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A systematic approach to evaluate the economic viability of Combined Cooling Heating and Power systems over conventional technologies

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ABSTRACT

This paper presents an analytical methodology of evaluating the economic viability of a CCHP system, over three alternative configurations: (1) boiler and electric chiller, which have been extendedly analyzed in literature, (2) boiler and gas driven absorption chiller and (3) reversible heat pump, which have been slightly investigated in comparison with CCHP systems. An adjusted Levelized Cost of Electricity (LCOE) is defined for those cases and used as a decision-making criterion. A sensitivity analysis is carried out to explore the effect of technical and economic data and load characteristics on the LCOE. The viability of the CCHP system is determined by comparing the LCOE with the electricity market prices. Two different economic viability problems are considered: (1) investing viability for new CCHP systems, and (2) operating viability for existing CCHP systems. The results demonstrate interesting interactions and encouraging perspectives, especially when CCHP system is used in combination with conventional technologies like boilers and chillers.

1. Introduction

Cogeneration of thermal and electrical energy is a commonly recognized solution to achieve the European 2030 energy targets, related to improvement in energy efficiency and the reduction of greenhouse gas emissions [1]. Combined heat and power (CHP) or combined cooling, heat and power (CCHP) systems generate electrical, and useful thermal and cooling energy on-site or near site, by converting about 80–85% of the fuel into useful energy. In this way, compared to conventional energy production, they offer a number of advantages to end-users, including high efficiency, economic, environmental and reliability benefits [2,3].

In general, cogeneration is designed either to be installed as an autonomous and stand-alone system covering fully the energy needs of the user, or to be added to an existing configuration in order to improve energy cost and gas emissions. This work focuses on the latter category. Among the conventional systems, the gas boiler for heating and the electric chiller for cooling are those that are usually examined. However, apart from these, there are also alternative systems that gain interest during the years, like the gas driven absorption chiller for cooling and the reversible heat pump for both heating and cooling, which is lately gaining a lot of interest.

The economic viability of CHP plants has always been a point of debate. Although cogeneration is recognized as the most energy efficient way to produce useful forms of energy from fossil fuels, decision makers are frequently hesitant in investing, or even in operating it. Even when the market gives the right price signals, the estimation of cogeneration feasibility depends on numerous factors and numerous estimation methodologies, which repel investors seeking less complicated and certain projects. A literature research on this field, pointed out some of the most common factors that seem to affect the viability of CHP systems.

A large number of authors examines the impact of different types of prime movers on the feasibility of cogeneration plants [4–7]. The technologies that are usually investigated are: the internal combustion engine, combined cycle, gas turbine, microturbine and Stirling engine. Furthermore, high emphasis is given lately in the penetration of fuel cells, an alternative option which leads to high electrical efficiencies [8–11]. All the above technologies have the flexibility to operate with various fuels with the most common to be the natural gas, propane and biogas, while fuel cells additionally can also use methanol and hydrogen [12,13]. The kind of prime mover often depends on the size of the required CHP unit, and therefore, on the type of facility, which specifies the load

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Nomenclature

C_e	Grid electricity cost (€/MWh)
C_{eq}	Equipment cost (€/W)
CF	Capacity factor (-)
C_g	Natural gas cost (€/MWh)
C_m	Maintenance cost (€/MWh)
COP_a	Coefficient of performance of absorption chiller (-)
COP_c	Coefficient of performance of heat pump for cooling (-)
COP_e	Coefficient of performance of electric chiller (-)
COP_g	Coefficient of performance of gas chiller (-)
COP_h	Coefficient of performance of heat pump for heating (-)
CRF	Capital recovery factor (-)
E	Electricity produced by the cogeneration (MWh)
E_{ae}	Avoided electricity from electric chiller (MWh)
E_{ahpc}	Avoided electricity from heat pump for cooling (MWh)
E_{ahph}	Avoided electricity from heat pump for heating (MWh)
f	Cogeneration recovery heat fraction to cooling (-)
G	Natural gas spent by the cogeneration (MWh)
G_{ab}	Avoided natural gas from boiler (MWh)
G_{ac}	Avoided natural gas from gas chiller (MWh)
i	Cost of capital (-)
$LCOE$	Levelized cost of electricity (€/MWh)
N	Project lifetime (y)
η_b	Boiler efficiency (-)
η_e	Cogeneration electrical efficiency (-)
η_{th}	Cogeneration thermal efficiency (-)
Q_c	Useful cooling energy produced from cogeneration (MWh)
Q_h	Useful thermal energy produced from cogeneration (MWh)
t_y	Annual operating time (h)

Abbreviations

CCHP	Combined cooling, heating and power
CHP	Combined heat and power
LCOE	Levelized cost of electricity

characteristics of the system.

The examination of cogeneration viability for different types of facilities (load characteristics), is also a subject that has been extensively investigated in literature. In general, the most popular applications of cogeneration belong to the so called MUSH market (municipalities, universities, schools, hospitals), as well as large residential complexes, since they have both thermal and cooling demands during the winter and summer, respectively [7,14–16]. Moreover, the adoption of small and micro CHP units for smaller-scale uses is also being encouraged by national governments with the aim to meet energy and social targets like greenhouse gas emissions, reduced energy cost to users, energy security, and higher reliability [11,17–19]. Nevertheless, cogeneration can also be met in industrial or other special facilities, where there is need for heating and/or cooling [20–22]. In fact, topping-cycle CHP systems are broadly used in large industrial applications which require either large amount of mid/low pressure steam or cooling load.

Apart from the technical and load characteristics, there is a lot of effort focused on the influence of the regulatory framework of each country on the cogeneration viability [14,23–25]. The evaluation approaches that are generally met concern either the comparison of different incentives policies among various countries, or the viability of CHP systems in a specific country in regards to various policy support mechanisms. In this way, the regulatory framework can be evaluated, the barriers of each case study can be identified, and specific proposals can be done in order to improve the existing promoting policies.

The regulatory framework of renewables and cogeneration in each country is determined according to the structure of the electricity market. Despite the efforts for developing an attractive and fair framework for the decision makers, the regulatory investment risk always exists, especially in liberalized electricity markets. For this reason, the CHP viability assessment in evolving markets has become a topic of broad and current interest [25–28].

The methodology that is commonly used in such studies, is the development of a model which calculates the economic viability of cogeneration, in terms of simple payback period, net present value, internal rate of return [3–7,20,21,23–30], and recently, Levelized Cost of Electricity (LCOE) [31–37]. The influence of the most crucial input variables is comparatively examined, in order to quantify the risk of the investment.

The majority of studies concludes that the natural gas and electricity prices, are the variables that mostly affect the economic result for the viability of cogeneration systems. This explains the fact why research has been recently focused on the relation between these energy prices [15,16,30,38–43]. Some researchers examine the viability of a CHP system by using the difference of these energy prices initially [39,40], while in previous work [42,44], it was proven that the ratio of electricity to natural gas price is the proper metric to use for the examination of cogeneration profitability.

In summary, the literature review on cogeneration economic viability confirms the fact that it is a complex issue under continuous investigation, which is affected by various different factors like: the conventional alternative system, the type of prime mover, the type of facility, the regulatory framework, the structure of electricity market, and the energy prices.

According to the above, the purpose of this paper is to extend the existing research on this field, including a comparison of CCHP system with alternative competitive technologies, for various load characteristics. The viability of the cogeneration system is examined by using a modified LCOE indicator. This metric considers the lifetime generated energy and costs and calculates the average cost per kilowatt hour of useful energy produced taking into account the allocation among the different energy products. With this metric, one can investigate the locus of the break-even points between the CCHP system and conventional technologies. Consequently, one of the main advantages of the developed formula, is that it can be used to determine both the investing and operating viability of any cogeneration system, as a function of electricity and gas prices.

More specifically, this paper investigates the investing and operating viability of a CCHP system, over three alternative configurations for heating and cooling:

(1) Boiler and Electric Chiller;
(2) Boiler and Gas Driven Absorption Chiller;
(3) Reversible Heat Pump.