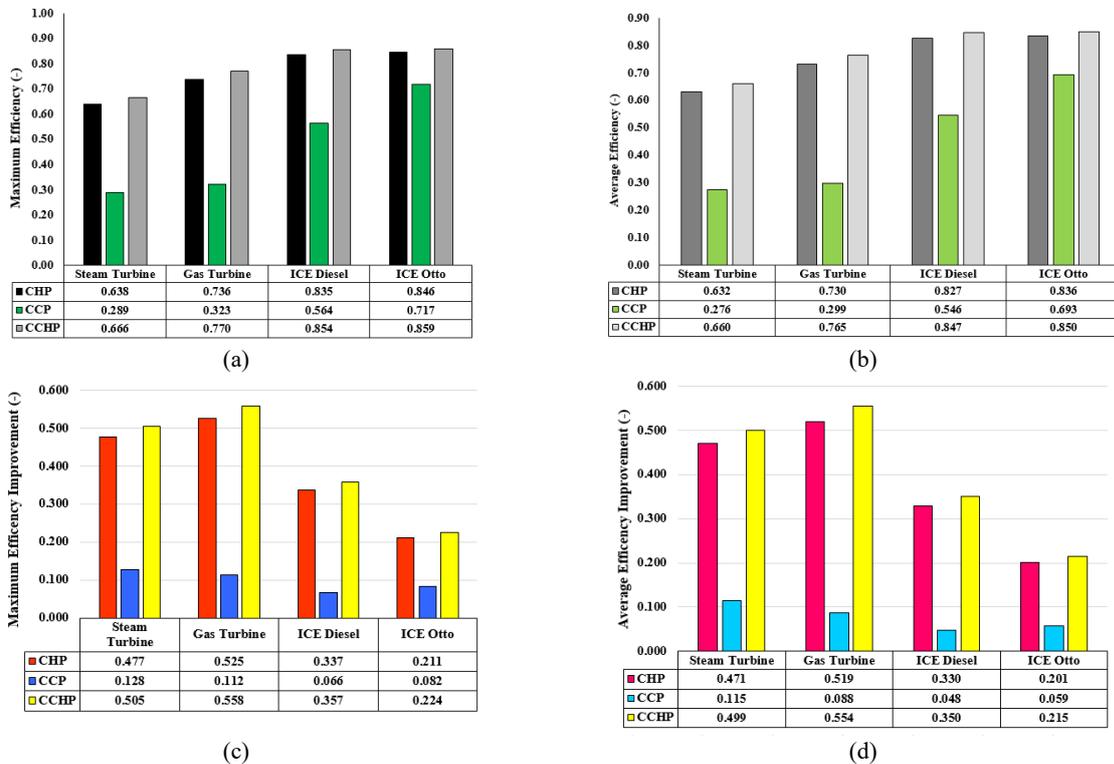


**Figure 18.** the operating pressure impact on the a) maximum exergy efficiency b) average exergy efficiency c) maximum improvement of exergy efficiency and d) average improvement of exergy efficiency

In order to evaluate the system by an economic index, it could be comparison the cogeneration system by conventional power and heat systems. In order to do such a comparison the effect of operating pressure on the fuel energy saving ratio of all prime movers cogeneration systems has been derived. As it can be seen in Figure 19 the operating pressure has a positive effect on FESR. As the operating pressure rises the FESR increases. Also the

highest FESR belongs to Otto cycle. On the other hand the lowest FESR is for gas turbine because of low energy efficiency. Also for all prime movers CCP mode has the lowest FESR, but for gas turbine and diesel engine the CHP mode is better than CCHP and for other prime movers the FESR of CCHP is higher than CHP.

Carbon dioxide could be a critical index for emission production of the prime movers. In order to evaluate the

prime movers carbon dioxide emission production has been studied and carbon dioxide emission reduction has been calculated. As it has been show in Figure 20, for all prime movers CDER of CCP mode is lower than other two modes. Also the best operating condition is CCHP for all prime movers except gas turbine and in gas turbine a different behavior has been occurred. In low pressure ratio the gas turbine ha better operating condition in CHP mode but in high pressure ratio the best operating mode is CCHP (from CDER point of view). The best operating behavior belongs to diesel engine CCHP mode and the lowest CDER is for steam turbine.

In order to make a comprehensive evaluation the maximum performance indexes like Efficiency, COP, Exergy Efficiency, COPex, FESR and CDER of each prime mover has been shown in Figure 21 and Table 6. As it has been shown the best efficiency from energy and exergy point of view belongs to Otto cycle, the best energy efficiency for CHP mode is in gas turbine prime mover and for CCP and CCHP the best operation happens in diesel engine. But from the exergy efficiency and FESR the best prime mover is Otto and from CDER point of view the best prime mover is Gas turbine for CHP and CCP but in CCHP the best one is diesel engine.
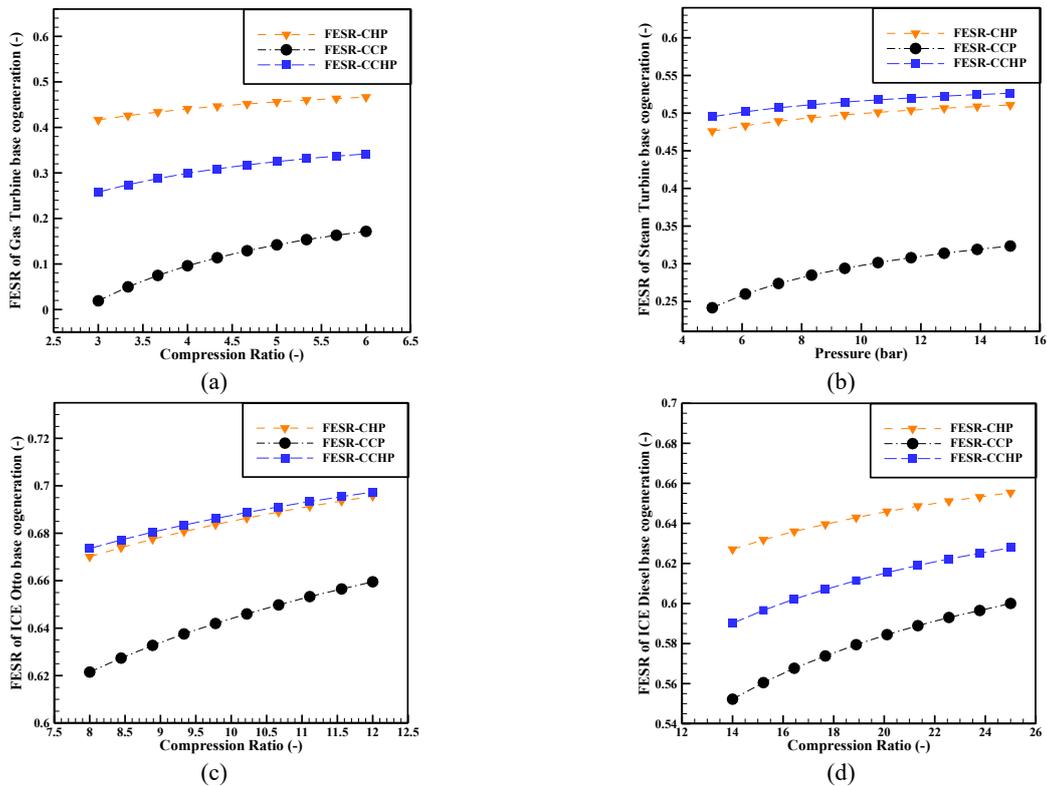


**Figure 19.** the operating pressure impact on the fuel energy saving ratio of a) Gas turbine b) Steam turbine c) Otto cycle d) diesel cycle for CHP,CCP and CCHP mode
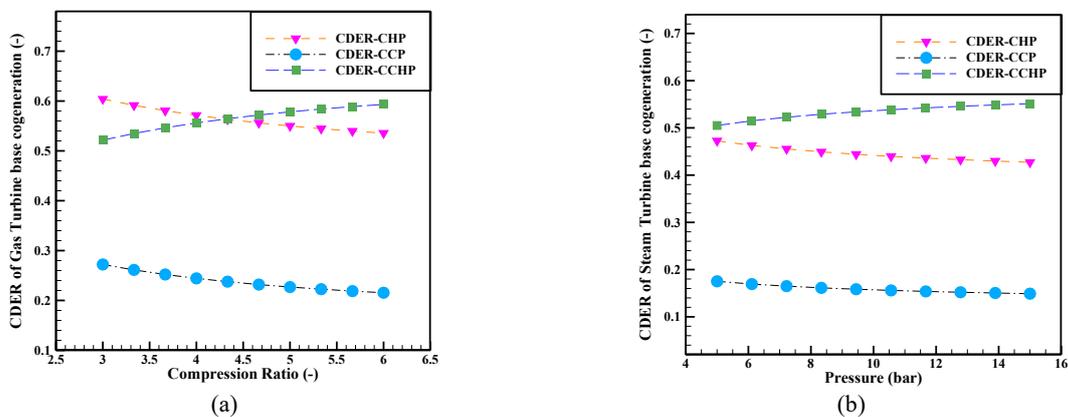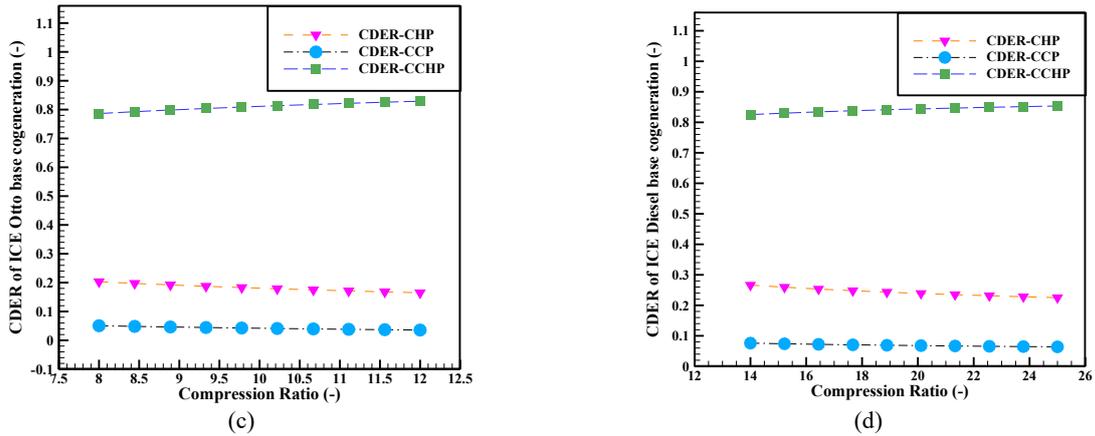
**Figure 20.** the operating pressure impact on the carbon dioxide emission reduction of a) Gas turbine b) Steam turbine c) Otto cycle d) diesel cycle for CHP,CCP and CCHP mode
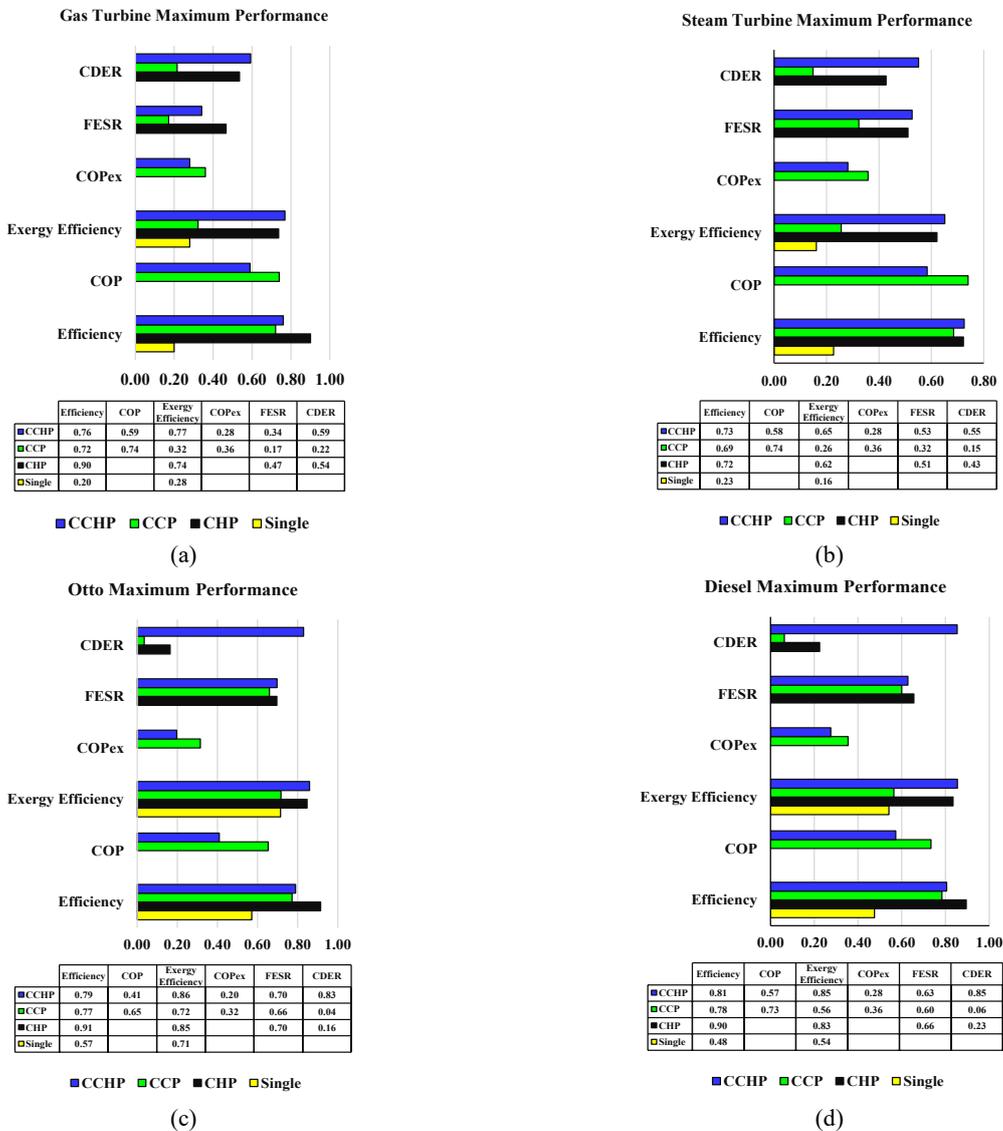


**Figure 21.** the maximum performance of a) Gas turbine b) Steam turbine c) Otto cycle d) diesel cycle for CHP,CCP and CCHP mode

**TABLE 6.** Comparison of the prime movers from 4E point of view

|  | Single | CHP | CCP | CCHP |
|---|---|---|---|---|
| Maximum Energy Efficiency | Otto | Gas Turbine | Diesel | Diesel |
| Maximum Exergy Efficiency | Otto | Otto | Otto | Otto |
| FESR |  | Otto | Otto | Otto |
| CDER |  | Gas Turbine | Gas Turbine | Diesel |

## 5. CONCLUSION

In this study, four prime movers were evaluated across four operational scenarios: standalone, CCP, CHP, and CCHP. These prime movers include a gas turbine, a steam turbine, a diesel engine, an Otto engine. The results were designed to meet the electrical demands of a residential building based on a reference framework, and the impact of varying operating pressure on the system's output characteristics was analyzed considering energy, exergy, economic, and environmental perspectives The study demonstrates that an increase in operating pressure leads to improved performance across all prime movers from an energy perspective, the results showed that efficiency improvement in steam turbine, gas turbine, diesel, and Otto cycle is 47.7%, 52.5%, 33.7% and 21.1% for CHP mode and for CCHP mode is 50.5%, 55.8%, 35.7%, and 22.4% respectively,  however, the best efficiency is associated with the Otto cycle, where the utilization of waste heat recovery can increase efficiency by an average of 40%. Crucial results are as follows:

**Energy**
- Waste heat recovery significantly improves the efficiency of cogeneration systems, with CHP mode showing the highest efficiency due to minimized thermal losses compared to CCP and CCHP modes.
- The Otto cycle demonstrates superior performance, achieving the highest efficiency across all operational modes (CHP, CCP, and CCHP), making it the most efficient prime mover for cogeneration applications.
- Operating pressure strongly influences the performance of most prime movers, except for gas turbines, which exhibit stable efficiency across varying pressure ratios.
- These findings highlight the importance of optimizing operational conditions and waste heat utilization to enhance system efficiency and sustainability.

**Exergy**
- Operating pressure influences the exergy efficiency of cogeneration systems, particularly when waste heat recovery is implemented in CHP, CCP, and CCHP modes.
- CCP mode exhibits the lowest exergy efficiency for all prime movers, as the recovered heat is directed to an absorption chiller, which introduces significant exergy destruction due to its complex components. Consequently, the system performs less efficiently in CCP mode compared to CHP and CCHP modes.
- CCHP mode achieves the highest exergy efficiency, though the difference between CCHP and CHP modes is minimal.
- Operating pressure has a limited impact on exergy performance across most prime movers, where pressure affects the fuel cell reaction and improves performance under optimal conditions.
- The Otto cycle delivers the highest exergy efficiency in the cogeneration system, while the steam turbine shows the lowest exergy efficiency.

**FESR**
- The evaluation of the cogeneration system using an economic index, specifically the fuel energy saving ratio (FESR), reveals that operating pressure positively impacts FESR, with an increase in pressure leading to a higher FESR.
- The Otto cycle achieves the highest FESR, indicating its superior energy efficiency in cogeneration applications.
- Gas turbines, due to their relatively low energy efficiency, exhibit the lowest FESR among the prime movers.
- CCP mode consistently shows the lowest FESR across all prime movers. However, for gas turbines and diesel engines, CHP mode outperforms CCHP in terms of FESR, whereas for other prime movers, CCHP mode provides better fuel energy savings than CHP.

**CDER**
- Carbon dioxide emission reduction (CDER) serves as a critical index for evaluating the environmental impact of prime movers. The study shows that CCP mode consistently results in the lowest CDER across all prime movers.
- CCHP mode provides the best operating condition for all prime movers, except for the gas turbine, which exhibits a unique behavior: at low pressure ratios, CHP mode performs better, while at high pressure ratios, CCHP mode is more favorable in terms of CDER.
- Diesel engines in CCHP mode exhibit the best operating performance in terms of CDER reduction, while the steam turbine achieves the lowest CDER among all the prime movers.

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Persian Abstract

چکیده

با توجه به کاهش منابع سوخت‌های فسیلی و افزایش آلودگی‌های زیست‌محیطی، بازیافت حرارت اتلافی از محرک‌های اولیه از اهمیت بالایی برخوردار است. در این راستا، یک ساختمان پایه با تقاضای الکتریکی ۴۲ کیلووات به‌عنوان مصرف‌کننده در نظر گرفته شده است. سیستم تولید همزمان شامل حالت‌های CCHP (تولید همزمان سرمایش، گرمایش و توان)، CHP (تولید همزمان گرمایش و توان)، CCP (تولید همزمان سرمایش و توان) و تولید مستقل توان، با استفاده از چهار محرک اولیه شامل توربین گاز، توربین بخار، سیکل اتو و سیکل دیزل می‌باشد. تأثیر فشار عملیاتی این محرک‌های اولیه بر عملکرد انرژی، اکسرژی، اقتصادی و زیست‌محیطی مورد بررسی قرار گرفته است. نتایج مطالعه نشان می‌دهد که افزایش فشار عملیاتی منجر به بهبود عملکرد تمامی محرک‌های اولیه از دیدگاه انرژی می‌شود؛ با این حال، بیشترین بازدهی مربوط به سیکل اتو است که استفاده از بازیافت حرارت اتلافی می‌تواند به‌طور میانگین بازدهی آن را تا ۴۰٪ افزایش دهد. از دیدگاه اکسرژی، بهترین عملکرد در سیکل‌های دیزل و اتو مشاهده می‌شود، اما بازیافت حرارت اتلافی بیشترین افزایش در بازده اکسرژی را در سیکل‌های توربین گاز و توربین بخار ایجاد می‌کند. به‌طور خاص، افزایش میانگین بازده اکسرژی در سیکل توربین گاز ۱.۵۸ برابر مقدار آن در سیکل اتو در حالت CHP است. علاوه بر این، بهترین عملکرد اکسرژی در حالت CCHP رخ می‌دهد. در نهایت، سیکل اتو بهترین عملکرد را از نظر صرفه‌جویی در مصرف سوخت دارد، در حالی که سیکل توربین گاز مؤثرترین گزینه در کاهش انتشار دی‌اکسید کربن می‌باشد.