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Energy versus economic effectiveness in CHP (combined heat and power) applications: Investigation on the critical role of commodities price, taxation and power grid mix efficiency

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ABSTRACT

Starting from PES (primary energy saving) and CSR (cost saving ratio) definitions the work pinpoints a "grey area" in which CHP (combined heat and power – cogeneration) units can operate with profit and negative PES. In this case, CHP can be profitably operated with lower efficiency with respect to separate production of electrical and thermal energy. The work defines the R-index as the ratio between the cost of fuel and electricity. The optimal value of R-index for which CHP units operate with both environmental benefit (PES > 0) and economic profitability (CSR > 0) is the reference value of electrical efficiency, η_{el_ref}, of separate production (national power grid mix). As a consequence, optimal R-index varies from Country to Country. The work demonstrates that the value of R corresponds to the minimum value of electrical efficiency for which any power generator operates with profit. The paper demonstrates that, with regard to the profitability of cogeneration, the ratio between the cost of commodities is more important than their absolute value so that different taxation of each commodity can be a good leverage for energy policy makers to promote high efficiency cogeneration, even in the absence of an incentive mechanism. The final part of the study presents an analysis on micro-CHP technologies payback times for different European Countries.

1. Introduction

According to the International Energy Agency (IEA) fossil fuels accounted for 81.4% of world total primary energy supply [1], in 2013. Most part of coal and natural gas was used to produce electricity and/or thermal energy. In particular, the share of fossil fuel on worldwide electricity production resulted to be 67.43% [1]. Cogeneration is universally recognized to be a leading technology to reduce worldwide primary energy needs from fossil fuel. In Europe, cogeneration is one of the most important technologies identified in order to achieve European energy efficiency targets by 2020 [2–4]. Several authors [5–10] already stressed the fundamental role of energy policy measures to promote cogeneration. Moya [5] analysed the effectiveness of different support measures to promote cogeneration in the European Union showing that there is no evidence of a relationship between the economic advantage offered by support measures and the deployment of cogeneration in the Member States and that the presence of incentives to promote RES has not significantly affected the promotion of CHP. Westner at al. [6] investigated which kind of CHP technologies are most likely to be installed after the new regulatory framework in force in Germany aiming at increasing the share of CHP from currently about 13%–25% by 2020. The same authors in Ref. [7] gave an overview of the promotion schemes for CHP in various European Countries and after applying the Mean-Variance Portfolio (MVP) theory concluded that the returns on CHP investments differ significantly depending on the Country, the support scheme, and the selected technology studied. Lončar et al. [8] studied the changes in the regulatory context relevant to the CHP sector in Croatia and analysed the cogeneration viability in municipal district heating, industry, services and the residential sector finding that a strong institutional support for initial penetration of the micro-cogeneration technologies into the Croatian energy system is necessary. Brown et al. [9] evaluated ex-ante a federal policy option aimed at promoting industrial cogeneration in U.S. showing that the current 8.9% market share could increase up to 18% in 2035 with

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Nomenclature

CHP	combined heat and power – cogeneration
C_{CHP}	annual total energy bill amount with cogeneration system (€/year)
C_{wo_CHP}	annual total energy bill amount without cogeneration (€/year)
C_{el}	cost of electricity (€/kWh)
C_{f_boiler}	cost of boiler fuel (€/kWh)
C_{f_CHP}	cost of CHP fuel (€/kWh)
C_{NG}	cost of natural gas (€/kWh)
CSR	cost saving ratio
E_{el_CHP}	electricity produced by CHP (kWh/year)
E_{th_CHP}	useful thermal energy produced by CHP (kWh/year)
m_{f_CHP}	CHP yearly fuel consumption (kg/year)
m_{f_boiler}	Boiler yearly fuel consumption (kg/year)
m_{NG_CHP}	CHP yearly natural gas consumption (m^3/year)
m_{NG_boiler}	Boiler yearly natural gas consumption (m^3/year)
η_{el_CHP}	CHP electrical efficiency (–)
η_{th_CHP}	CHP thermal efficiency (–)
η_{el_ref}	reference electrical efficiency of the national electric power production (–)
η_{th_ref}	reference thermal efficiency (–)
η_{th_boiler}	thermal efficiency of the boiler (–)
LHV_{f_CHP}	low heating value of CHP fuel (kWh/kg)
LHV_{f_boiler}	low heating value of boiler fuel (kWh/kg)
LHV_{NG}	Natural gas low heating value (kWh/m^3)
K	ratio between cost of boiler fuel and cost of CHP fuel (–)
PES	Primary Energy Saving
R	ratio between cost of fuel and electricity (–)

benefits for manufacturers and the public sector thanks to energy bills reduction and pollution; in another work the same authors [10] investigated the job generation impacts of expanding industrial cogeneration. Several authors recognized the role of commodities price in influencing the profitability of a cogeneration plant. Radulovic et al. [11] analysed the profitability of a district heating CHP project in Croatia showing how a best practice, such as cogeneration technology, can become an investment dilemma influenced by administrative overregulation and illiberal market prices regulation. Frangopoulos [12] showed that only proper design and operation of the CHP unit lead to reach the threshold of efficiency required by the European Directive to promote cogeneration. Ziębik et al. [13] investigated the optimal coefficient of the share of cogeneration in district heating plants, presenting an optimization algorithm that maximizes the profitability of the CHP plant. Aguilar et al. [14,15] analysed how to increase efficiency and consequently profitability of a CHP system with gas turbines in Spain. Badami et al. [16] compared the expected energetic and economic results with the real performance and economic profitability of industrial CHP plants showing that, in the design phase the simple payback time is usually underestimated and that thanks to the future incentives of Italian legislation simple payback can be reduced of about 15–20%. Shnaiderman et al. [17] presented a techno-economic model to evaluate the opportunity of installing cogeneration plant as a profitable alternative to natural gas boiler. Colmenar-Santos et al. [18] identified institutional and financial barriers faced by district heating networks and cogeneration projects in the EU-28 such as: distinctive competence, fuel price volatility, and much of the current regulatory framework. Napoli et al. [19] carried out a techno-economic analysis to verify the performance of PEMFC and SOFC based micro combined heat and power systems aiming at analysing different support schemes that can facilitate the technology competitiveness in the market. González-Pino et al. [20] analysed the operational and economic viability of Stirling engine micro-cogeneration units in single-family houses in Spain taking into account Spanish regulation and economic framework, particularly fuel and electricity prices; they found that there is no opportunity for these devices to be feasible in new and retrofitted single-family dwellings sited in any climatic zone of Spain but in the coldest ones, where the micro-CHP plants could become viable if the Stirling engine investment cost decreases. Lately, some authors focused on energy and economic profitability of micro-CHP technologies in household sector [21–24].

The idea of this work started from a previous study that presented a survey of cogeneration in the Italian pulp and paper sector [25]. One of the results of this study, carried out in 2012, was that in Italy some paper mills operated with profit CHP plants with negative primary energy saving index. The conclusion was that, in 2012, in Italy, existed a commodities price context under which a CHP plant could profitably be operated with a primary energy consumption higher than the one achievable with separate production. Starting from this result, the goal of this work is to investigate the energy and economic conditions which can lead to indirectly promote inefficient energy operation of CHP unit.

The paper is organized as follows: Section 2 presents the methodology proposed in the study to pinpoint the "grey-area" between energy and economic saving; Section 3 presents the results and comments with reference to European Countries; Section 4 presents an analysis on micro-CHP technologies payback time according to the different cost of commodities in the European countries; finally, Section 5 reports the conclusions of the work.

2. Goal of the work: investigation of the "grey area" between energy and economic saving

2.1. PES (Primary energy saving) and CSR (cost saving ratio): definitions

Cogeneration (Combined Heat and Power or CHP) is the simultaneous production of electricity and heat, both of which satisfy useful demand [4]. Cogeneration can be evaluated under an energy and economic point of view. From the energy point of view, the main index to evaluate CHP effectiveness is the PES (primary energy saving), which quantifies the amount of primary energy saved by producing useful heat and electricity by means of cogeneration with respect to the separate production of the same amount of useful heat (in a boiler whose reference thermal efficiency is η_{th_ref}) and electricity (in a centralized thermal power generation plant whose reference electrical efficiency is η_{el_ref}). PES is a non-dimensional index and it is calculated as [4,26]:

$$PES = 1 - \frac{1}{\frac{\eta_{el\_CHP}}{\eta_{el\_ref}} + \frac{\eta_{th\_CHP}}{\eta_{th\_ref}}} \tag{1}$$

From the economic point of view, the effectiveness of operating a CHP unit can be evaluated by the CSR (cost saving ratio) index,