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

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Michel Noussan[a,*]

[a] *Politecnico di Torino, Department of Energy "Galileo Ferraris", c.so Duca degli Abruzzi 24, 10129, Turin, Italy*

Abstract

The energy sector is facing a significant transition towards Smart Energy Systems, in which the generation units are being optimized to reach sustainability targets including primary energy savings and CO_2 emissions reduction. In such a context, 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. 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 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.

Keywords: Combined Heat and Power, Allocation Factors, Multi-Energy Systems, Primary Energy, Emissions

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 are able to simulate the entire range of operation conditions of those units, thus ensuring the optimal configuration of the energy system [5]. Some recent works

*Corresponding author

Email address: michel.noussan@polito.it (Michel Noussan)

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 operate. 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]). Energy policies needs to be able to 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 [12] or with a specific application such as the definition of CO_2 emission factors [13] or the allocation of waste and input fuels in Life Cycle Assessment calculations [14]. Wang et al. [15] 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 [16] comparing different methods for allocation factors in a specific case study, as a support for CHP design and policy making. Holmberg et al. [17] discussed the allocation of fuel costs and CO_2 emission factors on a specific case study based on an industrial CHP unit.

Whereas theses 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:

$$\alpha_E = E/(E+Q) \tag{1}$$

$$\alpha_Q = Q/(E+Q) \tag{2}$$

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:

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

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:

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

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:

$$\alpha_E = 1 - \alpha_Q \tag{5}$$

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 realt 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 described for the application to District Heating Systems. This regulation is the update of EN 15316-4-5:2007 that was focused on the primary energy factor calculation for District Heating networks, where distribution network losses are taken into account by calculating the heat supplied to the users Q_{del} from the total heat production Q, including the network losses. In this update the methodology is extended also to the calculation of CO_2 emission factors and other indicators, but without major changes.

The primary energy factor of the district heating is defined in the Regulation by the following equation:

$$f_{P,DH} = \frac{E_{P,in}}{Q_{del}} = \frac{\sum_i E_{F,i} \cdot f_{P,F,i} - E_{el,CHP} \cdot f_{P,el}}{Q_{del}} \tag{6}$$

being $E_{P,in}$ the total primary energy consumption of the system, by removing the fraction required for the generation of the exported electricity, which is quantified by the amount of electricity production $E_{el,CHP}$ multiplied by the conventional primary energy factor of the electricity $f_{P,el}$. These notations have been obtained directly from the Regulation, and therefore they are not compliant with the others used in this paper.

A similar logic can be applied to any CHP unit, by considering its primary consumption and its heat production in the following equation:

$$f_{P,Q} = \frac{F \cdot f_{P,NG,ref} - E \cdot f_{P,E,ref}}{Q} \tag{7}$$

with F as the fuel consumption (in this case natural gas) and $f_{P,NG,ref}$ its primary energy factor that may include a share of energy required for its supply chain to the final user (e.g. extraction, transport, transformation, etc.).

From the previous equation, the allocation factors chosen for heat and electricity can be derived, by fixing the heat factor and calculating the electricity factor by difference:

$$\alpha_Q = (Q \cdot f_{P,Q})/(F \cdot f_{P,NG,ref}) = \frac{F \cdot f_{P,NG,ref} - E \cdot f_{P,E,ref}}{F \cdot f_{P,NG,ref}} \tag{8}$$

$$\alpha_E = 1 - \alpha_Q \tag{9}$$

Some primary energy factors are provided as examples in the Annex B of EN 15316-4-5:2017 (e.g. $\mathrm{f_{P,Q,ref}} = 1.5$ for heat produced by natural gas boilers and $\mathrm{f_{P,EE,ref}} = 2.5$ for electricity produced by CHP and exported to the grid), but each Member State must define specific values depending on National conditions and policies. The primary energy factors provided by the current Italian Regulation are $\mathrm{f_{P,NG,ref}} = 1.05$ and $\mathrm{f_{P,EE,ref}} = 2.42$, but the Annex to the new Regulation is not yet available. Italian values will be used due to the location of the plants that are used in the case studies.

These reference factors can have a significant impact on the allocation factors of CHP systems, due to a large number of different aspects that may arise. A particular issue may be when some CHP units have an energy efficiency higher than the one associated to the reference primary energy factor: in this case the allocation factor for heat may become negative. In this case the heat allocation factor is set to zero, but this choice leads to a distortion in the application of this method, which results in a non-correct allocation for such systems.

The reference primary energy factor for electricity is strongly related to the National electricity mix, to the conversion efficiency of the power plants, and in a minor share to the transmission losses of the Power Network. The efficiency of power plants shows a large variability in relation to the source, the technology, the size, and the operational strategies.

2.1.4. Heat bonus

The same concept applied to electricity in the previous methodology can be translated to the heat production, by defining a "heat bonus" method. Therefore, the following equations can be used:

$$\alpha_E = (E \cdot f_{P,E})/(F \cdot f_{P,NG,ref}) = \frac{F \cdot f_{P,NG,ref} - Q \cdot f_{P,Q,ref}}{F \cdot f_{P,NG,ref}} \tag{10}$$

$$\alpha_Q = 1 - \alpha_E \tag{11}$$

While natural gas primary energy factor is the same than in the previous case, $\mathrm{f_{P,NG}} = 1.05$, the primary factor for heat needs to be defined. Two hypotheses are proposed for alternative heat generation:

- heat production with distributed conventional natural gas boilers, which are the existing standard, with a conventional seasonal thermal efficiency of 90% (based on LHV);
- heat production based on air-source heat pumps, to evaluate the effect of a potential penetration of this technology in the future, by considering an average seasonal Coefficient of Performance (COP) of 3.0.

These performance indicators (efficiency and COP) have been set by taking into account the relatively high temperatures at which the space heating is currently operated in a number of countries in Europe. Lower temperatures would lead to better COPs for heat pumps and to the possibility of using condensation natural gas boilers, with higher thermal efficiency. These evaluations have been integrated in the sensitivity analysis.

2.1.5. Alternative generation

This method is considering the primary energy that would have been consumed with the separate production of heat and electricity to define the allocation factors. The following equations are used:

$$\alpha_E = \frac{E/\eta_{E,ref}}{E/\eta_{E,ref} + Q/\eta_{Q,ref}} \tag{12}$$

$$\alpha_Q = \frac{Q/\eta_{Q,ref}}{E/\eta_{E,ref} + Q/\eta_{Q,ref}} \tag{13}$$

where $E/\eta_{E,ref}$ and $Q/\eta_{Q,ref}$ are the reference electricity and heat efficiency for separate production respectively. The electricity efficiency is usually the average of the National power plants, while the heat efficiency is set to a conventional natural gas boiler (but also a heat pump could be considered, as evaluated in this paper). In this paper the electrical efficiency is set to 41%, in accordance with the Italian Regulation, while the heat alternative generation has the same hypotheses of the previous method (i.e. 90% of efficiency for natural gas boilers, COP of 3.0 for heat pumps).

2.1.6. Price

An additional possibility is the use of energy prices to weight the importance of the heat and power outputs. In particular the electricity price can be related to the selling price in the market, and the heat price to the heat usually sold to DH users or to the natural gas price by using the reference heat efficiency for separate production described in the previous cases.

The electricity and heat allocation factors can be calculated as following:

$$\alpha_E = \frac{E \cdot p_E}{(E \cdot p_E + Q \cdot p_Q)} \tag{14}$$

$$\alpha_Q = \frac{Q \cdot p_Q}{(E \cdot p_E + Q \cdot p_Q)} \tag{15}$$

being p_E and p_Q the specific prices for electricity and heat.

In this method the definition of the prices is subject to a large number of hypotheses. The approach can be based on the price paid to the final users, on the revenues obtained by selling heat and power, or on the avoided cost of the separate production of heat and power. Moreover, the prices may show a variability in the selected time frame (especially electricity) and therefore the variable price may be considered instead of the average. In this paper the base prices for electricity and heat have been set to 50 Euro/MWh and 75 Euro/MWh respectively. These prices are based on the selling prices of electricity to the grid (average value of wholesale price in the Italian Market over the last 4 years) and the heat to district heating users (including the average network losses).

2.1.7. Other methodologies

Other methodologies are available, but are not considered in this work, due to their limited application in common practice. The main are the following [16]:

- The *200% method*, promoted by the Danish Energy Authority, which considers a reference 200% efficiency for heat to evaluate the allocation factors. This method is similar to the power bonus method.
- The *British Standard PAS 2050* is based on the intensity of GHG emissions of the fuel and the technology. The formulation is the same that the one used in the energy method, but the electricity is multiplied by a coefficient based on the fuel and technology of the CHP unit.
- The *Power loss* methodology has been mainly developed for steam turbines, and it takes into account the avoided power production due to the steam extraction in the turbine to supply the heat demand. This method is limited to the technologies for which the heat production causes a decrease of power production.
- The *Dresden* methodology [18] has been proposed as an approach to integrate exergy concepts in the power loss method that has been previously described. Also this method is limited to the technologies with a power loss caused by the heat recovery.

2.2. Synthesis of influencing parameters

Different parameters are influencing the result of the allocation, both from the energy system features and from the external context. Table 1 reports the parameters that have an influence on the allocation procedure for each methodology. The trade-off between internal and external parameters is a crucial aspect, as each system should be considered both for its performance and for its relationship with the external context in which it operates.

The effects of these parameters are analyzed by considering multiple case studies, as discussed below. A sensitivity analysis will be performed on some external parameters, to highlight the weight of each choice of any specific reference indicator.

Table 1: Parameters affecting the results of the allocation

	System parameters	External Parameters
Energy Method	Power-to-heat ratio	-
Exergy Method	Power-to-heat ratio, heat temperatures	Reference Temperature
Power Bonus	Electric and thermal efficiency	Electric reference efficiency
Heat Bonus	Electric and thermal efficiency	Thermal reference efficiency
Alternative Generations	Power-to-heat ratio	Electric and thermal reference efficiency
Price Method	Power-to-heat ratio	Power and heat prices

2.3. Case studies

Different case studies are proposed, to investigate multiple aspects of the problem: (1) different technologies can show a wide range of variation of performance parameters, (2) in real operation the same technology can show different results based on its operational strategies including part load performance and (3) the same unit can have a wide range of hourly operation modes, leading to a statistical distribution of allocation factors if the analysis involves high-time step calculations.

For these reasons, the case studies have been chosen based on these approaches, to evaluate the effect of the methodologies with a wider perspective.

2.3.1. Case 1: Different technologies and nominal performance

The first case takes into account the main available CHP technologies based on natural gas that are currently in commercial operation. Some nominal values of multiple parameters have been considered for combustion engines [19, 20], gas turbines [21, 22, 23], combined cycles [3]and fuel cells [24].

The fuel has been limited to natural gas to avoid a too large variation of parameters and indicators, especially when considering CO_2 emissions. The main drivers that have been analyzed in this case study are the nominal electric and thermal efficiencies, and the power-to-heat factor that can be easily calculated from them. Different unit sizes have been used, to enlarge the range of the indicators and to provide more insightful results.

2.3.2. Case 2: Operation data of natural gas engines connected to DH networks

A following step is the shift from nominal performance indicators to the real operation of CHP units. In this case study a statistical analysis on the annual performance of a large number of natural gas engines has been performed. The available data for around 120 units of different output power has been used, considering a database of CHP units connected to the Italian District Heating networks [25].

The interest in considering real data lays in the possibility of evaluating the variability of allocation factors in relation to a group of units that represent a range of operation conditions in real applications. Although many units have similar nominal capacities and performances, their operational logics lead to very different annual results, due to a number of reasons including the users' demand, the environmental conditions, the interaction with other generation units, the quality of the maintenance, etc. [26].

2.3.3. Case 3: Hourly analysis on a single unit

The last step is the shift from annual data to high time-step data, e.g. hourly. This choice leads to the evaluation of the variation of allocation factors in the perspective of the need of using them for live applications such as energy markets. The analysis of allocation factors distributions would also provide additional insights than the average values that can result from annual calculations.

In this case the analysis has been performed on a single unit, a natural gas combined cycle connected to a large DH network. The operation data are available from CEMS (Continuous Emissions Monitoring Systems), with an hourly time step over 8 years of operation [27]. The current work has considered the operation data for 2017, as the results from the other years provide similar values.

The NGCC plant has 395 MW of net power output when operating in full electric mode, with a nominal efficiency of 58%. When switching to CHP operation the output power is reduced to 340 MW, and the available heat supplied to the DH network is 260 MW, being the global efficiency equal to 90% [27]. Unfortunately the CEMS is not monitoring the heat supply and return temperatures, and therefore also in this case nominal values need to be considered for the exergy analysis.

2.4. Sensitivity analysis

A sensitivity analysis is performed to evaluate the weight of some external parameters on the results of the calculations with different methodologies. The analysis will be focused on electricity and heat reference efficiencies. Energy prices are not considered as they are very site-specific, and their impact is quite straightforward (given the simple price proportion among the two energy types) leading to less interesting results. Consequently, only the affected methodologies will be evaluated. Moreover, to simplify the representation the sensitivity analysis will be performed on the data of Case 2, as annual values are usually the ones that show the highest interest for this type of calculation in real applications.

Electricity reference efficiency represents the average efficiency of the alternative generators supplying energy to the Power Grid. The reference value used in the other calculations was 0.41 (corresponding to the reference efficiency value for Italian power plants), and this value will be varied from a minimum of 0.35 (representing traditional fossil-fired power plants) to a maximum of 0.60 (representing the best available techniques for natural gas combined cycles).

The reference efficiency for heat was considered with two approaches in the previous calculations: (1) an average annual value of 90% by considering natural gas boilers as alternative technology for separate heat production, and (2) a COP of 3.0 in the hypothesis of heat production with a heat pump in the case of low-temperature heat users (i.e. a total equivalent thermal efficiency of 123% if considering a 41% conversion efficiency of the power plants). The sensitivity analysis will span the entire range of potential thermal efficiencies, from a minimum of 85% for existing boilers after several years of operation, to a maximum of 185% of equivalent system efficiency when considering a heat pump with a value of COP of 4.5 (and a conversion efficiency of the power plants equal to 41%).

It has to be highlighted that an equivalent efficiency for heat pumps larger than 100% is a choice that is consistent with the common practice. This choice originates from the idea of neglecting the amount of energy that is recovered from the air or from the ground, in accordance with the definition of COP. This choice is not fully consistent with the energy balance of the system, and a further study may be performed to evaluate this specific matter.

3. Results

3.1. Case 1 - Nominal values

The first step is the calculation of allocation factors from nominal values of different natural gas CHP technologies, and their application for the definition of indicators, such as primary energy factor and CO_2 emission factor.

Figure 1 shows the variation of electricity and heat allocation factors for different technologies and with the different methodologies that have been described in section 2.1, in relation to the power-to-heat ratio of each unit. The methodologies are reported with different colors, while the technology is shown by the shape of each data point. The trends show a generalized increase of the electricity allocation factor with the power-to-heat ratio, regardless of the methodology that is considered.

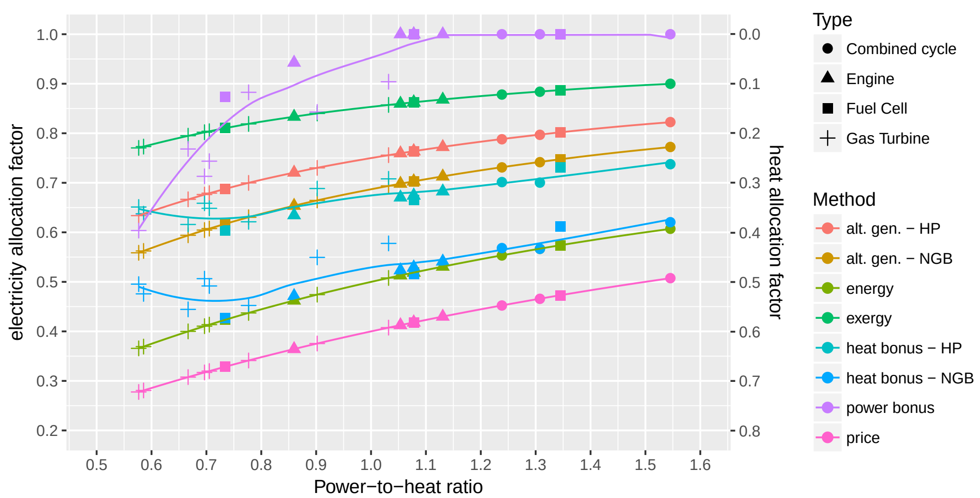

Figure 1: Nominal values - Allocation factors

The only exception is the saturation to 1 occurring for the *power bonus* methodology for the units that have an electrical efficiency that is higher than the reference value for separate production. For these units, the resources allocation is charged totally on the power output, and the heat is therefore considered as "free". This anomaly provides a distortion in the comparison of different units, which can be avoided by setting a proper reference efficiency related to each specific technology or fuel (as it happens for other calculation procedures, e.g. the Primary Energy Savings index for the evaluation of high-efficiency CHP performance). The calculations of the *power bonus* method leading to this plot have been performed in accordance with the current EU Regulation, considering the Italian reference indicators.

Comparing the results of each methodology, some aspects can be highlighted:

- All the methods but the *heat bonus* and *power bonus* show a regular dependence on the power-to-heat ratio, in accordance to their definitions. This aspect is clearly noticeable from the trend lines in Figure 1. The resources are therefore allocated depending on the amount of energy produced for each type. For *power bonus* and *heat bonus* methods there is a similar effect, but with some significant discontinuities, related to the conversion efficiencies of each unit.

- Considering a power-to-heat ratio of 1, i.e. the same conversion efficiency for the two outputs, the energy method is obviously charging equally heat and power, while almost all the other methods provide higher allocation factors for electricity. The only exception is the *price* method, due to the low price of electricity in the current wholesale markets.

- The choice of the method appears to have a significant impact on the results, as there is a large variability of allocation factors for each unit. This variability among methods does not appear to be influenced by the power-to-heat ratio value.

An example of the application of these allocation factors can be the calculation of CO_2 emission factors for heat and electricity in CHP units. A plot of the values for the same units considered above is reported in Figure 2.

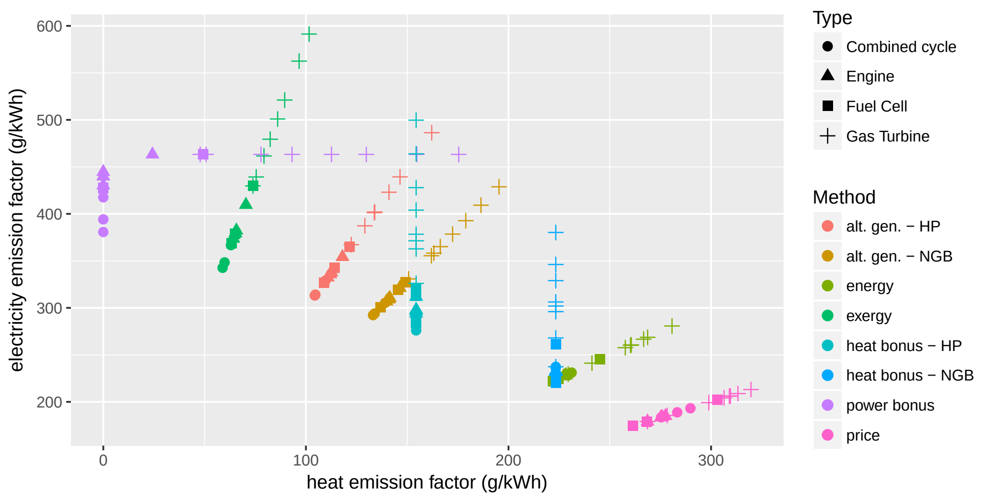

Figure 2: Nominal values - Emission factors

In this case, the power-to-heat ratio is no longer the only parameter, as both thermal efficiency and electrical efficiency have an impact on the emission factor, given the fact that each unit has the same type of fuel input (i.e. natural gas, with an emission factor set to 201 g/kWh). Even in this case the *power bonus* and *heat bonus* methodologies lead to different trends, i.e. fixed emission factors for heat in the case of *heat bonus* and for electricity in the case of *power bonus*. However, the saturation to 1 of the allocation factor in the *power bonus* already discussed for Figure 1 leads to a null emission factor for heat, and a consequently variable power emission factor, driven by the electric efficiency variation.

The other methods have proportional variations, and the higher emissions are related to gas turbines, which are generally the less efficient units in the group considered for this study. The emissions factors for electricity are in the range 180-600 g/kWh, and for heat they vary from 0 to 320 g/kWh. The asymmetry between the two types of outputs already discussed above emerges clearly from these results.

3.2. Case 2 - Annual values

The second step of this analysis is the evaluation of how the different operation logics of CHP units of the same technology can lead to variable allocation factors when considering the annual average operation. The data comes from around 120 units connected to Italian DH networks, having similar purposes (i.e. mostly space heating) but with some differences.

The allocation factors distributions are reported in Figure 3, differentiated for the methodology that has been used. The histograms have been reported together with the probability density function to give a better representation of each distribution.

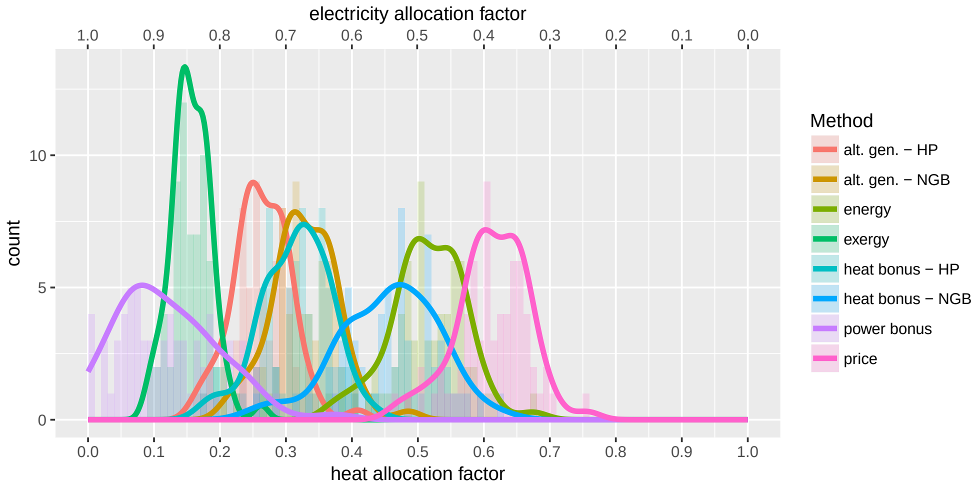

Figure 3: Annual values - Allocation factors

The plot of Figure 3 highlights both the variability between methodologies, but also the variability that occurs inside each methodology. While the first aspect has been already discussed in the previous case study, the second was less clear when considering nominal indicators. The distributions are all comparable, with the *power bonus* and *heat bonus* being more scattered, and the *exergy* method leading to more concentrated results, i.e. being less influenced by the internal parameters of each system. It has to be mentioned that the exergy has been calculated with reference to the design values of the supply and return heat temperatures of the DH networks, reported by the owners, as actual average annual temperatures were not available as a precise measurement.

The allocation factors are distributed in a similar range that the one of Figure 1, with a saturation to $\alpha_E = 1$ for the *power bonus* method in few systems. However, in this second case the results' distributions are more mixed, but the median values are in the same order compared to Figure 1.

Figure 4 reports the application of the allocation factors for the calculation of the CO_2 emission factors. The results are comparable to the nominal results obtained in Figure 2. However, some particular aspects can be highlighted:

- The general distribution of the values shows a slightly worst performance than for nominal conditions, in accordance to common practice. This aspect is more noticeable for the emission factor of heat, as the engines are usually driven in power priority.

- There are remarkable outliers on both ends of the distributions, which represent CHP units with very low or very high performance with respect to the average. Considering the *power bonus* method, only few systems reach a null emission factor for heat, due to the fact that natural gas engines are usually having an annual electric efficiency lower than the reference value of 41%.

- The fact that the lines are crossing each other means that for some methodologies the results are comparable, and there is not a fixed order of methodologies in the results.

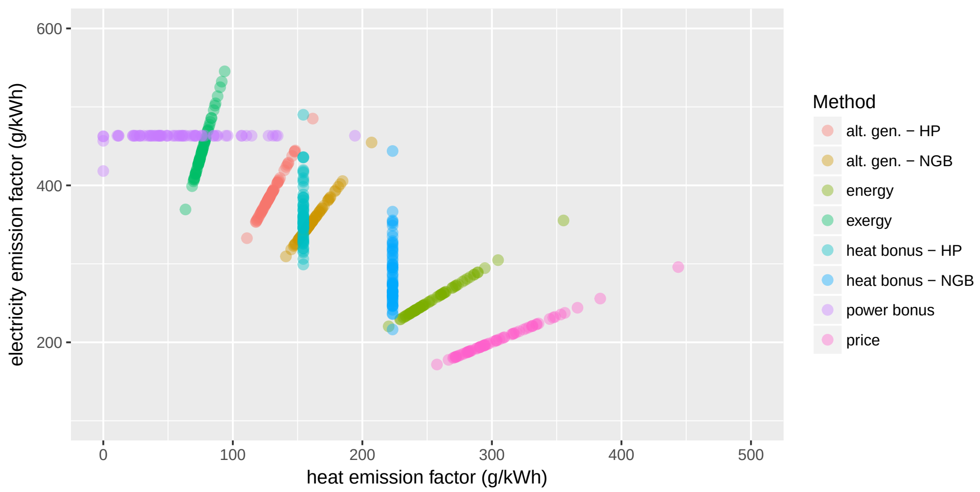

Figure 4: Annual values - Emission factors

3.3. *Case 3 - Hourly values*

The third step of the analysis is focused on a single CHP unit, but considering the different operation conditions throughout the year, i.e. hourly values have been considered. The choice of selecting a NGCC unit has been done to present a different technology than the one of the previous case (i.e. natural gas engines).

Figure 5 reports the boxplots of the values for each methodology. Due to the particular technology, with very high power-to-heat ratio and electrical efficiency, the *power bonus* methods leads almost always to a saturation to $\alpha_E = 1$. These aspects also lead to very high values of electricity allocation factors for all the methodologies considered, giving a rather different picture than for the combustion engines reported in the previous case. However, the differences among methodologies remain similar to the previous case, but they are all shifted towards higher electricity allocation factors.

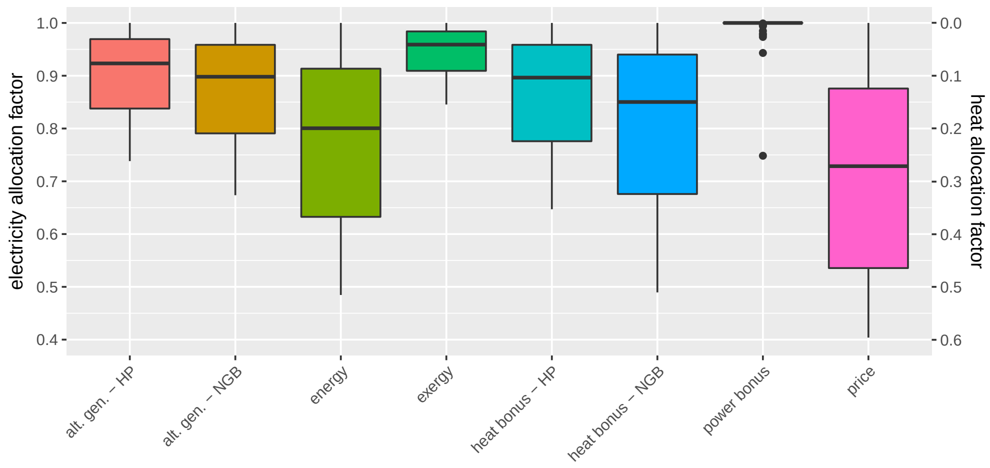

Figure 5: Hourly values - Allocation factors

The calculation of CO_2 emission factors is reported in Figure 6. With respect to the values previously obtained for engines, the range of CO_2 emission factor for electricity is reduced to 180-475 g/kWh, while for heat it can reach values as high as 600 g/kWh for the *energy price* methodology. This last effect is related to the combined effect of a high allocation factor to heat and a low thermal efficiency: the largest share of CO_2 emissions is allocated to a small amount of heat output, leading to high specific emission factors.

Some outliers are noticeable from the plot. These values may refer to startup/shutdown procedures that have been erroneously reported as regular operation by the CEMS. Also in this case there are some intersections between the "proportional" methodologies and the "fixed" methodologies.

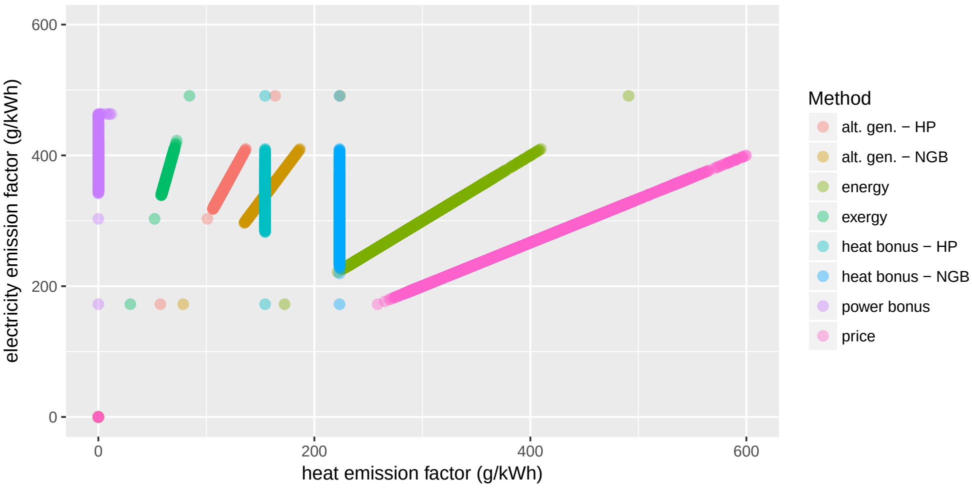

Figure 6: Hourly values - Emission factors

3.4. Sensitivity analysis

A sensitivity analysis has been performed to evaluate the effect of some external parameters on the calculation of the allocation factors. With reference to Case 2 (i.e. annual operation values of natural gas engines) the variation of the efficiency in electricity and heat separate production has been applied to the relevant methodologies.

Figure 7 reports the effect of the increase of the electricity separate production efficiency on the allocation factors. For each methodology, the median and the lower and upper quartiles values have been reported. The vertical dashed line represents the value that has been used in the previous calculations. A generalized decrease of the electricity allocation factor along with the increase of the electricity separate production efficiency value is noticeable for all the methods. The *power bonus* method appears to be the most affected, being its steepness higher than the *alternative generation* method, both considering natural gas boilers and heat pumps as heat separate production technology.

The higher the reference efficiency value for separate electricity production, the lower the "bonus" of primary energy consumption in the heat allocation factor calculation, resulting in its increase. For electricity efficiency values higher than 53% the median values for the *power bonus* method are as lower than the ones of the *alternative generation* method.

Moreover, for electricity efficiency values lower than 38% a "saturation" phenomenon is clearly noticeable: as the analyzed units are producing electricity with an higher efficiency than the reference value, all the primary energy is allocated to the electricity production. As already discussed in the previous sections for combined cycles, this phenomenon leads to considering the heat production with virtually no impact. The consequences of this phenomenon will be further discussed in the following section.

A similar sensitivity analysis can be performed on the heat separate production efficiency, with some similar aspects and some significant differences. Figure 8 reports the effect of the variation of heat separate production efficiency on the *alternative generation* method and on the *heat bonus* method.

A similar pattern of the one described for electric efficiency sensitivity can be remarked. The higher the heat separate production efficiency (which is virtually higher than 100% due to the effect of the heat pumps'

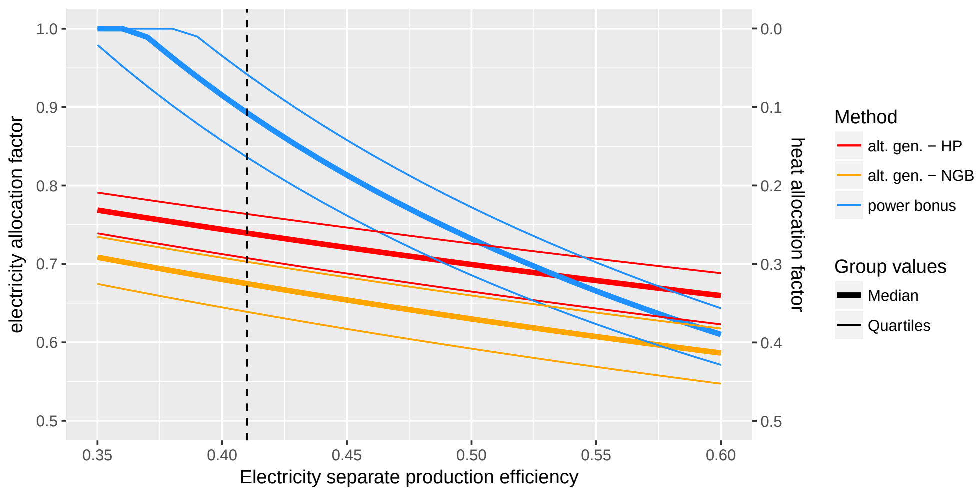

Figure 7: Sensitivity analysis - Electricity separate production efficiency

COP), the lower the heat allocation factor. In the range of efficiency values considered in this analysis the results of the *heat bonus* method are not reaching the values of the *alternative generation* method, as instead happened in the previous plot.

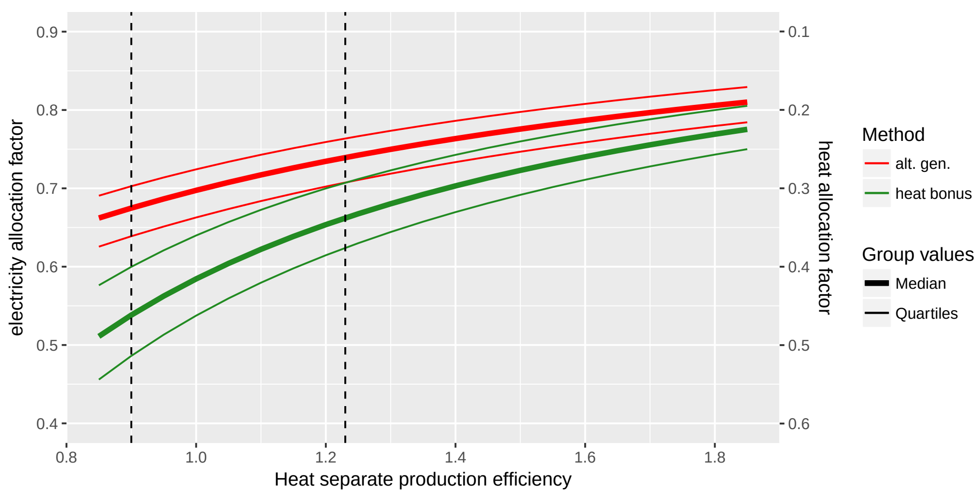

Figure 8: Sensitivity analysis - Heat separate production efficiency

In this second case, the *heat bonus* method has never ”saturation” issues, as the heat efficiency in CHP units is always much lower than the efficiency in separate heat production, which is not the case for electricity.

4. Discussion

The results described in the previous sections highlight the variability of the allocation factors based on multiple drivers, among which the CHP technology, the allocation method, the operating conditions and the reference values for separate production efficiency. This fact confirms the complexity of determining the existence of an optimal methodology, as several aspects must be discussed. Moreover, the allocation factors should also be analyzed by considering their use and applications, especially when defining indicators related to the output energy flows.

The proper definition of allocation factors has an impact on the interaction of the CHP systems (and more generally multigeneration systems) in the energy planning and policy making. In the framework of energy and climate targets aiming at reducing primary energy consumption and CO_2 emissions, the combined production of multiple energy carriers should be properly evaluated to avoid being penalized by the methods that are primarily defined for separate production of energy vectors.

The current standard in the European Union is the *power bonus* method, which is proposed by the EU Commission in the EN 15316:2017 to calculate the primary energy factor and the CO_2 emission factor for the heat supplied to the users of district heating networks. However, as remarked in the considered case studies, when a given system in CHP operation shows an electric efficiency higher than the reference value for separate production, the allocation factor for heat is set to null, i.e. all the resources/emissions are allocated to the electricity production. This choice can have significant consequences when the indicators calculated for heat need to be compared with other technologies or other systems. An amount of heat that has virtually no impacts can lead to significant distortions in policy making or energy planning.

A real case is the calculation of primary energy factors of heat produced in district heating systems: in the case of high efficiency CHP units the primary energy factor of the heat could eventually reach zero. In this case, the comparison with other heat generation technologies can push towards the choice of DH network just because its primary energy consumption is totally charged to power production. On the other hand, a reference to alternative generation solutions is useful to consider any CHP unit in its proper context, as the choice of any energy production technology cannot be properly evaluated without taking into account the available alternatives. Considering this aspect, the *alternative generation* method shows probably a better allocation for the cases considered in this study.

However, while the choice of the methodology is important, the results obtained from the *power bonus*, *heat bonus* and *alternative generation* methods are strongly affected by the reference values for separate production efficiency of heat and power. As reported in the sensitivity analysis, a proper choice of the reference electricity production efficiency could avoid the "saturation" effect. However, the choice of the proper value is non-trivial. In some applications aiming at evaluating the performance of specific CHP technologies, such a reference value should be differentiated based on the available energy source, as done for example when calculating the PES indicator for CHP units (i.e. the Primary Energy Savings indicator, see [28]). This would lead to a better analysis for fuels that show lower efficiencies than natural gas (e.g. solid biomass or waste). On the other hand, in applications in which different sources need to be compared (e.g. the calculation of indicators related to the output that is produced) a single reference value appears to be a more coherent choice.

Another aspect that is worth mentioning is the time resolution of the analysis. Although these allocation methods can be applied potentially to any time resolution, attention must be paid on the significance of the results in relation with the specific application that needs to be pursued. The comparison of different units and/or technologies is probably better performed by considering nominal or annual operation values, whereas a more detailed analysis on a single unit can be useful to highlight specific patterns or to define the interactions of the output energy flows with other connected processes.

5. Conclusions

This paper presents an application of different methods to calculate the allocation factors of Combined Heat and Power units, with the aim of providing useful insights on the main features of the different methodologies and the effects of their choice. Some indications can be derived from the results of this research work:

- The choice of the methodology is an important aspect, as the allocation factors to heat and power that are obtained from the calculations show a significant variability driven by the methodology. The results presented in this study, which are based on a range of technologies that use natural gas as energy source, suggests that some methods generally provide allocation factors shifted towards electricity production (e.g. *exergy* and *power bonus* methods), whereas other are generally more near the middle (e.g. *energy* method). These evaluations are valid for technologies with a good electric efficiency, while the results could be different in cases with very low power-to-heat ratios (e.g. some ORC units).

- Besides the choice of the methodology, both internal and external parameters have an effect on the allocation factors. The main impact is due to the features of the CHP unit itself, i.e. its electric and thermal efficiencies, and the ratio among these two values that is generally defined as power-to-heat ratio. The external drivers are peculiar for each method, but the main are the reference efficiency values for separate heat and electricity generation.

- The *power bonus* method, which is defined as a standard in EU countries, shows a "saturation" effect for CHP units that have an electric efficiency higher than the reference efficiency for separate production: in this case the allocation factor for heat is set to zero, i.e. all the resources and impacts are being allocated to the electricity production. The consequence of this phenomenon is the heat being "primary-energy-free" and "emissions-free", which results in a bias in the comparison with other generation technologies. The same phenomenon could in theory happen also with the *heat bonus* method, but in this case the heat reference efficiency is always higher than the achievable thermal efficiency of the CHP unit.

- The results of the sensitivity analysis show that the reference efficiency values have an impact also on the *alternative generation* method, but with a lower impact that for *power bonus* and *heat bonus* methods. The other approaches are not affected by these parameters. The only method that is not related to any external parameter is the *energy* method, which has the drawback of applying the same weight to heat and power production. This limit can be solved by using the *exergy* method, but additional information is required on the supply and return temperatures of the heat.

- Finally, it had to be mentioned that the results of this work, which are focused on combined heat and power, can be extended to a more general concept of multi-output energy systems, as the discussion on the qualitative aspects remains valid.

In conclusion, attention must be paid on a proper choice of the methodology as well as of the reference parameters that are used for the definition of the allocation factors in CHP systems. The policy makers should evaluate all the possible range of operation conditions to avoid potential issues and conflicts between CHP systems and the other energy conversion units. An usual application is the heat supply to DH networks, in which the operation of CHP units is often compared to alternative technologies to define performance indicators for the heat supplied to the final users.

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