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Allocation factors in Combined Heat and Power systems – Comparison of different methods in real applications

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ABSTRACT

The planning and operation of multi-generation units needs to be properly addressed, to guarantee a correct assessment of their performance with respect to standard energy generation units. Performance indicators are defined to compare energy conversion units, and in presence of multiple outputs an allocation methodology is required. There is currently no single method to allocate input resources and impacts in cogeneration and multi-generation systems, as the number of aspects that are involved leads to different approaches. Each method provides specific advantages related to the target for which it has been defined, but attention must be paid on the entire range of boundary conditions that could affect the results. This paper evaluates the current methodologies for allocation factors calculation in Combined Heat and Power plants, to present an indication of the strengths and the limits of each approach. The methods are applied to multiple case studies, by considering the operation data from existing natural gas plants of different size, technology and conversion efficiency. The use of real data allows to consider actual situations in which the choice of the method could lead to different indications. The results show the significant variability of the allocation factors, the main drivers being the choice of the methodology itself, the conversion technology and the reference efficiency values that are set for separate production of heat and power. A discussion is proposed on the importance of defining proper methods and reference parameters, with particular attention to the applications for which the allocation factors need to be calculated and the potential effects on energy policies and regulations.

1. Introduction

Current energy systems are facing a significant transition towards Smart Energy Systems [1], with the potential of integrating different energy sectors and infrastructures to optimize their operation. The attention towards primary energy savings and environmental impacts is a global concern for several reasons, including the fight against climate change, local pollution issues, energy security and reliability of the energy supply. The recent developments in Information and Communication Technologies (ICT) solutions can support the operation and optimization of energy systems in this radical shift in approach and understanding.

Multi-energy systems are crucial for this transition, as the integration of multiple sources allows exploiting the synergies that lead to different optimization configurations depending on variable boundary conditions. Combined Heat and Power (CHP) technologies are currently the multi-output energy systems with the largest diffusion, both as distributed generation or centralized units combined with District Heating (DH) networks [2]. When properly designed and operated, they represent a powerful tool to decrease primary energy consumption [3] and to limit environmental impacts [4]. The correct sizing of multi-generation units needs to be performed with dedicated algorithms that can simulate the entire range of operation conditions of those units, thus ensuring the optimal configuration of the energy system [5]. Some recent works proposed a probabilistic approach to take into account a risk analysis for considering long term uncertainties in energy demand [6]. In general, the higher complexity with respect to single output energy systems leads to the importance of dedicated optimization strategies at design and operational phases [7], both for CHP units connected to DH networks [8] and for distributed micro-CHP solutions [9].

However, while the design and operational phases are important in ensuring the optimal energy performance, the planning and installation of CHP units needs to be considered in the framework of energy planning and policies, that are also connected to the economic conditions in which those units need to be operated. Energy policies needs to take into account a number of aspects that affect CHP operation strategies, including stakeholders priorities [10] and the evolution of electricity market options (e.g. reserve and balancing market [11], distributed energy resources scheduling [12]). Energy policies need to be able to

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face the complexity of including multi-energy systems in a framework that is usually defined based on mono-energy conversion units, i.e. separate production of heating, cooling and power. The combined production of multiple energy carriers needs specific attention when performance indicators are at the basis of energy planning measures. In particular, the allocation of fuel consumption as well as environmental impacts is a significant aspect in CHP systems. There is currently no single method for fuels and impacts allocation in CHP units, since multiple aspects are involved. In some countries a reference method is defined (e.g. European Union), but in the wide range of operational conditions the results could lead to issues of compatibility with other existing energy policies.

Some authors have addressed the allocation methods for cogeneration plants, either with a general perspective [13] or with a specific application such as the definition of CO_2 emission factors [14] or the allocation of waste and input fuels in Life Cycle Assessment calculations [15]. Wang et al. [16] proposed an exergy cost methodology to assess the cost associated to each energy flow in multi-energy systems, by performing a thermo-economic analysis. Tereshchenko and Nord presented an interesting work [17] comparing different methods for allocation factors in a specific case study, as a support for CHP design and policy making. Holmberg et al. [18] discussed the allocation of fuel costs and CO_2 emission factors on a specific case study based on an industrial CHP unit. Aldrich et al. [19] highlighted the importance of considering real system efficiency for the allocation of emissions, to be compared with best available efficiency ratios provided by regulations. Pina et al. [20] evaluated the allocation of resources in a trigeneration system coupled to an heat storage in buildings, focusing on the hourly unit costs calculation for each internal flow and final product. Gao et al. [21] presented an exergoeconomic analysis for the allocation of CO_2 emissions in coal-fired CHP plants, providing also a brief comparison with other models. Allocation methods have been used in a wide range of studies, including CHP in district heating applications [22], combined cooling heating and power based on biomass gasification [23], co-products emissions allocation in biorefineries [24], and a solar polygeneration plant to produce power, desalted water, cooling and process heat [25].

Whereas these studies provide significant insights on single case studies, the comparison of various situations could provide additional information on the strengths and limits of each methodology, by highlighting the effect of CHP technology, unit size, operation conditions and time resolution of the analysis.

This paper presents the main methodologies that are currently used for allocation factors calculations in CHP systems. The focus has been put on natural gas CHP units with different technologies. Three approaches have been developed, to highlight multiple applications: (1) Nominal values of different technologies and sizes, (2) real annual data of several natural gas engines connected to District Heating networks and (3) real hourly operation data of a natural gas combined cycle over an entire year.

2. Methodology

The aim of this paper is to compare the consequences of choosing a specific allocation factor methodology on the indicators that can be calculated for heat and power as a support for various applications, including energy policies, energy systems simulations, energy certifications, etc.

2.1. Allocation factors methodologies

Different methodologies are currently used to allocate primary energy consumption, emissions or other indicators in multi-output energy systems. The main methods that will be compared in this paper are discussed below. The methods are analyzed with reference to natural gas fired CHP units, but the methodology can be extended to energy systems with different inputs and with more than two outputs.

2.1.1. Energy methodology

The simplest method is based on the calculation of the share of energy produced for each type, i.e. heat and power. The electricity and heat allocation factors α_E and α_Q can be easily calculated as following:

$$\alpha_E = E/(E + Q) \quad (1)$$

$$\alpha_Q = Q/(E + Q) \quad (2)$$

with E and Q being the amount of electricity and heat produced by the CHP system in a given time frame.

The simplicity of this method represents both its strength and its weakness: the allocation respects the amount of energy produced for each type, but the quality of energy is not taken into account (i.e. the exergy of the output energy flows). For this latter reason, this method is seldom applied in energy policies, although it can provide an immediate idea of the importance of each energy output of the system.

However, an interesting aspect of this method, which is not available in other approaches, is its independence from external parameters that may have an impact on the results of the allocation. The only system parameter that affects the allocation factors is the power-to-heat ratio, which is related to the electrical and thermal efficiencies of the system.

2.1.2. Exergy methodology

The exergy methodology aims at including the aspect of the energy quality, i.e. the exergy contained into the energy outputs of the system. While for the electricity production the exergy coincides with the energy, the exergy content of the heat is related to the temperature at which it is produced and supplied to the user.

The heat allocation factor is therefore calculated by using the Carnot factor:

$$\alpha_Q = \frac{Q\cdot(1-T_{ref}/T_Q)}{E + Q\cdot(1-T_{ref}/T_Q)} \quad (3)$$

where T_{ref} is the reference temperature, which can be fixed by specific reference conditions (e.g. usually 15 °C, 25 °C or 0 °C) or calculated as the average outdoor temperature during the analysis time frame, and T_Q is the mean logarithmic temperature of the heat produced by the CHP unit, calculated as:

$$T_Q = \frac{T_S-T_R}{\log(T_S/T_R)} \quad (4)$$

where T_S and T_R are the supply and return temperatures (in Kelvin units). The mean logarithmic temperature is used in spite of a simple mean due to its higher significance in the analysis of heat exchangers. The supply and return temperatures are usually measured with reference to the CHP unit, but in the case of DH networks the heat losses should be included, and the temperatures measured by the final users, where available, may lead to a more accurate calculation.

The allocation factor for electricity can be obtained by difference:

$$\alpha_E = 1-\alpha_Q \quad (5)$$

In this case the heat temperatures are required system parameters, in addition to the power-to-heat ratio already seen in the previous method, that have an influence on the allocation factors. Moreover, the choice of the reference temperature is an external driver that may influence the results: both in the case of a fixed temperature set by a National regulation, or for the use of real outdoor temperature which is not related to the energy system behavior itself (although it may already have an impact on the system performance for some technologies).

2.1.3. Power bonus

This method is extended from EN 15316-4-5:2017, where it is