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# Energetic, exergetic, economic and environmental (4E) assessment of a residential micro-CHP system: A case study

# *Konut tipi bir mikro-kojenerasyon uygulamasının enerji, ekserji, ekonomik ve çevresel analizi*

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# Energetic, Exergetic, Economic and Environmental (4E) Assessment of a Residential Micro-CHP System: ACase Study

## *Highlights*

- *Energetic, exergetic, economic and environmental (4E) assessment of a micro-CHP application in a multi-family building in Konya is conducted.*
- *The first residential use is reported and analysed in this communication.*
- *Thermodynamic analyses showed that the cycle efficiency of micro-CHP system was 87% .*
- *II. Law analysis revealed inefficiencies of the system, exposing the parts requiring improvement.*
- *The economic and environmental analysis indicated that how profitable and environmentally friendly the CHP system is.*

## *Graphical Abstract*

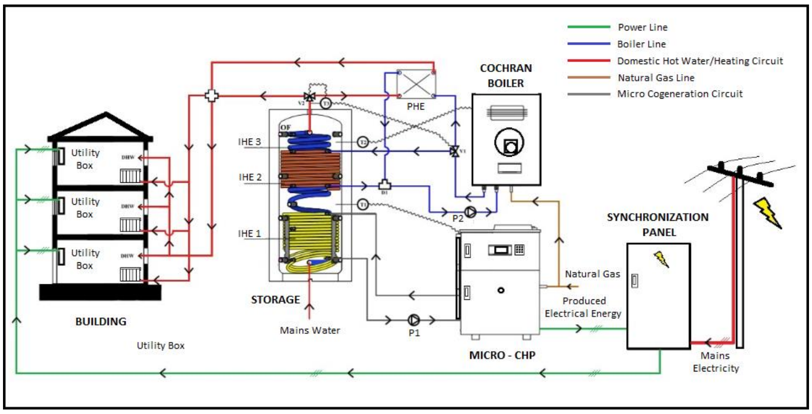


**Fig .** Schematic view of the CHP system set-up

## *Aim*

*The aim of this study is to conduct detailed energy, exergy, economic and environmental (4E) performance analysis of a 73 kWe and 115 kWt capacity micro-CHP system applied in a multi-family house in Konya.*

## *Design & Methodology*

*The studied micro-CHP system has an electrical capacity of 71 kWe and thermal capacity of 115 kWt. The system provides supplementary thermal energy to approximately 10% of the entire heat load of the building.*

## *Originality*

*This study is novel in terms of reporting and analysing the first known residential micro-CHP application in Turkey.*

## *Findings*

*Thermodynamic analyses showed that the micro-CHP system was capable of reaching 87% of cycle efficiency. Moreover, II. Law analysis revealed inefficiencies across the system such that the high temperature heat exchanger had the lowest exergy efficiency of 63.7%, which is the part requiring improvement.*

## *Conclusion*

*The heat capacity of the CHP system should not exceed 15% of the heat required by the building. Due to in-situ energy generation, the elimination of electrical energy transmission and distribution losses is ensured through CHP systems.*

## *Declaration of Ethical Standards*

*The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.*

# Energetic, Exergetic, Economic and Environmental (4E) Assessment of a Residential Micro-CHP System: A Case Study

***Araştırma Makalesi / Research Article***

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**ABSTRACT**

In this study, energetic, exergetic, economic and environmental (4E) assessment of a micro-cogeneration system implemented in a multi-family building with 137 flats in Konya is conducted. Although industrial CHP applications are prevalent in Turkey, the first residential use is reported and thoroughly analysed in this communication. Thermodynamic analyses showed that the micro-CHP system was capable of reaching 87% of cycle efficiency with 70 kWe of electrical and 115 kWt of thermal power, respectively. Moreover, II. Law analysis revealed inefficiencies across the system such that the high temperature heat exchanger had the lowest exergy efficiency of 63.7% which is the part requiring improvement. The economic analyses showed that the system could generate $22.10/month of economic return per flat and the payback period was found to be 5.48 years. Lastly, environmental analysis indicated that how environmentally friendly the CHP system is and argued that the system has prevented more $CO_2$ emissions in winter than summer due to operating at full capacity. The findings support the potential and elucidate the specific conclusion for the practice of residential CHP applications in Turkey.

**Keywords: Micro-CHP, residential building, thermodynamic analysis, economic and environmental analysis.**

# Konut Tipi Bir Mikro-Kojenerasyon Uygulamasının Enerji, Ekserji, Ekonomik ve Çevresel Analizi

**ÖZ**

Bu çalışmada, Konya'da 137 dairelik bir siteye uygulanan mikro-kojenerasyon sisteminin enerji, ekserji, ekonomik ve çevresel değerlendirmesi yapılmıştır. Türkiye'de endüstriyel kojenerasyon uygulamaları yaygın olmakla birlikte, ilk konut kullanımı bu çalışmada ayrıntılı olarak analiz edilmektedir. Termodinamik analizler, 70 kWe elektrik ve 115 kWt termal güç kapasitelerine sahip mikro-kojenerasyon sisteminin, çevrim verimliliğinin %87'lere ulaşabildiğini göstermektedir. Yapılan çalışma kapsamında gerçekleştirilen II. Kanun analizi, yüksek sıcaklıklı ısı eşanjörünün % 63,7 ile en düşük ekserji verimliliğine sahip olduğunu ve bunun en çok iyileştirme gereken kısım olduğunu ortaya koymuştur. Ekonomik analizler, sistemin daire başına 22,10 $/ay ekonomik getiri sağlayabildiğini ve geri ödeme süresinin 5.48 yıl olduğunu göstermektedir. Son olarak, çevresel analizle CHP sisteminin ne kadar çevre dostu olduğuna dikkat çekilmiş ve sistemin tam kapasite çalıştığı için kış mevsiminde yaz mevsiminden daha fazla $CO_2$ emisyonunu önlediği savunulmuştur. Bulgular, kojenerasyon sistemlerinin sağladığı enerji verimliliği potansiyelini desteklemekte ve Türkiye'de konutlarda kojenerasyon uygulamaları için belirli bir potansiyeli ortaya koymaktadır.

**Anahtar kelimeler: Mikro-kojenerasyon, konut, termodinamik analiz, ekonomik ve çevresel analiz**

## 1. INTRODUCTION

Energy consumption in the building sector accounts for nearly 30% of overall energy consumption in Turkey while residential buildings alone constitutes 14% of the total figure [1]. The residential energy consumption in Turkey has increased around 25% between the years 2002 and 2019 as the country's energy use is expected to experience a substantial increase by 50% over the next decade [2] and corresponding $CO_2$ emissions were nearly tripled from 2000s and to-date [3]. To reduce the carbon emission, Turkey set an ambitious goal in Energy Efficiency Strategic Plan for reducing carbon emissions by 20% from the level of 2011 until the year 2023 [4]. Therefore, to reduce the energy consumption and carbon emissions in the residential sector, use of small scale combined heat and power systems (micro-CHP) delivers sustainable, energy efficient building solutions by providing electricity and heat together as opposed to conventional buildings where electricity and heat are supplied separately by grid and boiler. The heat recovered from the CHP is utilised in space heating, domestic hot water heating while electricity is supplied for the load.

Due to the great potential of CHP, there are many studies on the applications of CHPs in residential buildings [5-7]. To exemplify a few, Lee et al. [8] analysed a micro-CHP applied to a medium-sized multi-family building with a floor heating representing a typical Korean residential scenario. After installing the CHP unit, total primary energy consumption was reduced by 18.4%, $CO_2$

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emissions by 11.8% and operation cost by 9.6%, respectively. The payback year was found to be 10.2 years based on the operating cost. Ehyaei et al. [9] carried out a technical, economic and environmental feasibility study on the application of a CHP system to meet the electricity, domestic hot water (DHW) and heating/cooling requirement of a 10 floor 40 units residential building in Tehran city, Iran. Each apartment has 200 $m^2$ sitting area. The peak demands of electricity, DHW, heating and cooling loads of the building were found to be 32.96 kW, 0.926 kW, 1590 kW and 2028 kW, respectively. As a result of employing five identical CHP units, findings showed that average unit cost of electricity could be obtained as low as 0.05 US$/kWh and yearly entropy generation was attained as 29,903 GJ/year. Ciampi et al. [10] worked on energy, environment and economic dynamic simulation of a micro-CHP system for an Italian multi-family house by using TRNSYS software. According to the scenario set in TRNSYS simulation environment, the system could achieve 6.5% reduction in the primary energy consumption, up to 12.8% reduction in $CO_2$ emissions and almost 30% reduction in the operation costs. Aliabadi et al. [11] compared three micro-CHP technologies performance-wise. The examined units were fuelled by NG and produce combined heat and power for residential use. The analysis showed that IC system provided the highest energy and exergy efficiencies at relatively higher heat use and obtained 76.7% of energy efficiency, 57.2% of exergy efficiency, and 71% of heat use factor. Paepe et al. [12] dynamically determined the electricity and heat demands of various buildings (detached, terraced and a two storey apartment) and designed different CHP systems (market available natural gas engines, Stirling engines and a fuel cell). The results primarily revealed that although a reduction in primary energy use was achieved, natural gas fuelled engines provided the best performance. Above studies verified the performance of the NG fed IC type micro-CHP units as analysed in the present study.

In addition to the IC based micro-CHP systems, fuel cell based micro-CHP systems offer several benefits for residential use and have attracted great deal of interest in the existing literature. To name a few, Brett et al. [13] explored various options of fuel cell based micro-CHP for building use. After reviewing current designs, they concluded that although this technology provides various advantages including high electrical efficiency, low emissions and low heat to power ratio, the fuel cell based micro-CHP systems and present building application scenarios/configurations are still immature and need substantial improvements. Gandiglio et al. [14] performed a techno-economic analysis to validate the performance of PEMFC and SOFC based micro-CHP system. The results revealed that the PEMFC and SOFC based micro-CHP systems positively contributed the reduction in primary energy consumption of domestic users. Comparatively, PEM system provided more energy savings due to the higher flexibility and low temperature operation. Longo et al. [15] conducted a life cycle energy and environmental impacts of a SOFC based micro-CHP system for residential applications. The results showed that main impacts of the system are due to the fuel supply and operation (98% of cumulative energy demand and 63% of examined environmental impacts). The analysis also proved that eco-design solutions can be achieved without sacrificing system efficiency and durability. Above studies confirmed that fuel cell based systems are still in research phase and optimum configuration has yet to be achieved especially for residential applications.

In this study, detailed energy, exergy, economic and environmental (4E) performance analysis of a 73 kWe and 115 kWt capacity micro-CHP system applied in a multi-family house in Konya. It is worth noting that this is the first known residential application reported in Turkey. Initially, the first (energy) and second law (exergy) performance of the micro-CHP system is presented to highlight the significant inefficiency during the energy conversion process. Following, economic and environmental analysis are carried out to contribute to the existing literature that such data have not been publicly reported.

## 2. MATERIAL AND METHOD

The studied micro-CHP system has an electrical capacity of 71 kWe and thermal capacity of 115 kWt. The system provides supplementary thermal energy to approximately 10% of the entire heat load of the building. The aim is to benefit from the maximum use of waste heat generated during the electricity generation. In addition, the thermal recovery obtained. from the flue gas is found to be 38 kWt and approximately 5 kW of this provides reinforcement to the building hot water tank. While this is sufficient in summer and seasonal transitions, it provides only thermal support in winter. The system description, climatic condition of the studied site and the numerical analysis are presented in the following sections.

### 2.1. System description

The micro-CHP system used is internal combustion piston engine type (IC) which is based on the principle that the positive pressure created by the combustion moves the piston. Internal combustion engines are widely preferred in micro cogeneration applications [16-17]. The schematic representation of the installed system is given in Fig 1.

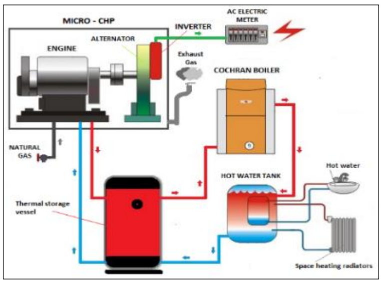



**Fig 1.** Schematic representation of the internal combustion engine based system [17]

The main reason for the CHP systems to work with higher efficiencies compared to the systems with simple cycle is that it enables a secondary energy production by making use of heat from exhaust gases and engine block jacket cooling. In simple cycles, the gas turbine or engine generating electricity converts only 30-40% of the natural gas into the electricity, and the rest is largely released as waste heat. In CHP systems, however, most of this waste energy is recovered for utilisation.

**Fig 2.** Installed micro-CHP system

The CHP system, analysed in this study, is in the form of a set consisting of engine-alternator, radiator and water cooling pump and piping system for engine cooling and heat exchanger that provides water transfers heat from exhaust gas. In addition, silencer is used to prevent high power noise from the exhaust of the gas engine. The sound level of the module used with additional measures was determined as 52 dB.

Gas engines allow low waste-heat energy recovery compared to turbine systems. Since the gas engines are also produced for smaller power levels, they are the most suitable solution, especially in low electricity-heat applications. While one unit of electrical energy is produced in turbine-based CHP facilities, three units of heat energy are released as by product. However, in gas-powered cogeneration plants, this rate is approximately one-to-one. Of the fuel energy burning in a proportioned piston gas engine, 35-40% is converted to mechanical power (from mechanical power to electrical power through an alternator), 30-35% to engine liner temperature, 25-30% to exhaust temperature, and remaining 7–% is lost energy in the form of radiation.

In operation, mechanical energy is generated when ignition takes place. Then, the generated mechanical energy is converted into electrical energy through a synchronous generator. Thermal energy is collected from exhaust gas, engine block, collector pipe and engine grease oil. Then, recovered heat is utilised as a supplement to domestic hot water or indoor heating. Thus, high levels of energy efficiency (up to 90%) can be achieved. The technical features of the system installed is given in Table 1 and the system is shown in Fig 2.

**Table 1.** Technical specifications of the CHP system

| | |
|---|---|
| Engine type | MAN E 0836 E |
| Electrical power | 71 ekW |
| Thermal power | 115 tkW ± %5 |
| Fuel consumption | 204 tkW ± %5 |
| Exhaust outlet temperature | 610 °C |
| Electrical efficiency | % 34,3 |
| Thermal efficiency | % 56,4 |
| Total cycle efficiency | % 90,7 |
| Returning temperature min./max. | 60 °C / 70 °C |
| Flow rate of heating water | 4,9 $m^3/h$ |
| Maximum operating temperature | 10 Bar |
| Noise level | 52 dB |

In cogeneration systems, in order for the engine to work efficiently and properly, the heat generated on the engine jacket must be removed from the engine. Therefore, a coolant called jacket water is circulated in the engines. The temperature of coolant is in the range of 80-95°C. This water, cooled in the plate heat exchanger, is discharged to the jacket or to the radiator to be cooled with the aid of a three-way thermal valve at the exit from the heat exchanger. Here, the cooled water (75–80°C) is sent back to the motor jacket again. In addition, the exhaust gas generated by the natural gas burning in the engine has a high temperature of 400 to 600°C. There is heat recovery from the flue gas as well. In gas engines, 2/3 of the waste heat is recovered from jacket cooling and 1/3 from exhaust gas. There is also heat recovered by cooling the oil on the engine. The thermal energy obtained here is at relatively low levels. Also known as intercooler, this warm water pool is used in low temperature applications such as tap water heating.

A schematic view of the micro-CHP system is shown in Fig 3. The overall system loop consists of a micro cogeneration device, a combined hot water tank, three internal heat exchangers (IHE1, IHE2, IHE3), an auxiliary boiler, plate heat exchanger (PHE), thermostats located in various places (T1 , T2, T3), pump (P1, P2), three flow guides (D1, D2, D3), three 3-way valves (V1, V2, V3) and synchronous board.

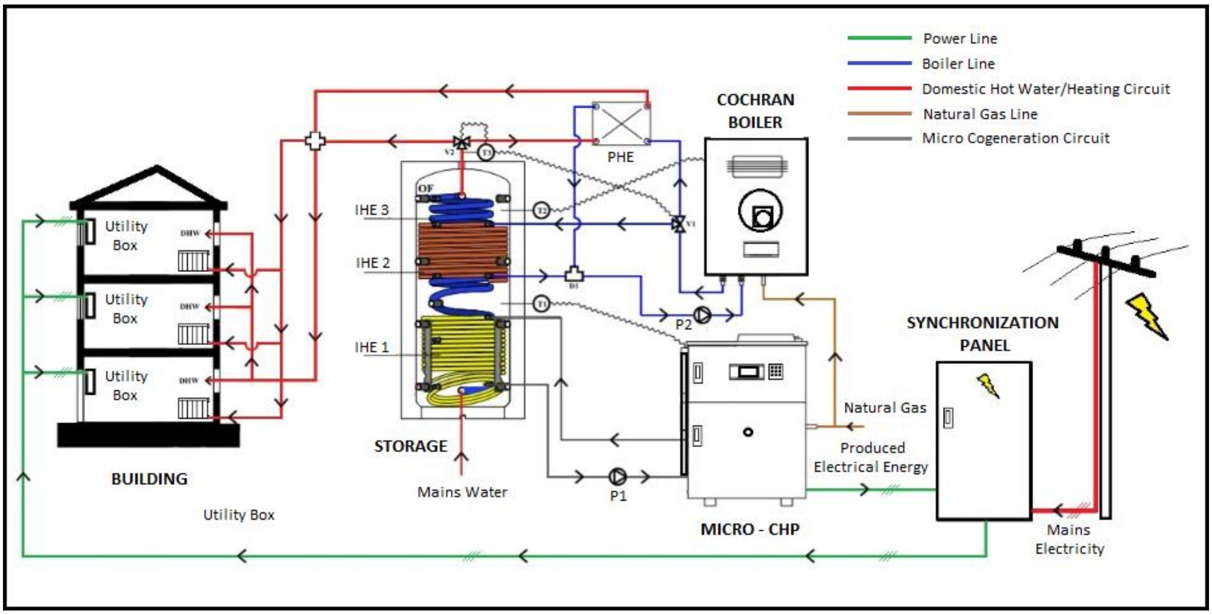



**Fig 3.** Schematic view of the CHP system set-up

### 2.2. Climatic Conditions

In this study, the first residential type micro-CHP application in Turkey is installed in order to meet the electricity and heat requirements of a multi-family house with 137 units in Konya city. The installation site is shown in Fig 4a.

Konya is geographically located in the centre of Anatolia, above the sea level of 1028 m. It has latitude of 37° 52' 28.7076" N and longitude of 32° 29' 35.3616" (Fig 4b). It is a characteristic continental climate with a dry and sunny inland region. Table 2 provides the mean climatic conditions of 3 years covering the study period.

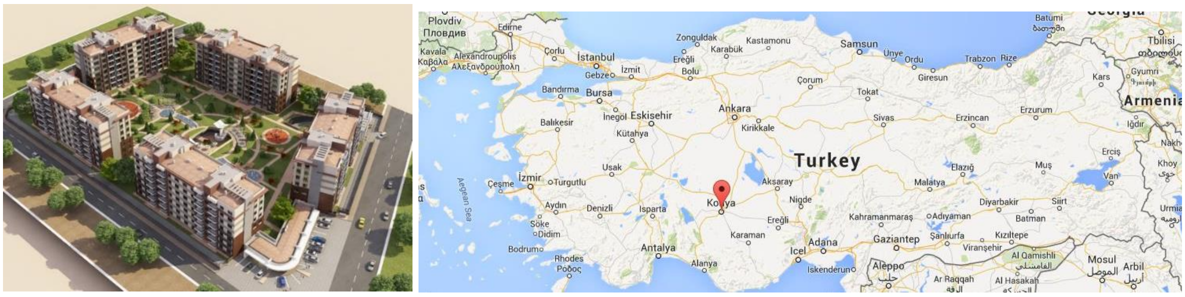



**Fig 4. a)** Application site **b)** Konya city

**Table 2** 3-year mean values of meteorological parameters in Konya covering the study period

| Year | Ambient temp. (°C) | | Wind speed (m/s) | | Relative Humidity (%) | |
|---|---|---|---|---|---|---|
| | Mean | STD | Mean | STD | Mean | STD |
| 2015 | 12.66 | 8,86 | 3,04 | 2,35 | 49,75 | 13,67 |
| 2016 | 11.75 | 9,66 | 2,88 | 1,72 | 55,58 | 17,68 |
| 2017 | 11.65 | 6,75 | 3,15 | 1,54 | 51,67 | 10,99 |

## 3. MATHEMATICAL MODELING

A numerical model that is well suited to the thermophysical properties of the micro-CHP system was adapted in order to simulate the performance of the system through EES (Engineering Equation Solver) software. The method and formulations employed in this study are not necessarily the most accurate available, but they are extensively applied, easy to practice and adequate for most of the design computing.

### 3.1. Energy Analysis

The fuel flow into the control volume is measured as volumetric or mass flow rate. The mass flow rate of fuel into the engine is, then, used to compute the heat power supplied by the fuel, $\dot{Q}_{fuel}$ as [18]

$$\dot{Q}_{fuel} = \dot{m}_{fuel} \times LHV \tag{1}$$

where LHV is the lower heating value of the fuel in kJ/kg and $\dot{m}_{fuel}$ is the mass flow rate of the fuel across the control volume, measured in kg/s. The data used in this communication is cyclic and the performance parameters are calculated as follows [5]

$$\dot{Q}_{jw,HE} = C_{p,w}\dot{m}_{hot}(T_{jw,HE,out} - T_{jw,HE,in}) \tag{2}$$

where $\dot{Q}_{jw,HE}$ is obtained heat from jacket cooling, $c_{p,w}$ is specific heat of water, $\dot{m}_{hot}$ is mass flow rate of hot water, $T_{jw,HE,in}$ and $T_{jw,HE,out}$ is water temperature at inlet and outlet of jacket heat exchanger, respectively.

$$\dot{Q}_{eg,HE} = C_{p,w}\dot{m}_{hot}(T_{eg,HE,out} - T_{eg,HE,in}) \tag{3}$$

where $\dot{Q}_{eg,HE}$ is retrieved heat from exhausted gases, $T_{eg,HE,in}$ and $T_{eg,HE,out}$ is water temperature at inlet and outlet of exhausted gases heat exchanger, respectively.

The electrical power delivered, $\dot{W}_{el}$ is calculated by using the measured electrical current, $I_{out}$ and voltage output, $V_{out}$ [8].

$$\dot{W}_{el} = V_{out} \times I_{out} \tag{4}$$

and

$$r_{el\_th} = \frac{\dot{W}_{el}}{\dot{Q}_{jw,HE}+\dot{Q}_{eg,HE}} \tag{5}$$

where $r_{el\_th}$ is the ratio of electricity to thermal heat recovery and $\dot{W}_{el}$ is the electrical power output.

Cogeneration systems are of great interest since these systems generate heat and power simultaneously from a single source of fuel with higher efficiencies rather than generating electricity and heat in two separate processes (see Fig 3). Therefore, the electrical efficiency, $\eta_{el}$ is calculated as [5]

$$\eta_{el} = \frac{W_{el}}{Q_{NG}} \tag{6}$$

where NG is natural gas, $Q_{NG}$ is its energy input in lower calorific value (48.5 MJ/kg). The thermal efficiency, $\eta_{th}$ is [5]

$$\eta_{th} = \frac{Q_{jw,HE}+ Q_{eg,HE}}{Q_{NG}} \tag{7}$$

Overall efficiency including electrical and thermal efficiency, $\eta_{total}$ is [5]

$$\eta_{th} = \eta_{el} + \eta_{th} \tag{8}$$

### 3.2. Exergy Analysis

The first law of thermodynamics provides insights about how effective an energy conversion system is, however, it does not assess the work potential of the energy input. Therefore, second law analysis, exergy, is required to quantify the work potential (quality). Second law analysis exposes system inefficiencies, which is embodied as exergy destruction, signifying areas/sub-components where energy conversion efficiency can be improved [18].

Exergy determines the maximum work that a system could produce in a state of equilibrium with its environment. Therefore, both the system and its surroundings take role in exergy. Having said that exergy quantifies the process between a predefined beginning state (system) and end state (surroundings, or dead state). The dead state for this analysis is taken to be atmospheric air at 298 K, with a composition of 8.07 % $CO_2$, 16.05 % $H_2O$, 72.65 % $N_2$ and 3.23% $O_2$ and measured local atmospheric pressure [19].

Thermo-mechanical exergy, $X_{TM}$ is often termed if a non-reacting system could produce maximum work by making use of kinetic and potential energy, pressure, temperature between the system and dead state. If maximum work is drawn out of a chemical reaction that the system responds chemically within the dead state, it is regarded as chemical exergy, $X_{CH}$. Adding the chemical and thermo-mechanical exergies yields the total exergy in the system, $X_{tot}$, given as [18]

$$X_{tot} = X_{TM} + X_{CH} \tag{9}$$

Thermo-mechanical and chemical exergies are calculated separately by defining ‘restricted dead state’ and ‘true dead state’. In the restricted dead state, the system and its contents are brought to thermal and mechanical balance with the surroundings, but no constraints are imposed on its equilibrium with chemical composition. Yet, the true dead state demands that the system is also in balance chemically with the surroundings. As shown in Fig 1, fluid flows are mainly responsible for the energy streams in and out of the system. When a fluid flow crosses a control volume, flow exergy is the term, defining the thermomechanical exergy of the stream. For each fluid flow, the flow exergy, $\psi_i$ is given by [18]

$$\psi_i = (h_i - h_{i,0}) - T_0(s_i - s_{i,0}) \tag{10}$$

where $h_i$ and $h_0$ are the specific enthalpies of the flows at the system and restricted dead state, respectively. $T_0$ is the temperature of restricted dead state (true dead state as well), $s_i$ and $s_0$ are entropies of flows at the system and restricted dead state conditions, respectively. The full thermomechanical exergy, $X_{TM}$

$$X_{TM} = \sum_{i=1}^{n} m_i\psi_i \tag{11}$$

If a stream has variety of reactive species, as in the case of commercial natural gas, total chemical exergy, $X_{CH}$ of the streams can be obtained by adding i species as [18]

$$X_{CH} = \sum_{i=1}^{n} X_{CH,i} \tag{12}$$

This is the second part of the Eq. 11 and summation with Eq. 12 would deliver the total exergy of a fluid stream. Exergy can also be transmitted with heat as well with mass and work crossing the control volume. The exergy related with a given quantity of heat, $X_{heat}$ is [18]

$$X_{heat} = Q \times (1 - \frac{T_0}{T}) \quad (13)$$

$Q$ is the amount of heat supplied at a temperature, $T$. The exergy is simply equivalent to the work produced, $W$.

$$X_{work} = W \quad (14)$$

### 3.3. Economic analysis

In order to estimate the amount of energy savings associate to the utilisation of the micro-cogeneration system rather than the conventional counterpart, the following indicator namely Primary Energy Saving (PES) can be used as [10]

$$\text{PES} = \frac{E_{p,CS} + E_{p,CHP}}{E_{p,CS}} \quad (15)$$

where $E_{p,CS}$ and $E_{p,CHP}$ represent the primary energy consumption related to the cogeneration and conventional system.

### 3.4. Environmental Analysis

Environmental impact of the applied micro CHP system is assessed through carbon dioxide emission factor. In buildings, $CO_2$ is generated through electricity and gas consumption. For electricity, $CO_2$ factor is calculated based on the power plant sources of Turkey, depending on 31.4% hydraulic, 28.6% natural gas, 22.4% coal, 8.1% wind, 6.2% solar, 1.6% geothermal and 1.7% other sources [20]. Therefore, the emission factor from power plants is found to be around 1 $kgCO_2.kWh^{-1}$. Similarly, $CO_2$ emission factor of the natural gas is obtained as around 2 $kgCO_2.m^{-3}$ [21]. By using above factors, total emissions are calculated as [8]

$$CO2_{baseline} = E_{elec} \times CO2_{elec} + E_{NG} \times CO2_{NG} \quad (16)$$

$$CO2_{CHP} = E_{CHP,elec} \times CO2_{elec} + E_{CHP,NG} \times CO2_{NG} \quad (17)$$

where $E_{elec}$ is the electricity consumption, $E_{NG}$ is the natural gas consumption, $CO2_{elec}$ and $CO2_{NG}$ are carbon dioxide emissions from electricity and natural gas, respectively. Lastly, the reduction in $CO_2$ is calculated as a means of percentage difference by [8]

$$CO2_{reduced} = \frac{CO2_{baseline} - CO2_{NG}}{CO2_{baseline}} \times 100 \quad (18)$$

where $CO2_{baseline}$ and $CO2_{CHP}$ are carbon dioxide emissions for cases without and with CHP, respectively.

## 4. RESULTS AND DISCUSSION

In this section, findings from energy, exergy, economic and environmental analysis will be presented and results will be discussed. The analysis are performed based on a periodic average. Moreover, performance of the CHP is compared to the conventional systems from economic point of view and relevant economic indicators are presented in a tabular form.

### 4.1. Energy Analysis

In Figure 5, energy flow balance diagram of the micro-CHP module is illustrated. In the energy balance, the conversion of the energy input obtained from natural gas to electricity, thermal and lost energy is shown schematically. With the combustion of the natural gas in the internal combustion engine, the gas engine gains mechanical rotational motion. This rotation movement turns into electrical energy in the synchronous generator located in the system. 36.8% of the natural gas consumed turns into mechanical energy and 2.5% of this mechanical energy is eliminated as mechanical loss.
Also, thermal energy is generated during the combustion of the natural gas. This thermal energy is the accumulation of pipe temperature, exhaust gas temperature, engine block temperature and grease oil temperature. While 56.4% of the thermal energy generated is converted into useful thermal energy, 6.8% is discarded as a loss of residual heat and radiation.

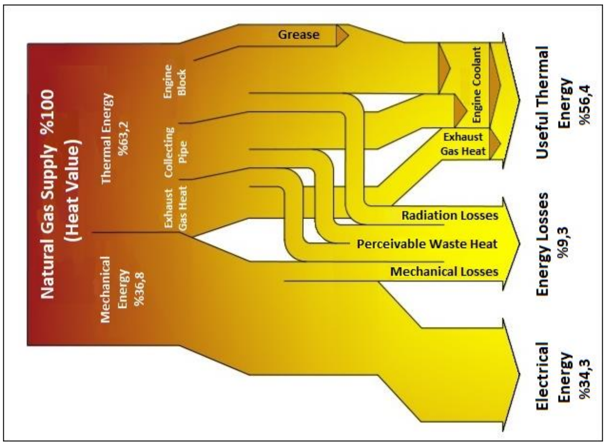



**Fig 5.** Energy flow diagram

Figure 6a is the energy flow diagram of the buildings, powered with traditional means. In this method, the conversion amount of 200 units of energy into useful energy is obtained as 118 units and the remaining 82 units of energy are dumped to nature as waste heat. This energy loss causes both rapid degradation of energy sources and climate changes due to the gas emissions, let alone financial losses due to the inefficient utilisation of energy source. In Fig 6b, it is shown that the CHP generates heat and electricity with 90.7% total of mechanical energy losses, sensible residual heat and radiation losses constituting 9.3% are the total loss through the micro-CHP system. The total efficiency rating of the micro cogeneration unit is the sum of available electrical and thermal energies

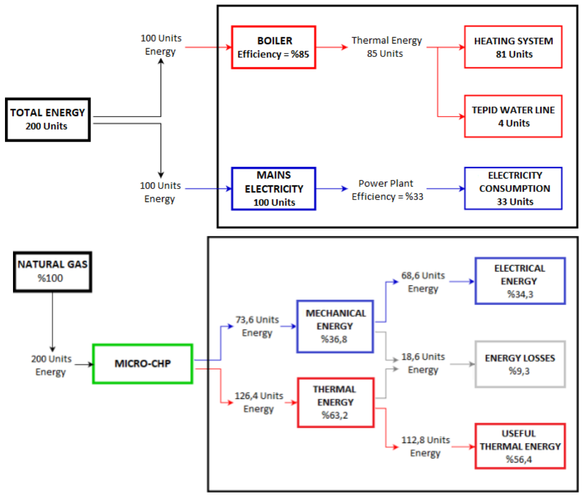



**Fig 6.** a) Conventional energy flow in buildings b) Energy flow of the building with CHP

Electricity and thermal energy flow diagram with respect to the amount of natural gas consumption is given in Fig 7a. Accordingly, 70.65 kWh of electrical, 116.6 kWh of thermal and 19.63 kWh of radiant heat loss was generated from 21.56 m³/h NG consumption. The boiler comparison diagram against the thermal energy recovery of the building with micro-CHP is given in Fig 7b. If CHP was not installed in the building, it would be necessary to install a boiler with an input/output capacities of 137.1 kW/116.6 kW, and operating at 85% efficiency. Therefore, separate boiler for the required thermal energy is not used due to the thermal gain of the CHP unit, which is a saving in financial expenditure.

was put into operation, an average of 51% decrease was detected in the electrical energy drawn from the network. In addition, the heat generator (boiler) is not used in the summer season, and additional heat is supplied to 2 boilers with a capacity of 1120 kWt in the winter season and intermediate seasons. Thus, maintenance times of boilers are prolonged due to intermittent use.

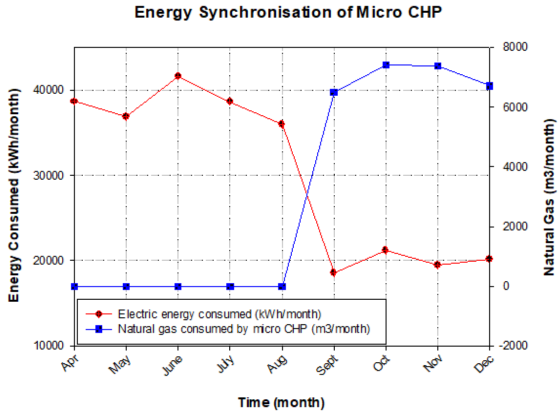



**Fig 8.** Energy synchronisation of micro CHP

As shown in Fig 9 (a), the average hourly power production is around 48 kW in winter although it was nearly 30 kW in the summer season due to sleep mode that the module was frequently introduced into. This could be due to the holiday season of the occupants, the prolongation in the daily sunshine hour and the failure mode that could affect the operation period of the micro-CHP unit in summer and winter season. At the lower and upper limits of set value of the module (42 kW), the

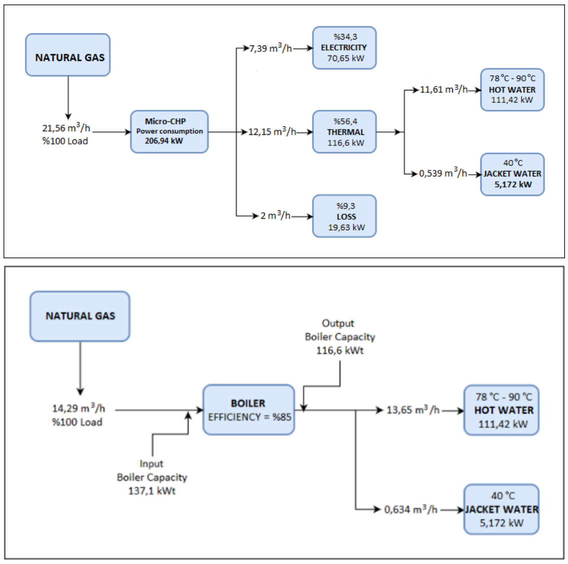
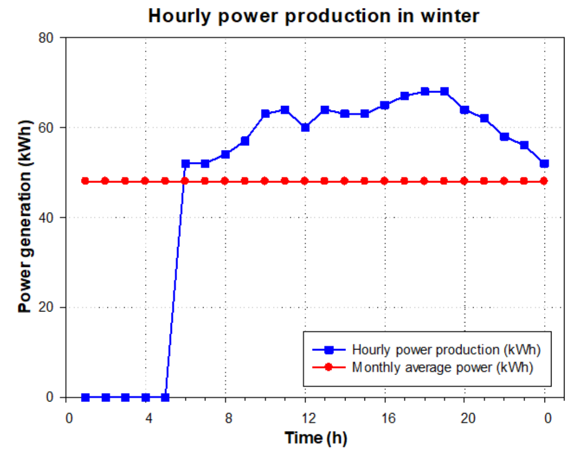



**Fig 7.** a) Natural gas consumption step diagram, b) Boiler capacity diagram with respect to thermal energy gain

In operation, the micro-CHP module consumes natural gas for generating electricity, exhaust heat energy and block water heat in return. Fig 8 pertains to the test campaign, and shows the electricity production of 18480 kWh/month in return for 6998 m³/month of natural gas consumed. As of the month when the micro cogeneration

system performed under self-control, to minimize the energy waste and be efficient. This points out that the module was introduced to sleep mode to extract maximum performance from the fuel. Therefore, the fuel was consumed efficiently



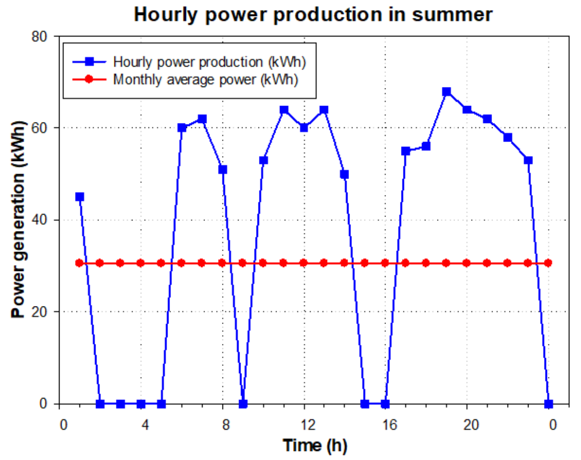
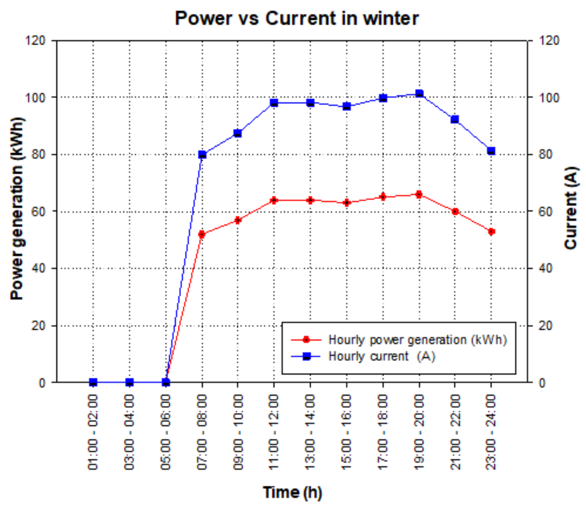




**Fig 9** (a) Hourly average power generation in winter (b) Average hourly power generation in summer

As shown in Fig 10a, average electrical current drawn from the system was between 72 A and 102 A in the winter season. The current rate in summer was around 70 A - 101 A (see Fig 10b). The current drawn from the system varied slightly due to the sleep mode reduced the mean power production.



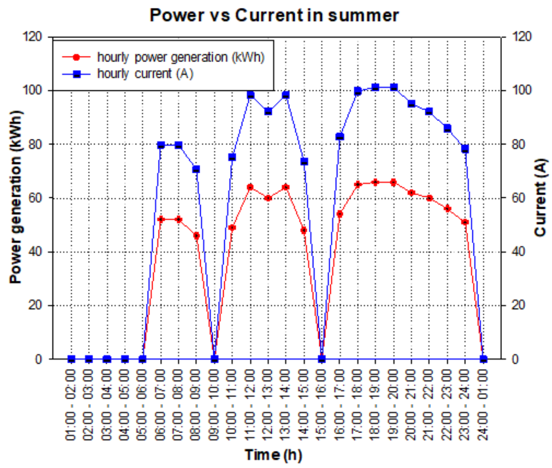
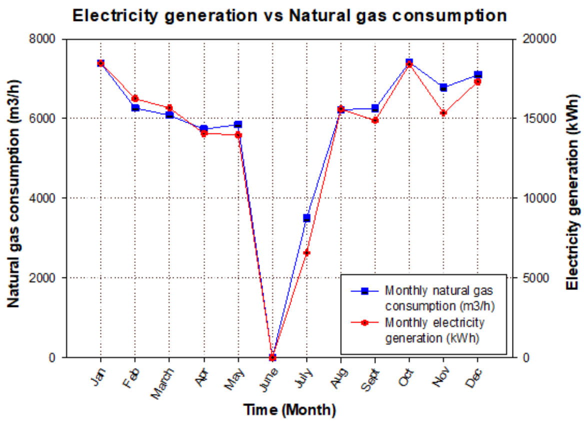




**Fig 10** (a) Hourly average power generation in winter (b) Hourly average power generation in summer

The CHP module generates electricity and thermal energy by consuming NG. In Fig 11a and Fig 11b, natural gas consumption was not observed due to the system closure in June and July for maintenance purposes. The major point to consider here is that extra thermal energy was formed as shown in Fig 11b. That is to say, thermal energy was saved without extra NG consumption (see Fig 11b).



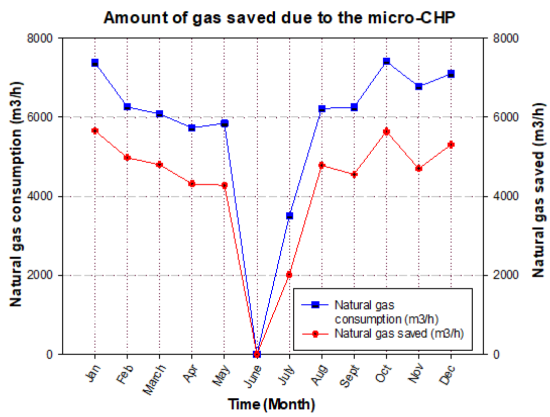




**Fig 11.** (a) Electricity generation against natural gas consumption (b) Amount of natural gas saving

In addition to the electrical energy generated in the system, the cooling water temperature reached up to 92°C by means of engine block cooling heat exchanger (engine block and grease) and exhaust gas heat exchanger (see Fig 12). The plate heat exchanger at the inlet temperature of 92°C transferred part of its heat to the heating water and dropped to 81°C at the outlet. When the cooling water temperature was 81°C at the outlet, the heating water temperature was 90°C. So, when the inlet and outlet temperatures in the plate heat exchanger were 92 and 81°C, the heating water inlet and outlet temperatures would be 70 and 90°C, respectively. Thus, with the help of cooling water, the system performance was improved and thermal energy to-be-dissipated was recovered as useful heat. This could eventually be utilised for space heating and domestic hot water needs.

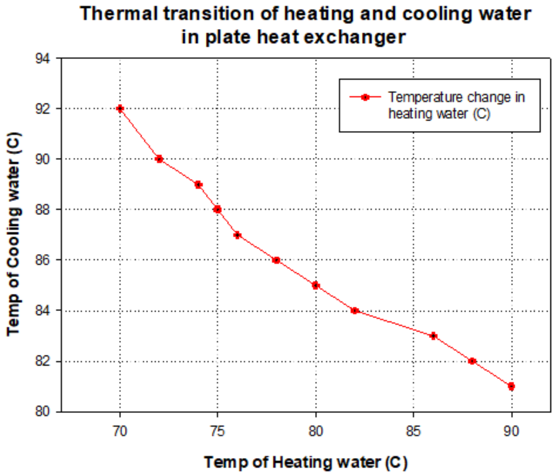



**Fig 12.** Thermal energy conversion in plate heat exchanger

Table 3 shows the inlet/outlet temperatures and heat gain at the heat exchangers. The fluid temperature rises from 80°C to 88°C in the engine block cooling heat exchanger and increases from 88°C to 92°C through this exhaust gas exchanger. Thus, as shown in Table 3, the fluid temperature rises and transfers heat to heating water by means of plate heat exchanger and the water temperature is increased from 70°C to 90°C. This is a supplement to the building hot water system

In the CHP system, $T_c$ (coolant temperature) derived from the engine jacket and $T_{e,w}$ (temperature of the outlet water from the exhaust), which corresponds to the working loads of the gas engine, are given in Fig 13. Heated water at 80°C from jacket cooling gained extra heat from the exhaust unit and its temperature reached to nearly 90°C. It is worth noting that the corresponding jacket cooling water temperature and exhaust-gas heat recovery raised while the engine load increased substantially.

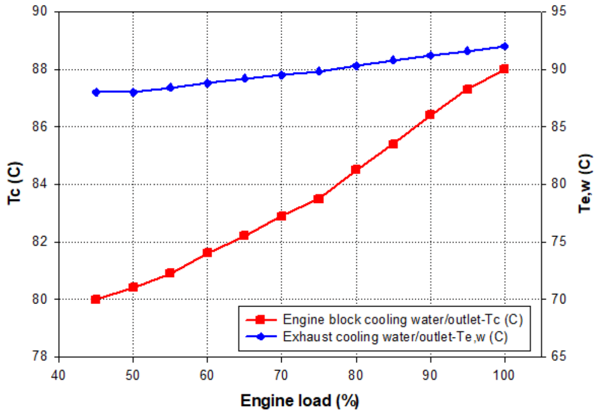



**Fig 13.** Outlet temperature change of water heated by motor jacket and exhaust gas

## 4.2. Exergy Analysis

The system instrumentation diagram of the micro-cogeneration unit is illustrated in Fig 14. The second law efficiency of the system was obtained by analysing over 20 points across the system as shown on this diagram. The current paths are numbered in Fig 24 and brief thermodynamic data related to each point are given in Table 4.

**Table 3** Thermal transition of cooling water and heating water in plate heat exchanger

| | Heat Power (kWt) | Temperature of Cooling Water | |
|---|---|---|---|
| | | Inlet (°C) | Outlet (°C) |
| Engine block cooling heat exchanger | 77 | 80 | 88 |
| Exhaust gas heat exchanger | 38 | 88 | 92 |
| Plate heat exchanger | 115 | 92 | 81 |

| | Plate Heat Exchanger | |
|---|---|---|
| | Inlet (°C) | Outlet (°C) |
| Temperature of Cooling Water | 92 | 81 |
| Temperature of Heating water | 70 | 90 |

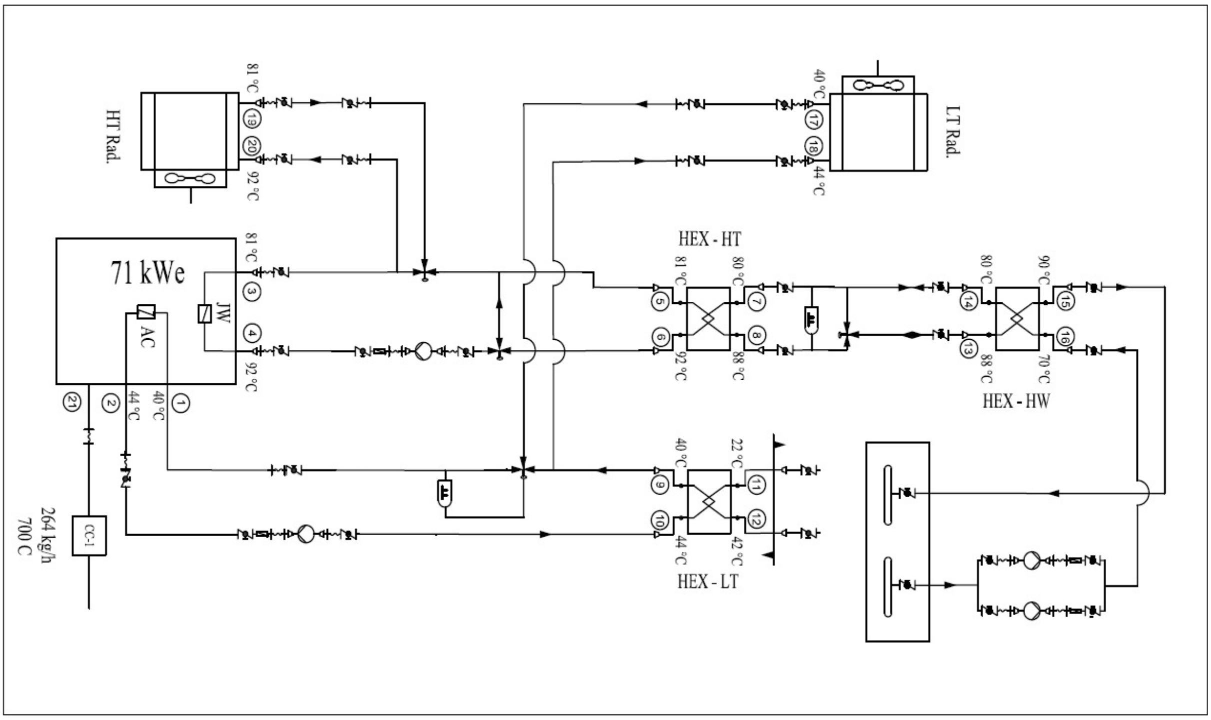


**Fig 14**. Instrumentation diagram of the micro-CHP unit

**Table 4.** Thermophysical properties of CHP unit flow paths

| Flow path # | T (°C) | T (K) | P (kPa) | h (kJ/kg) | s (kJ/kg.K) | Flow path # | T (°C) | T (K) | P (kPa) | h (kJ/kg) | s (kJ/kg.K) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 40 | 313,15 | 1000 | 168,4 | 0,572 | **11** | 22 | 295,15 | 1000 | 93,1 | 0,324 |
| **2** | 44 | 317,15 | 1000 | 185,1 | 0,625 | **12** | 42 | 315,15 | 1000 | 176,7 | 0,599 |
| **3** | 81 | 354,15 | 1000 | 339,9 | 1,087 | **13** | 88 | 361,15 | 1000 | 369,3 | 1,169 |
| **4** | 92 | 365,15 | 1000 | 386,1 | 1,215 | **14** | 80 | 353,15 | 1000 | 335,7 | 1,075 |
| **5** | 81 | 354,15 | 1000 | 339,9 | 1,087 | **15** | 90 | 363,15 | 1000 | 377,7 | 1,192 |
| **6** | 92 | 365,15 | 1000 | 386,1 | 1,215 | **16** | 70 | 343,15 | 1000 | 293,8 | 0,954 |
| **7** | 80 | 353,15 | 1000 | 335,7 | 1,075 | **17** | 40 | 313,15 | 1000 | 168,4 | 0,572 |
| **8** | 88 | 361,15 | 1000 | 369,3 | 1,169 | **18** | 44 | 317,15 | 1000 | 185,1 | 0,625 |
| **9** | 40 | 313,15 | 1000 | 168,4 | 0,572 | **19** | 81 | 354,15 | 1000 | 339,9 | 1,087 |
| **10** | 44 | 317,15 | 1000 | 185,1 | 0,625 | **20** | 92 | 365,15 | 1000 | 386,1 | 1,215 |

The variability of enthalpy and entropy rates depending on the temperature of the current flow points across the system causes the flow and exergy value of each point to differ as shown in Fig 15. This causes exergy destructions shown in the flow diagram in Fig 16. It is observed in the graphs that the points where the values related to the current paths 7 and 8 peaked, belong to the high temperature heat exchanger output. The high temperature exchanger operates in the range of 92-81˚C, providing back-up for building heating in the winter months. The high temperature heat exchanger feeds the hot water heat exchanger and supplies hot water requirements of the apartments in the range of 70-90˚C. The heat transfer rate in the heat exchanger is increased along with the exergy value on the current path number 8. The same is true for the flow path point 13, which is the hot water exchanger inlet. Similarly, this point is the inlet of the hot water exchanger where the exergy rate is maximum. This hot water heat exchanger operates in the range of 70-90˚C and supports building heating in the winter months

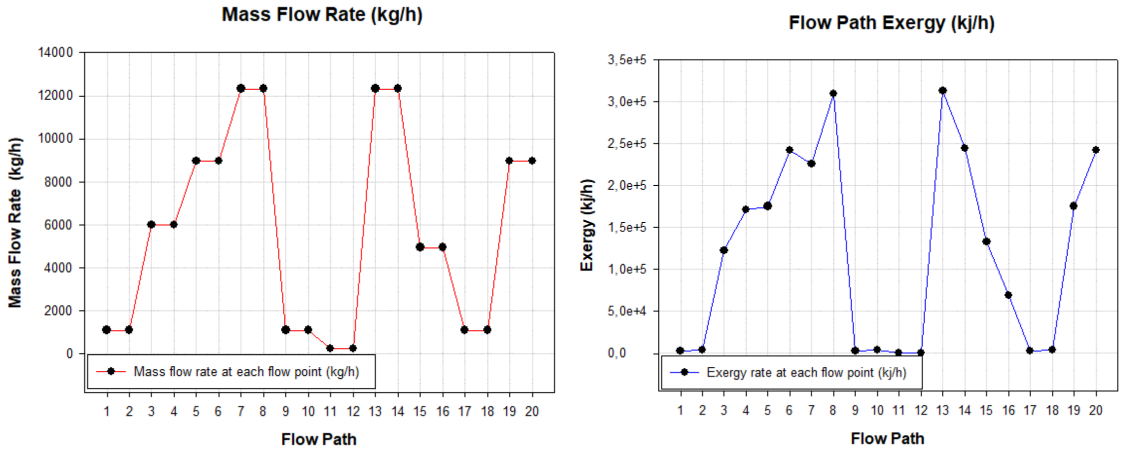



**Fig 15.** System path flow and exergy change

The exergy destruction flow diagram of the system is demonstrated in Fig 16a. This diagram and related data

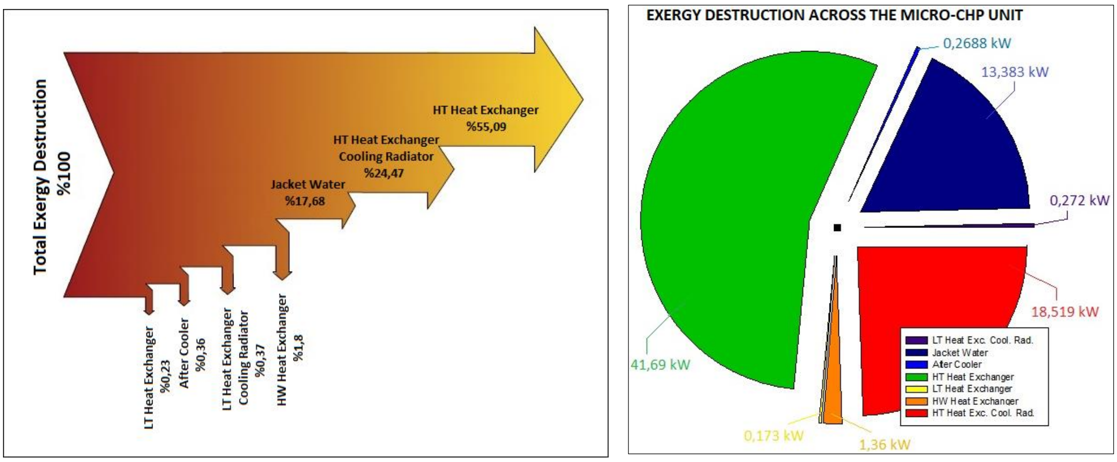



**Fig 16.** Exergy destruction distribution through the micro-CHP unit as a) percentage b) in kW

provides information about inefficiencies across the system that requires improvement. The exergy destruction in the high temperature heat exchanger was found to be around 55%, which led to the conclusion that this unit should be examined carefully. Furthermore, exergy losses of each unit are indicated in kW in Fig 16b. It can be seen that the highest exergy destruction rate takes place in the high temperature heat exchanger as 41.69 kW. Maximum efficiency increase can be achieved throughout the system by improving this relatively inefficient unit.

In Fig 17, the second law efficiencies of micro-CHP system sub-parts are shown. As can be seen that the efficiency of high temperature heat exchanger with the lowest efficiency with 63.7% affects the overall system efficiency adversely. Therefore, performing improvements toward this component would positively contribute to the system performance. In this way, output water temperatures would increase from 80°C to 90°C as the outlet of the hot water exchanger is between 70°C and 90°C. This would lead to extract more useful energy with less NG consumption. Thus, since the energy performance of the installed system would increase, and therefore, return of investment period would be shortened

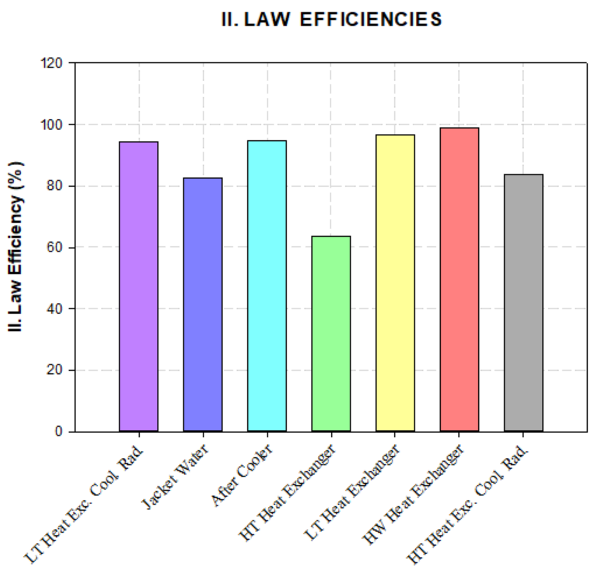



**Fig 17.** Second law yields of cogeneration system units

The temperature and exergy formation of the flow path points of the micro-CHP system are shown in Fig 18. As shown in the figure that HT (high temperature) heat exchanger with flow path numbers 5, 6, 7 and 8 came to the fore in terms of having high level of exergy change. As can be seen in Fig 18, there has been an increase in exergy with temperature increase, but exergy destruction increases from the high heat loss rate, which decreases the efficiency of the related part.

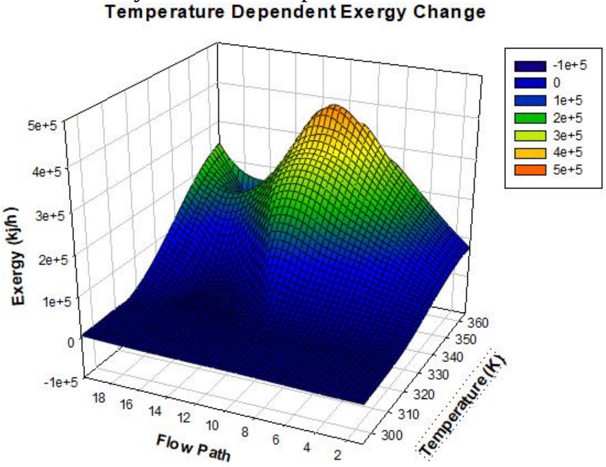



**Fig 18.** Exergy change depending on the temperature of the current path points

The thermodynamic analysis of the micro-CHP subcomponents was carried out with EES software and the system efficiencies with respect to exergy destructions are illustrated in Fig 19. The analysis also highlights the improvement points throughout the system. The highest exergy destruction and the lowest efficiency are detected in the HT heat exchanger while the lowest exergy destruction and the highest efficiency are found to be in the hot water exchanger. Therefore, the way to improve the efficiency of the micro CHP system installed is to improve the HT heat exchanger.

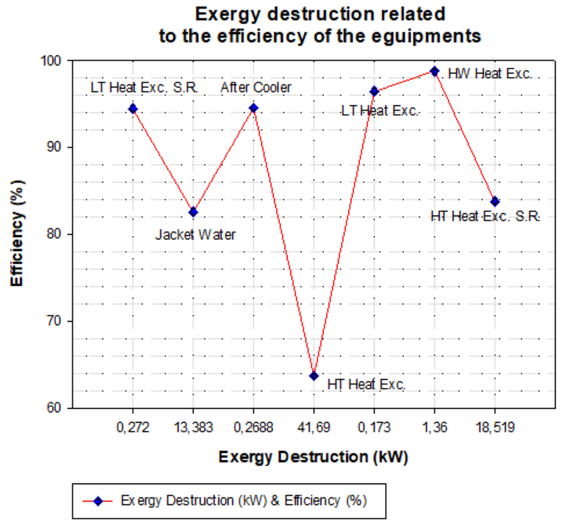



**Fig 19.** Exergy destructions corresponding to the system efficiencies

### 4.3. Enthalpy and Entropy analysis

The enthalpy and entropy ratios of each point on the energy flow path of the micro-CHP system were determined and visualized in Fig 20. The temperature of each current path point varies while the system pressure is fixed at 10 bar. Enthalpy and entropy values of system flow path points were determined separately under these temperature and pressure conditions. While these are used to determine the exergy value of each point, it also provides the exergy destruction and efficiency of each system sub-component.

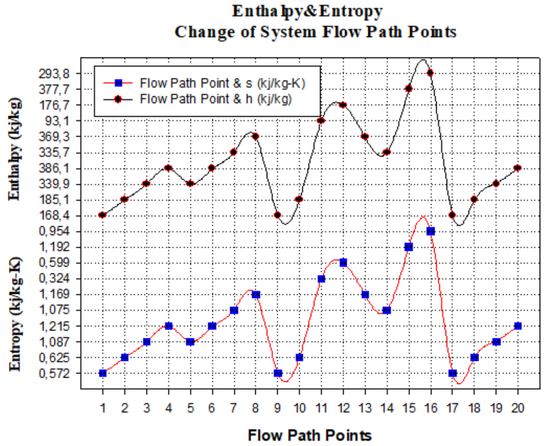



**Fig 20.** Enthalpy and Entropy values of system flow path points

The change in entropy values of $CO_2$, $H_2O$, $N_2$ and $O_2$ gases at 25°C and 700°C, are shown in Fig 21. It is exposed that entropy, known as the measure of disorder, tends to increase with temperature. With the changes in the entropies of gases at 25°C and 700°C temperatures, flue gas exergy destruction is calculated. In this way, efficiency can be enhanced by determining the improvement points in the micro cogeneration system.

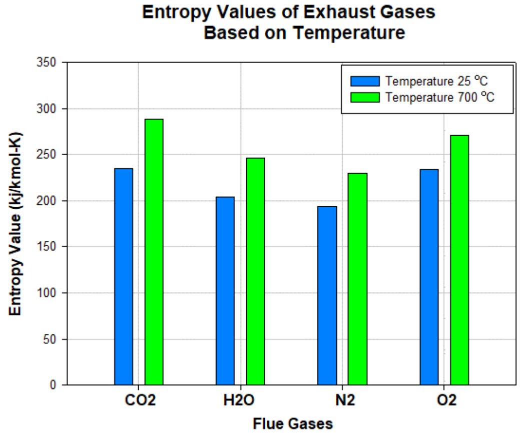
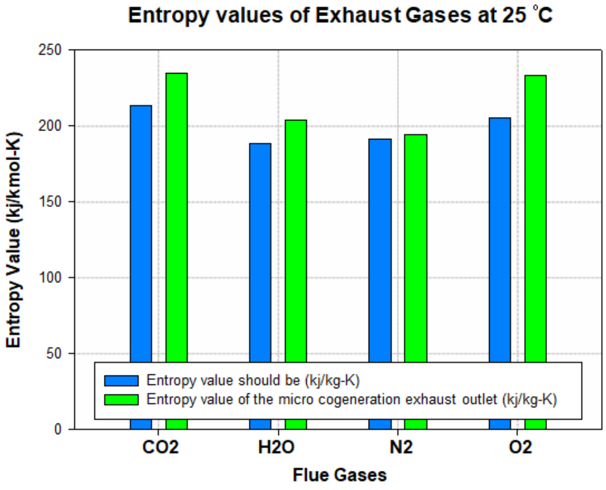



**Fig 21.** Entropy Values of Exhaust Gases Based on Temperature

There is a slight difference between the values of exhaust gases at 25°C and 700°C under normal conditions and the entropy values of the installed system. This is illustrated in Fig 22. In other words, since the molar weights of each flue gas ($CO_2$, $H_2O$, $N_2$ and $O_2$) in the exhaust channel vary under variable ambient conditions, the entropy values of the micro cogeneration exhaust outlet gases differ slightly, although the temperature remains unchanged. This difference allows to obtain flue gas entropy



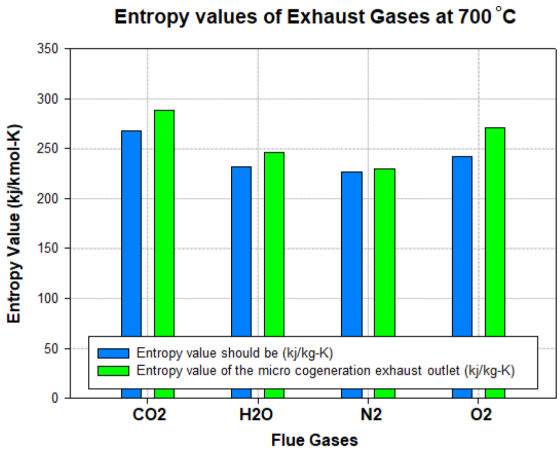
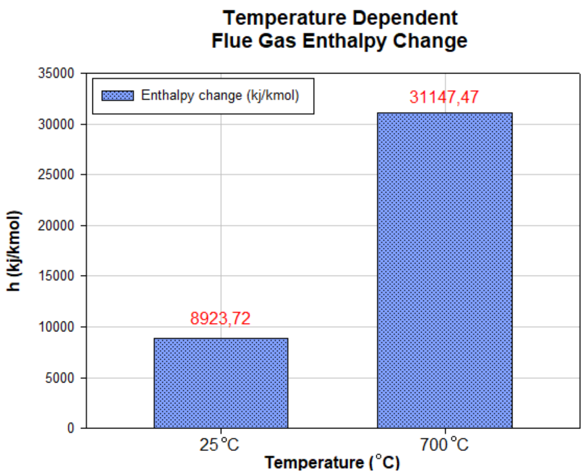




**Fig 22.** Entropy changes of exhaust gases at 25 °C and 700 °C

The calculated enthalpy and entropy changes of $CO_2$, $H_2O$, $N_2$ and $O_2$ gases at 25°C and 700°C are shown in Fig 23a and 23b. The sum of the enthalpies of each gas relative to the molar weight ratio gives the enthalpy of the flue gas per mole. Therefore, the value of enthalpies at 25°C and 700°C varied substantially. This difference is shown in Figure 23a. Likewise, the entropy value of each gas was found with respect to the molar weight ratios of the gases per mole of the flue gas and the these values at 25°C and 700°C varied as expected. This difference is demonstrated in Fig 23b. As a result, the greater the difference between the temperature-dependent flue gas enthalpy and entropy values, the higher the flue gas exergy.

## 4.4. Economic Analysis

In micro-CHP applications, there are various operating scenarios with different capacities based on heat and electricity. The higher the annual working hours of the cogeneration system, the greater the savings. Depending on the amount of heat and electrical energy produced, the payback period is extended or shortened. In the current structure, the system is based on an electric energy scenario rather than heat load that can be domestically consumed. In this way, all of the produced electrical energy is used in domestic consumption and the generated heat is recovered for heating or domestic hot water use. Related data based on the measurements on the CHP module are given in Table 5. According to the data, the return time of the investment is 5.48 years. It is worth noting that the projections are dependent on the current electricity and gas costs and currency exchange rate as well.



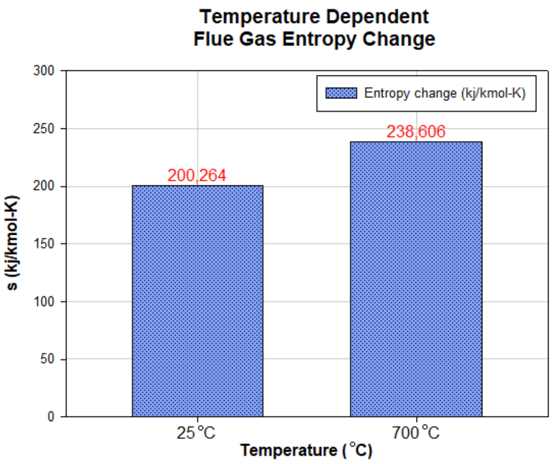




**Fig 23.** a) Enthalpy and b) entropy formation with respect to the flue gas temperature

**Table 1.** Application data on the CHP unit

| **Parameters** | | | |
|---|---|---|---|
| Number of apartments | 137 + 4 | | |
| Daily period of operation | 15 h | | |
| Data collection period | 980 h | | |
| Internal consumption | 1 kW/h | | |
| **Capacity** | | **Efficiency** | |
| Electrical power | 71 kWe | Electrical | %34,3 |
| Thermal power | 116 kWt | Thermal | %56,4 |
| **Economic indicators** | | **Investment cost** | |
| Maintenance cost | 0,4 $/h | Transformer and infrastructure investment cost | $ 101,694.00 |
| Monthly profit per apartment | $ 22,10 | Device cost | $ 91,525.00 |
| Total monthly profit (all site) | $ 3,115.93 | Counter cost | $ 11,949.00 |
| RoI | 5.48 years | **TOTAL** | **$ 205,168.00** |
| Percentage of residents' monthly earnings per year | %15,34 - %34 | | |

**Table 6** Economic performance of the residential type micro-cogeneration unit

| | **CHP PERFORMANCE DATA** | | | | | |
|---|---|---|---|---|---|---|
| **w/o CHP** | POWER GENERATION IN CHP | Electricity generation | kWh | 46,849.00 | **Economic Return of CHP** | **$ 40,643.62** |
| | | Unit price of Electricity (for sale) | $ | 0.157 | | |
| | | Electricity contribution of CHP | $ | 7,368.79 | | |
| | HEAT RECOVERY IN CHP | Thermal energy | kw | 115 | | |
| | | Adjusted consumption | m3 | 13,98 | | |
| | | Economic value of total heat gain | $ | 4,645.81 | | |
| | ELECTRICITY CONSUMPTION OF BUILDING | Total electricity consumption of the building | kwh | 39,775.00 | | |
| | | Unit price of Electricity | $ | 0,157 | | |
| | | Electricity consumption w/o CHP | $ | 6,256.13 | | |
| | NG CONSUMPTION IN BOILER | Thermal Energy consumption w/o CHP | m3 | 66,000.00 | | |
| | | Unit price of NG | $ | 0,338 | | |
| | | NG consumption w/o CHP | $ | 22,372.88 | | |

Table 6 presents the economic performance chart of the micro-CHP system in October and November in the year of 2016. Comparing to conventional systems, the total economic return of the CHP system for two months was $6,232.50 given that monthly amount was $3,116.25. Also, the monthly economic return per apartment was around $22,10, respectively

| CHP PERFORMANCE DATA | | | | | | |
|---|---|---|---|---|---|---|
| w/ CHP | NG CONSUMPTION OF CHP | NG consumption | $ | 6,830.33 | Lump sum of CHP | $ 34,411.11 |
| | | | | | | |
| | | | | | | |
| | ELECTRICITY CONSUMPTION OF CHP | Electricity consumption | kW/h | 1,00 | | |
| | | Unit price of Electricity | $ | 0,118 | | |
| | | Total Consumption expense | $ | 116,27 | | |
| | | | | | | |
| | O&M COST | Unit price of maintenance cost (h) | Euro | 0,35 | | |
| | | Maintenance cost | $ | 453,45 | | |
| | | | | | | |
| | NG CONSUMPTION IN BOILER | NG consumption for heating | m3 | 66,000.00 | | |
| | | Unit price of NG | $ | 0,338 | | |
| | | NG consumption w/o CHP | $ | 22,372.88 | | |
| | ELECTRICITY CONSUMPTION IN BUILDI | Electricity consumption w/o CHP | kW/h | 39,775.000 | | |
| | | Unit price of Electricity | $ | 0,118 | | |
| | | Electricity consumption w/o CHP | $ | 4,638.16 | | |
| **Net Profit** | | | | | | **$6,232.50** |
| **Profit per month** | | | | | | **$3,116.25** |
| **Monthly profit per apartment** | | | | | | **$22,10** |

### 4.5. Environmental Analysis

Fig 24 shows the seasonal amount of $CO_2$ emission prevented due to the use of CHP. Daily average data is taken into consideration in the graphs. As the system is ultimately prevents the reduction of more greenhouse gas emissions. As $CO_2$ is the most deadly gas among others released from the CHP system, therefore, the analysis have been carried out based on $CO_2$ emissions.

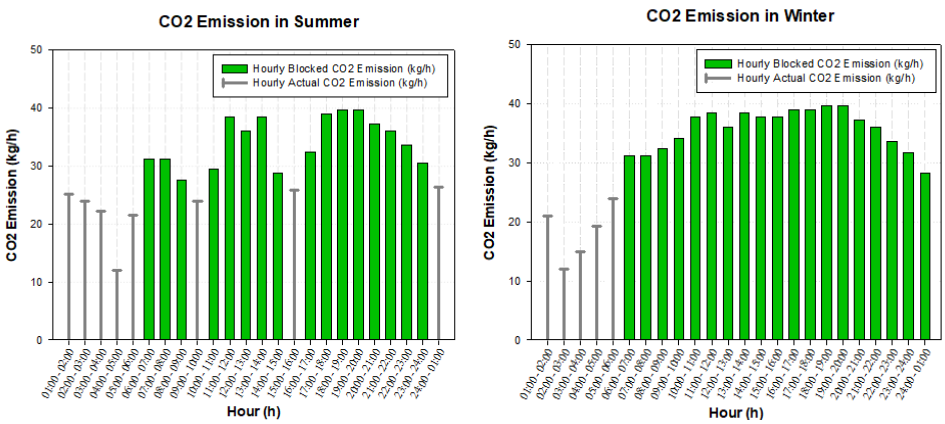



**Fig 25.** a) summer season b) winter season CO2 emission of the CHP system

in sleep mode at nights, electricity is drawn from the grid. Therefore, the equivalent amount of $CO_2$ released into the environment is indicated in kg per hour. Since the energy used in the daytime is produced efficiently by the micro-CHP system, the amount of greenhouse gas emission prevented is shown as well. It was determined that the CHP prevents more $CO_2$ emission in winter than the summer season related to operating under full capacity. In other words, as the CHP system operation is intermittent during the summer season, this causes the system introduced into the sleep mode often, which

## 5. CONCLUSION

In this study, a micro-CHP system applied in a multi-family residential building is assessed in terms of energy, exergy, economic and environmental aspects (4E). The key findings are outlined as follows;

The ambient conditions in the installation site have significant impact on the power production. Although maximum power rating of the micro cogeneration is 71 kW but it was not possible to exceed 65 kW due to the altitude of Konya city. As the altitude increases, the oxygen rate decreases which reduces the device performance. Therefore, the altitude effect must be considered before installation and the power must be determined according to the location where CHP is installed. Otherwise, energy production will be below the expected power, which will have direct impact on the investment return time.

The heat capacity of the CHP system should not exceed 15% of the heat required by the building. Otherwise, the time spent in sleep mode will decrease the performance of the system, as the system will be over capacity.

Due to in-situ energy generation, the elimination of electrical energy transmission and distribution losses is ensured through CHP systems. In addition, consumers are exempted from certain taxes.

Moreover, the payback period is relatively short due to its low operating cost and continuous operation.

Micro-CHP systems offer uninterrupted, high quality and high efficiency energy production by operating with propane, landfill gas, biogas etc. fuels. It is an environmentally friendly system with low exhaust gas emissions and high combustion efficiency. $CO_2$ emission is low since it obtains the same amount of energy by consuming less fuel. There is no dust and sulphur emission. Since waste heat recovery is provided, it does not heat the atmosphere unlike conventional systems.

## DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

## AUTHORS' CONTRIBUTIONS

**Mehmet KAPLAN:** Performed the experiments and analyse the results, Writing—original draft preparation.

**Mahmut Sami BÜKER:** Conceptualization, Supervision, Writing—review and editing.

## CONFLICT OF INTEREST

There is no conflict of interest in this study.

**Abbreviations**

| | | | |
|---|---|---|---|
| CHP | Combined heat and power | $h_0$ | Specific enthalpies of the flows at the restricted dead state |
| EES | Engineering Equation Solver | $c_{p,w}$ | Specific heat of water |
| HT | High temperature | $T_0$ | Temperature of restricted dead state |
| IC | Internal combustion | $T_{jw,HE,in}$ | Water temperature at inlet |
| LHV | Lower heating value | $T_{jw,HE,out}$ | Water temperature at outlet |
| IHE | Internal heat exchanger | $T_{eg,HE,in}$ | Water temperature at inlet |
| NG | Natural gas | $T_{eg,HE,out}$ | Water temperature at outlet |
| PEMFC | Proton exchange membrane fuel cell | $\dot{m}_{fuel}$ | Mass flow rate of the fuel |
| PHE | Plate heat exchanger | $\dot{m}_{hot}$ | Mass flow rate of hot water |
| PES | Primary energy saving | $I_{out}$ | Output current |
| SOFC | Solid oxide fuel cell | $V_{out}$ | Voltage output |
| $CO_2$ | Carbon dioxide | $\dot{W}_{el}$ | Electrical power output |
| $H_2O$ | Water vapor | $r_{el\_th}$ | Ratio of electricity to thermal heat recovery |
| $N_2$ | Nitrogen gas | $\eta_{el}$ | Electrical efficiency |
| $O_2$ | Oxygen gas | $\eta_{total}$ | Overall efficiency |
| $\dot{Q}_{fuel}$ | Heat power supplied by the fuel | $E_{p,CS}$ | Primary energy consumption of cogeneration systems |
| $\dot{Q}_{jw,HE}$ | Heat from jacket cooling | $E_{p,CHP}$ | Primary energy consumption of conventional systems |
| $\dot{Q}_{eg,HE}$ | Heat from exhausted gases | $E_{elec}$ | Electricity consumption |
| $Q_{NG}$ | Energy input of natural gas | $E_{NG}$ | Natural gas consumption |
| $X_{TM}$ | Thermo-mechanical exergy | $s_i$ | Entropy of flows at the system |
| $X_{CH}$ | Chemical exergy | $s_0$ | Entropy of flows at the restricted dead state |
| $X_{heat}$ | Exergy related with a given quantity of heat | $CO2_{elec}$ | Carbon dioxide emissions from electricity |
| $X_{tot}$ | Total exergy | $CO2_{NG}$ | Carbon dioxide emissions from natural gas |
| $\psi_i$ | Flow exergy | $CO2_{baseline}$ | Carbon dioxide emissions for cases without CHP |
| $h_i$ | Specific enthalpies of the flows at the system | $CO2_{CHP}$ | Carbon dioxide emissions for cases with CHP |

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