

Proceeding Paper

Modeling and Optimizing the Performance of an Industrial Trigeneration Unit [†]

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Abstract: Trigeneration provides an effective means of power, heat, and cold production on-site. Proper design and well-managed operation of such units can bring in substantial savings in consumed primary energy as well as in the amount of greenhouse gases released to the atmosphere, compared to separate production of all three media. The studied sub-MW-sized trigeneration unit comprises an internal combustion engine combined with an absorption chiller and a heat management system, delivering all three media to a nearby industrial facility. A mathematical model is developed based on available design and process data, a profit function is set up, and subsequent sensitivity analysis of economic parameters is realized. Lowered efficiency of summer operation is analyzed, and a suitable solution is proposed; with estimated total investment cost of 114,000 € and anticipated simple payback period less than 2 years.

Keywords: trigeneration; natural gas; waste heat; process data; cold production; profit function; energy efficiency

1. Introduction

Constant increase in energy prices forces consumers to operate more efficiently and in a more sustainable way. The industry sector in the European Union was responsible for 26.1% of the total energy consumption in 2020, with electricity and natural gas making up more than 60% (6000 PJ) [1]. Therefore, it is important to reduce the use of energies and fuels. Additionally, due to the developing environmental crisis, it is crucial to decrease the production of greenhouse gas emissions. Trigeneration is a combined cooling, heating, and power (CCHP) production from one or more energy sources. A common trigeneration unit consists of a cogeneration unit (CHP) in combination with an absorption chiller [2]. The sources of energy in CCHP vary from fossil fuels, e.g., oil, coal, or natural gas (NG), to renewables [3]. Additionally, it depends on whether the unit is installed in a residential sector, a small industrial sector, or in a large industry. Design and management of the trigeneration unit is a challenging task because the heat and cold consumption in both industrial and residential applications vary on an hourly or daily basis [4,5].

Alongside an increased overall efficiency, CCHP also offers a reduction in greenhouse gas emissions [6,7]. Usually, the overall efficiency of CCHP varies from 80% to 93% [8] and the efficiency of the CHP itself can reach 80% [3,6]. For a comparison, a conventional power plant where no heat or cold is produced reaches an efficiency from 27% to 40% [9,10]. A decreased CCHP efficiency may result from off-design operation and may negate the expected economic and environmental benefits. An example of this is summer operation, when space heating is not required, and cold production unit is unable to consume heat produced at the nominal CCHP load.

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This work analyzes the operation of an industrial trigeneration unit and proposes means of its improvement by debottlenecking the current design. A simple linear model is developed to describe the main features of the CCHP operation, yielding a profit function and enabling profit maximization.

2. Materials and Methods

The analyzed trigeneration unit and the related heat and cold consumers located in an industrial facility are schematically depicted in Figure 1. Two identical internal combustion engines are operated in the CHP, each with a nominal power output of 250 kW and a heat output of 362 kW, respectively. The absorption chiller produces up to 618 kW of cold with the related coefficient of performance of 0.836. Hence, it can consume all the heat obtainable from combustion engines to produce chilled water. A plate heat exchanger with rated capacity of 350 kW is installed as a heat killer, i.e., an emergency solution for summer conditions with low consumption of both heat and cold.

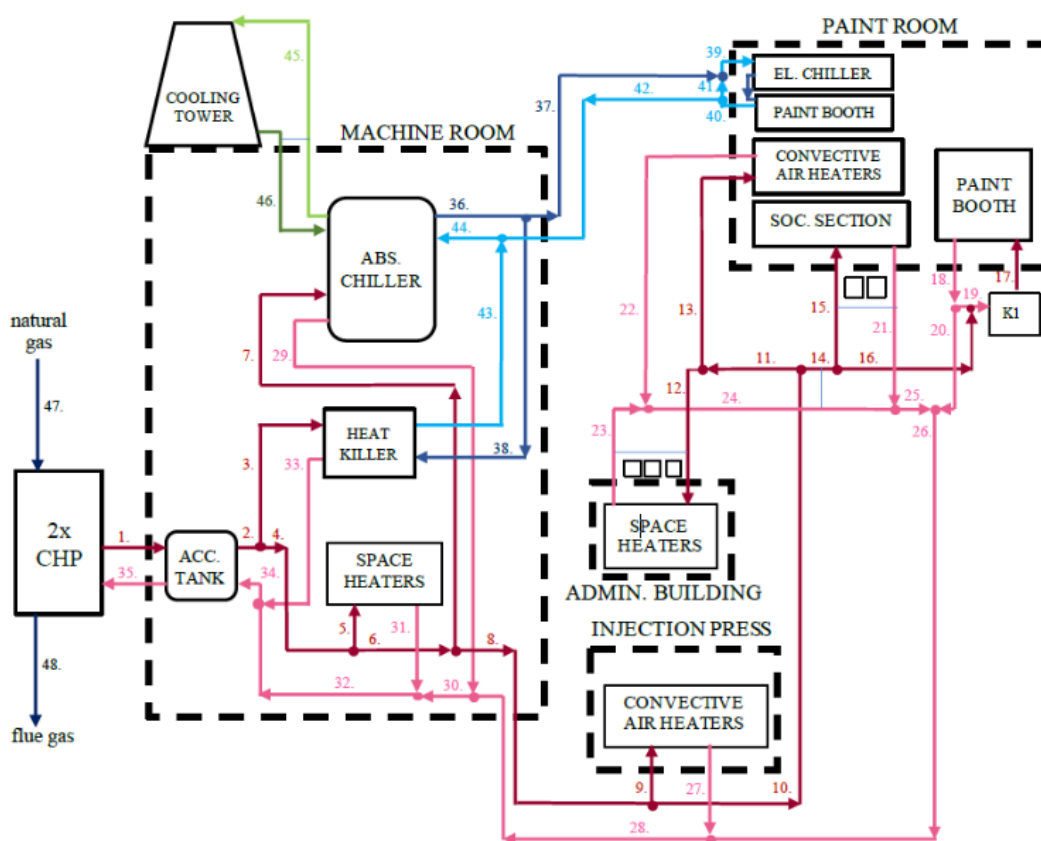


Figure 1. Depiction of the trigeneration unit layout and heat and cold consumers. ABS = absorption, ACC = accumulation, ADMIN BUILDING = offices, CHP = cogeneration unit, EL = electric, K = boiler, SOC = social. Colors: red and pink = hot water pipelines, blue = chilled water pipelines, green = cooling water, dark blue = natural gas and flue gases. Source: own elaboration.

According to the trigeneration unit operators, installation of the heat killer in the past partially helped to solve the problem, but the unit operation is still not optimal. The insufficient heat consumption results in high temperatures of the return water flowing to the CHP, which then results in an emergency shutdown of the CHP. This issue could be solved by decreasing the CHP electricity production, but the plant’s goal is to produce as much electricity as possible. Thus, if the temperature of the return water is too high, the operation of the CHP at full power cannot be guaranteed. As a solution, an emergency air cooler enabling the disposal of all heat produced by the CHP at maximal power production (500 kW) is proposed and designed.

Design procedure was adopted from [11,12] for summer on-site conditions: temperature of 32 °C, air pressure of 97 kPa. The associated total investment cost (TIC) estimation proceeded via guidelines provided in [13]. The TIC was converted to current equipment prices by the latest known Chemical Engineering Plant Cost Index (CEPCI) value of 799.1, valid for March 2023 [14]. Hourly profit values obtainable by emergency air cooler operation were determined as the difference in the profit function values, Equation (1), valid for the actual (representative summer period operation data available from 1 July to 11 September) and the maximal power production. Seasonal profit was obtained by summing the hourly profit values over the whole representative summer period. Single payback period was estimated as a ratio of the TIC and the seasonal profit.

The profit function was constructed to define the optimal trigeneration unit operation at various heat and cold demands as shown in Equation (1):

$$\text{PROFIT} = P_{\text{EE CHP}} + P_{\text{EE CHILLER}} + C_{\text{heat}} + C_{\text{CO}_2 \text{ technology}} - C_{\text{NG}} - C_{\text{CO}_2 \text{ CHP}} \quad (1)$$

where PROFIT is the calculated profit (€·h⁻¹), $P_{\text{EE CHP}}$ is the income from electricity produced by the CHP (€·h⁻¹), $P_{\text{EE CHILLER}}$ is the income from electricity saved in the electric chiller (€·h⁻¹) by producing cold in the absorption chiller instead, C_{heat} is the income from heat produced by the CHP (€·h⁻¹) substituting the heat production in a separate gas boiler in the technology, $C_{\text{CO}_2 \text{ technology}}$ is the income from CO₂ emissions avoided in the separate gas boiler in the technology (€·h⁻¹), C_{NG} is the cost of natural gas consumed in the CHP (€·h⁻¹), and $C_{\text{CO}_2 \text{ CHP}}$ is the cost of CO₂ emissions produced by the CHP (€·h⁻¹). Individual items in Equation (1) were calculated as the product of calculated production (MWh·h⁻¹, t·h⁻¹) and the unit price (€/MWh⁻¹, €/t⁻¹) of the given energy or medium. Heat and cold production were estimated as functions of power produced by the combustion engines based on their datasheets. Reduction of the power consumption in the electric chiller, $P_{\text{EE CHILLER}}$, was estimated as the ratio of cold production in the absorption chiller and the energy efficiency ratio of the electric chiller (which, according to the datasheet, equals 3.2). An emission factor of 2.75 t of CO₂ per 1 t of natural gas was considered in the calculations. The following price ranges were tested: electricity 100 to 450 €/MWh⁻¹, natural gas 25 to 180 €/MWh⁻¹, CO₂ 65 to 105 €/t⁻¹.

3. Results

Figure 2 shows values of the profit function for two extreme cases of CCHP operation: a. at the minimum possible power production (130 kW), and b. at the maximum power production (500 kW). The figure was constructed assuming the following model prices: 370 €/MWh⁻¹ for electricity, 35 €/MWh⁻¹ for NG, and 85 €/t⁻¹ for CO₂.

As can be seen, profit of the trigeneration unit increases with both increasing the heat production for space heating and technology and increasing heat delivery to the absorption chiller. However, producing cold in the absorption chiller is economically more attractive, regardless of power production. This leads to a defined hierarchy of optimal heat production and use, depicted in the form of a decision diagram for plant operators in Figure 3. This diagram is valid for model prices of energies and media; however, it can be updated based on the profit function analysis for any combination of prices.

The air cooler design yields two identical units with two fans per each unit, nominal cooling air flow per fan of 15 m³·s⁻¹, and total nominal power consumption of 8 kW. Anticipated TIC reaches 114,000 € and, with the model prices of energies and media, the seasonal profit reaches almost 65,000 €. The resulting expectable single payback period is around 2 years.

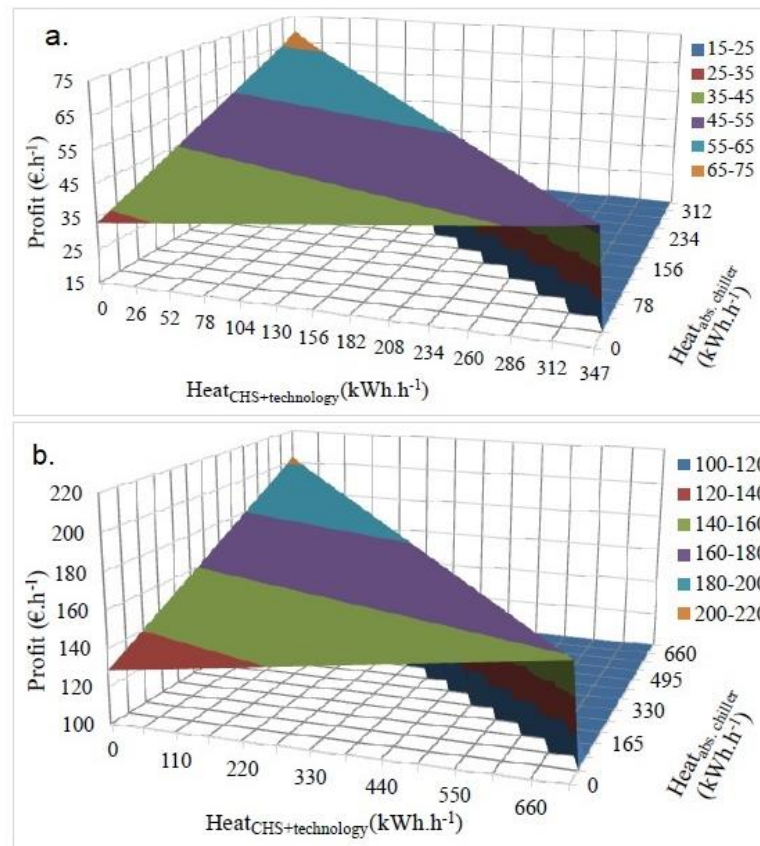


Figure 2. Profit function values as a function of the heat production for space heating (CHS) and technology and the heat consumption in the absorption chiller for a. minimal (130 kW) and b. maximal (500 kW) power production. Abs = absorption, CHS = space heating. Source: Own elaboration.

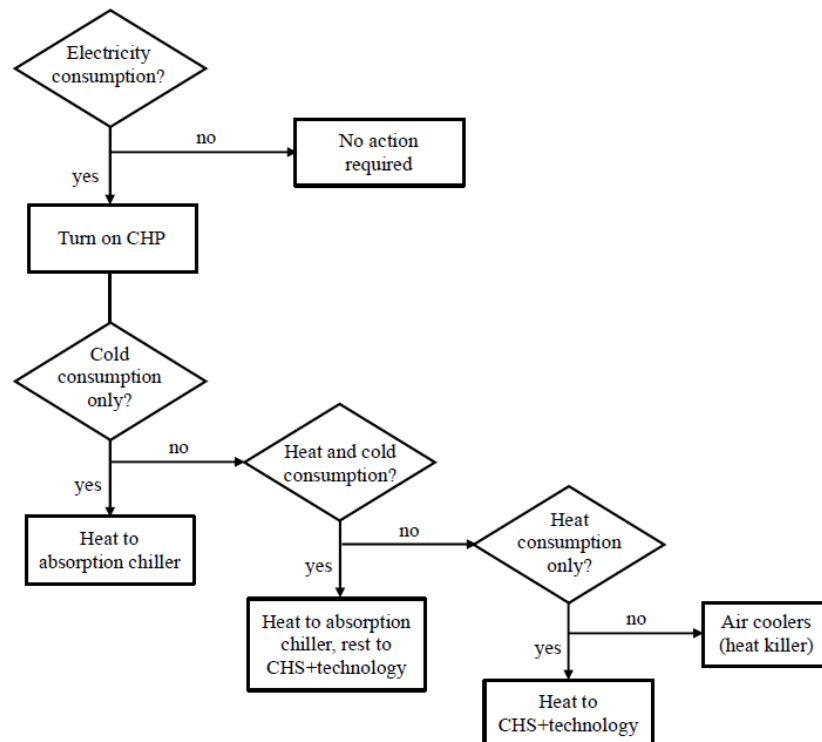


Figure 3. Decision diagram for optimal trigeneration unit operation valid for model prices of electricity. CHP = cogeneration unit (internal combustion engines). Source: Own elaboration.

4. Discussion

Figure 2 shows the profit function values for model prices, reflecting the prices currently valid for the industrial site within which the trigeneration unit is located. As can be recognized, the price ratio of electricity and natural gas exceeds the value of 10, which favors power production maximization even with zero heat delivery. This means the unit may operate in a purely power-plant mode as the favorable economics prevails over energy efficiency and environmental issues [15]. This fact is also reflected in Figure 3 which always recommends cogeneration unit being in operation. Even if the on-site power demand is low, the excess power can be exported to the outer grid. The second-in-hierarchy question is whether a fraction of the heat from the internal combustion engines could be used to produce cold in the absorption chiller. This way, the cold produced in the electric chillers in the technology would be replaced and the facility's power consumption would decrease. The least favorable, yet still viable and, therefore, being placed the lowest in the hierarchy, is the option to use the available heat for space heating and in the technology. As a result of this, the heat produced in the hot water boilers in the technology would be replaced and, thereby, a reduction in natural gas consumption would be achieved.

The discussed situation underlines the pressing need to solve the issues coupled with the summer operation of the unit. During this season, only a part-load operation of the unit is often possible. Eventually, it can even become impossible due to insufficient heat consumption. In the most extreme cases, the difference in profit function may reach almost $100 \text{ €}\cdot\text{h}^{-1}$ when comparing pure electricity production modes (see Figure 2). This explains the significant saving of almost 65,000 € which is achievable by air cooler commissioning and operation in summer, as it enables smooth full-load operation of internal combustion engines even in the pure electricity production mode by disposing of all waste heat. Obviously, with significant power and natural gas price changes [16], the situation may become different, i.e., the true trigeneration mode operation may be preferred to pure power production.

5. Conclusions

The presented study aims at analysis and optimization of a sub-MW-sized trigeneration unit supplying an industrial facility with power, heat and cold. The current layout of the unit hinders its efficient operation in summer due to the absence of a relevant heat consumer and due to the limited capacity of the "heat killer". The resulting part-load operation and frequent emergency shutdowns lower the operation profit and reduce the unit's expected lifetime. Optimal operation conditions are studied based on developed model in the form of a linear profit function. The analysis yields a useful tool for plant operators—a decision diagram—to ensure the most economic plant operation based on a set of hierarchically arranged criteria. Basic design parameters of a new air cooler are obtained and the economics of its installation and summer operation is evaluated; yielding a two-unit design with four air fans in total, internal power consumption of 8 kW, and expected seasonal profit of almost 65,000 €. As a result, an attractive simple payback period of 2 years can be expected.

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