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Utilizing primary energy savings and exergy destruction to compare centralized thermal plants and cogeneration/trigeneration systems

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A B S T R A C T

Rising energy conversion processes efficiencies reduces CO_2 emissions and global warming implications. Decentralized electricity production through cogeneration/trigeneration systems can save primary energy if it operates with high efficiency. High efficiency is obtained when the system produces electricity and a substantial amount of the energy rejected by the prime mover is used to meet site thermal demands. Environmental concerns and international agreements are directing governments of different countries to incentive high efficiency solutions. Centralized thermal plants and cogeneration/trigeneration efficiency are compared through efficiency indicators using the first law of thermodynamics and the second law of thermodynamics. This paper proposes the use of the primary energy savings analysis and the exergy destruction analysis to compare decentralized power production through cogeneration/trigeneration systems and centralized thermal plants. The analysis concluded that both methods achieve the same results if the thermal efficiency indicator is used to compare the methods. The analysis also revealed that trigeneration systems with the same energy input are comparable with quite different thermal efficiency centralized thermal plants. Case 1 is comparable to a 53% thermal efficiency power plant and case 2 is comparable to a 77% thermal efficiency power plant.

1. Introduction

In a world migrating from fossil fuel power generation to renewables, the efficient use of fossil fuels is an important path forward. Governors of different countries are planning, reviewing and implementing actions to incentive energy efficiency solutions. These incentive policies although contributing to reduce the CO_2 emissions need constant review to adjust improvements in methodologies and in efficiency values as the technologies are being developed, the efficiency indicators are better understood and as the initial standards are intended to be easily reached. More stringent standards push the market development. In 2008 the European Union launched a commission decision [1] detailed guideline for the application of cogeneration, the commission decision is an amendment to the directive 2004/8. Gambini at al [2] discussed the implementation of the directive 2004/8 and their amendments in Italy. New York State Energy Research and Development Authority (NYSERDA) has several energy efficiency incentive programs [3].

Natural gas can be used in transport, industrial process, power generation, heating, cooling, etc. Governmental incentive policies should prioritize country strategic areas and CO_2 emission reduction. Methods to compare efficiency of different natural gas uses are not so obvious in some circumstances, and methodologies, assumptions, prediction methods (optimization, simulation, etc), tests, energy efficiency indicators and targets, etc should be used to define the starting point at which the technology is eligible to receive incentives. Frangopoulos [4] discussed the directive 2004/8 and the 2008 commission decision [1] defining efficiency and primary energy savings requirements to be eligible for economic and financial benefits.

Cogeneration/trigeneration studies revealed that it can save energy and contribute to reduce CO_2 emissions. A review of trigeneration systems were developed by Jradi and Riffat [5] and Moussawi et al. [6]. The authors discussed prime mover options, heat recovery units, thermal energy storage, operational strategies, design methods, etc.

Badami et al. [7] developed a study of 11 industrial cogeneration systems. They commented that following the EU Directive 2004/08/EC and the commission decision of 21 december 2006, it was established that high efficiency cogeneration systems higher than 1 MW of electricity, should have a 10% primary energy savings (PES)

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compared with electricity production in centralized thermal plants with a thermal efficiency of 48.6% and heat production with an efficiency of 90%.

Colmenar-Santos et al. [8] discussed the use of cogeneration and district heating networks They concluded that the spread of this technology according to its potential needs change in the market or in the regulation. Soltero et al. [9] studied the potential for cogeneration and district heating in Spain using a top-down bottom-up methodology. Vandewalle and D'haeseleer [10] analysed the impact of a massive penetration of small scale cogeneration on the gas demand at distribution level.

Safaei et al. [11] developed an optimization model to minimize the live cycle costs of building energy demands via a combination of cogeneration, solar and conventional energy systems. Caf et al. [12] proposes the use of engine low temperature energy to boost electrical heat pump performance.

Thermal energy storage (TES) can contribute to rise cogeneration/trigeneration systems efficiency avoiding thermal energy rejection in reduced demand hours and auxiliary energy consumption in high thermal energy demand hours. Rezaie et al. [13] modeled and analyzed the transient behavior during charging and discharging of a fully mixed TES tank. Vandewalle and D'haeseller [10] revealed an evaluation method for perfectly stratified thermal storage tanks (perfect thermocline).

Countries are using different methodologies to evaluate trigeneration/cogeneration performance. Ertesvag [14,15] discussed methods and indicators that are being utilized in some countries. He mentioned that the existing regulations put different emphasis on power generation vs heat production and some of them appear to discourage thermodynamic improvements. Angrisani et al. [16] presented a review of several cogeneration and trigeneration energy efficiency indicators.

The analysis of cogeneration/trigeneration performance can be done based on the first law of thermodynamics and on the second law of thermodynamics. Kanoglu and Dincer [17] presented and discussed cogeneration energy and exergy efficiency indicators. Exergy analyses are being developed for different thermal systems, like heat pumps [18], gas turbines [19], absorption chillers [20] and ventilation systems with desiccant wheel cooling [21]. Thermoeconomic analysis combine exergy and economic methods for analyzing thermal systems [22,23]. Karaali and Orsturk [24] presented a thermoeconomic optimization study of four different cycles utilizing gas turbines.

First law of thermodynamics do not distinguish the energy quality. This limitation restrains the comparison between energy utilization factor - EUF (used to evaluate cogeneration/trigeneration performance) and thermal efficiency (used to evaluate centralized electricity production). The second law of thermodynamics takes into account the energy quality, but simply comparing exergy efficiency of cogeneration/trigeneration systems and exergy efficiency of centralized thermal plants, is not adequate since without a cogeneration/trigeneration system the building or process needs additional energy use to meet their thermal demands (cooling and/or heating). Cogeneration/trigeneration systems performance needs to be compared with the separate production of their products [14,25]. Primary energy savings (PES) are being utilized to compare trigeneration/cogeneration systems with the separate production of electricity, heating and cooling [1,4,7,25–28].

Primary energy consumption is used to reveal the process/building energy use while primary energy savings is used to compare the primary energy consumption of different solutions.

In this paper the authors propose the use of the primary energy savings analysis and the exergy destruction analysis to compare cogeneration/trigeneration systems and centralized thermal plants. Two different trigeneration systems are used, case 1 has an EUF equal to 78.22% and an exergy efficiency equal to 34.88% while case 2 has an EUF equal to 85.4% and an exergy efficiency equal to 41.04%. Both methods revealed to be adequate for the proposed comparison, since efficiency conversion factors are included in the PES analysis and energy quality is taken into account in the exergy destruction analysis. The same results are achieved when utilizing the thermal efficiency indicator for both methods.

2. Trigeneration configuration

To develop the comparison analysis between primary energy savings and exergy destruction, two different configurations of trigeneration systems are used.

The software COGMCI [29] was used to define equipment selection and the system energy balance.

2.1. Case 1

Fig. 1 shows the first trigeneration configuration evaluated here (case 1). Case 1 trigeneration system is suitable for applications with electricity, hot water and chilled water (air conditioning) demand, like hotels, malls, airports, etc. Table 1 shows the mass flow rate, temperature, pressure, enthalpy and entropy of the thermodynamic states in Fig. 1. The properties were obtained using the software EES (engineering equation solver). In Table 1 the enthalpy value of the fuel is the fuel LHV (lower heat value).

The trigeneration system is formed by one internal combustion engine, primary and secondary hot water circuits, one exhaust gas heat exchanger (EGHE), one hot water single stage absorption chiller, and auxiliary equipment (pumps, cooling towers, heat exchangers, etc). The secondary circuit recovers energy from the engine oil radiator and intercoolers and uses it to warm water for sanitary purposes at HE2. The primary circuit recovers energy from the engine jacket, the water is reheated at the EGHE utilizing the energy of the engine exhaust gases, after it is directed to the absorption chiller for chilled water production. Primary circuit energy that is not recovered in the absorption chiller is used to warm water for sanitary purposes at HE1 (after recovery at secondary circuit – HE2).

The engine performance is based on a commercial engine [30] fueled by natural gas with an electric power of 1060 kWe at the full engine load at 1800 rpm. The engine electrical efficiency at the full engine load is 39%. The engine energy balance and exhaust gas flow and temperature was previously used in other study [27]. The total produced electricity is 3% higher than the net engine power, taking into account the use of electricity in auxiliary equipment (parasitic load). A net electric power of 1028.2 kW is produced.

Design temperatures of hot water at the primary and secondary circuits are typical values utilized in engines. Water flows at primary and secondary circuits are designed taking into account the energy rate and the design temperature difference (constant flow). Secondary circuit hot water enters the engine at 35 °C [flow 11] and leaves it at 55 °C [flow 8], while primary circuit hot water enters the engine at 75 °C [flow 7] and leaves it at 90 °C [flow 2]. Sanitary use hot water enters HE2 at 22.2 °C [flow 12] and leave HE1 at 50 °C [flow 15]. Sanitary use hot water recovers energy at HE2 and HE1 in a series arrangement (cascade).

The exhaust gas heat exchanger (EGHE) has a heat loss of 1%. Exhaust gas composition is assumed to be constant. The exhaust gases temperature leaving the EGHE [flow 19] is designed to be 23.7 °C higher than the primary circuit hot water temperature entering the EGHE [flow 2] (approach point).

The absorption chiller (AC) selection is based on performance curves from a manufacturer (Trane Company, 1989) [31]. The selected AC has a nominal capacity of 520 tons (1774 kW) based on