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Experimental development, 1D CFD simulation and energetic analysis of a 15 kw micro-CHP unit based on reciprocating internal combustion engine

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HIGHLIGHTS

- This paper deals with energetic aspects of CHP referring to the study of a 15 kW micro-CHP plant.
- The 15 kW micro-CHP plant is based on a GPL reciprocating engine designed, built and grid connected.
- Some tests were carried out at whole open throttle and the experimental data were collected.
- It was needed to perform a 1D thermo-fluid dynamics simulation of the engine to completely characterize the micro-CHP.
- The analysed solution is particularly suited for supplying energy to residential users, hotel, hospital or sports centres.

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ABSTRACT

Cogeneration is commonly recognized as one of the most effective solutions to achieve the increasingly stringent reduction in primary energy consumption and greenhouse emissions. This characteristic led to the adoption of specific directives promoting this technique. In addition, a strategic role in power reliability is recognized to distributed generation. The study and prototyping of cogeneration plants, therefore, has involved many research centres.

This paper deals with energetic aspects of CHP referring to the study of a 15 kW micro-CHP plant based on a LPG reciprocating engine designed, built and grid connected. The plant consists of a heat recovery system characterized by a single water circuit recovering heat from exhaust gases, from engine coolant and from the energy radiated by the engine within the shell hosting the plant.

Some tests were carried out at whole open throttle and the experimental data were collected. However it was needed to perform a 1D thermo-fluid dynamics simulation of the engine to completely characterize the micro-CHP.

As the heat actually recovered depends on the user's thermal load, particularly from the required temperature's level, a comparison of the results for six types of users were performed: residential, hospital, office, commercial, sports, hotel. Both Italian legislative indexes IRE and LT were evaluated, as defined by A.E.E.G resolution n. 42/02 and subsequent updates, as well as the plant's total Primary Energy Saving.

1. Introduction

Energy supply is one of the most critical elements of developed countries. Increasing welfare levels and the indiscriminate exploitation of global resources create a precarious balance between energy supply and demand. The growing problems related to the pursuit of this balance are accompanied by the environmental impacts inherent in the use of traditional energy sources. Global human activity required a Total Primary Energy Supply (TPES) of approximately 130,000 TWh in 2009, corresponding to an average hourly power of 15 TW [1].

Examination of the individual sources of energy shows that oil contributes one-third to the TPES, coal contributes about one-fourth and natural gas contributes about one-fifth; the remaining 19% is achieved through a mix of different sources, both renewable and non-renewable, in which a significant role is played by nuclear

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and hydro power, whereas geothermal, solar and wind power make a more marginal contribution (Fig. 1).

At the current rates of extraction, humans may run out of oil sources in a few decades; the remaining resources are estimated at 2.7×105 million m^3 and began to form approximately three hundred million years ago [4]. It is thus evident that the development of an energetic system that is stable, environmentally sustainable and capable of ensuring a more equitable distribution of resources cannot be separated from a more efficient use of energy and an increasing use of renewable energy sources.

Various studies indicate that a reduction in energy consumption of 20% is achievable simply by correcting certain habits and using new technologies. The climatic and environmental consequences of the use of fossil fuels can also be overcome through an immediate transition to the use of renewable sources, which will represent a significant portion of the energy supply in 2035. However, studies conducted as part of the Global Climate Energy Project at Stanford University clearly showed the enormous exergetic potential available and currently unexploited. For example, it is estimated that the full use of geothermal and wind energy could satisfy the global demand several times over. Although hydroelectric and nuclear levels of growth are more theoretical than real, the data on incident solar energy are extremely important. Ground radiation alone could satisfy hundreds of times the current global energy demand in spite of a contribution that, on a global scale, hardly reaches 0.1% [5]. These margins of growth, even if theoretical, are huge, and they may justify the extensive conversion of existing production facilities to an economy based on the exploitation of renewable sources (Green Economy).

In this scenario, with 20% theoretical energy savings achievable in the near future, the widespread application of cogeneration technology could play a key role [6]. The development of a distributed power generation system, which is the logical culmination of the mature and large-scale application of cogeneration processes, could increase the potential reduction of global energy demand.

The study and prototyping of cogeneration plants has thus involved many research centres. Similar activities were carried out by DiME (now DII, University of Naples). These activities also highlighted the need to study the cogeneration system–user interaction to estimate the real energetic and economic benefits. The energetic and economic benefits generated by CHP plants, in fact, depend on plant and use characteristics, plant layout, management strategies, regulatory and tariff contexts. Therefore, the potential benefits that have attracted the attention of the scientific community are not always granted. For this reason, a predictive analysis is needed to find the optimum configuration of the plant (i.e., engine size, plant configuration, management strategies, absorption chiller size, engine number) that approaches the best energetic solution while ensuring a reasonable profit. The achievement of optimal energetic and economic results through combined heat and power plants is a complex problem. In fact, the number of variables involved in the problem could also completely change energetic and cost savings with changes in regulation, tariffs or reference energetic scenarios. For this reason, the determination of the plant optimal configuration needs complex numerical methods [7] often is pursued through a multi-objective approach [8,9].

Many studies [10–12] show how the search for configurations aimed at maximizing the global energy saving leads to the Simple Payback worsening results, confirming the inability to conduct any predictive analysis that disregards the use of numerical simulation methods.

The recognition of the strategic role of combined heat and power (CHP) and the need to rethink the energy supply system led the Department of Mechanical and Energy Engineering (now DII) at the University of Naples Federico II to focus its efforts on the study and prototyping of micro-CHP systems based on internal combustion reciprocating engines. Started in the early 1990s, this study aimed to solve a critical issue facing cogeneration plants: the adoption of an effective system for recovering thermal energy that would otherwise be dissipated [13].

Several prototypes developed through the 1990s have allowed for a deeper understanding of the issues underlying the construction of small CHP plants and led to significant knowledge regarding efficient heat recovery systems. Subsequent improvements led to the development of several LPG spark ignition reciprocating engine plants characterized by a variable electric power output in the range of 3–15 kW. Experimental tests demonstrated the possibility of obtaining higher Coefficients of Fuel Utilization (CFU) through the recovery of condensation heat in the water contained in the engine exhaust gases. However, this research emphasized the need for further study regarding the possibility of utilizing the recovered heat through a CHP system–user interaction analysis. With the use of small engines, assuming the absence of energy integrations, the energetic advantage of a CHP plant can be expressed as follows:

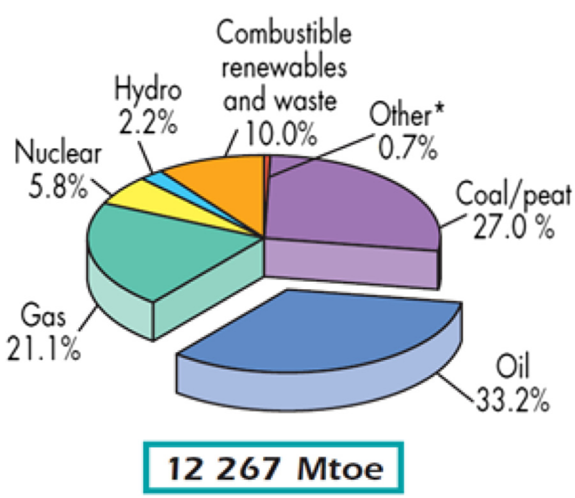

Fig. 1. Fuel shares of TPES in 2008 (142,665 TWh). *Other includes geothermal, solar, wind, heat, etc. [2].

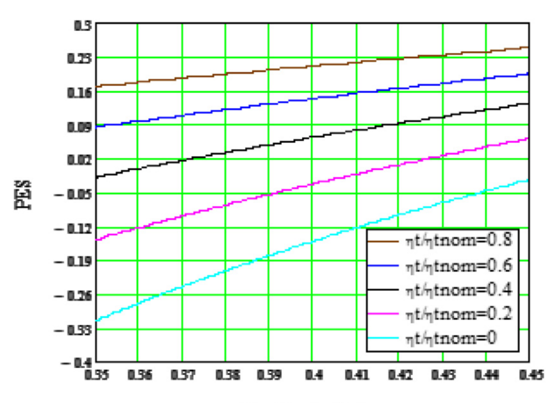

Fig. 2. PESav as a function of the CHP plant electrical efficiency for $\eta_{eREF} = 0.46$, $\eta_b = 0.9$, $\eta_{tnom} = 1 - 0.15 - \eta_e$, and for different values of the effective thermal efficiency η_t. The graph refers to cogeneration plants with reciprocating internal combustion engine. It was assumed that 15% of fuel's potential thermal energy is not recoverable in any way.