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Modeling combined heat and power plants in Life Cycle Assessment: a comparison among different approaches to deal with multifunctionality

Jacopo Famiglietti[1], Monica Lavagna[2], Mario Motta[1]
[1]Politecnico di Milano, Department of Energy
[2]Politecnico di Milano, ABC Department
Email: jacopo.famiglietti@polimi.it

Abstract

In the energy sector, the issue of what fraction of fuel consumed by an energy conversion plant should be allocated among several products, such as electricity and heat is still open. In this work, procedures used to deal with this aspect in attributional Life Cycle Assessment studies were reviewed. In particular, the authors analyzed three approaches of allocation and eight methods as follows, relationships beyond the system boundaries (three methods), physical relationships (two methods), and other relationships (three methods), all of them in compliance with ISO 14044. In order to test the methods proposed to manage multifunctionality, a real combined heat and power plant installed in a dairy placed in Lombardy Region (Northern Italy) was analyzed. According to this analysis, the separate productions reference method, under relationships beyond the system boundaries approach, seems to be the most appropriate.

1. Introduction

In compliance with the ISO standard 14044 (ISO, 2006), in scientific literature, many different procedures can be found to deal with multifunctionalities (i.e. dividing the unit process, expanding the product system, allocation using physical relationships, and allocation using other relationships). The difficulty of identifying the correct approach, due to lack of guidance in some sectors, causes different related methods. In particular in the energy sector, the issue of what fraction of fuel consumed (and the relative potential environmental emissions) by an energy conversion plant should be allocated among several products, such as electricity, hot water, and steam is still open. Different approaches and methods were proposed so far, but none of them is worldwide accepted (Ioara et al., 2013), i.e. the method proposed by EN 15316-4-5 (CEN, 2017).

In this work, procedures used to deal with this aspect in attributional Life Cycle Assessment (LCA) studies were reviewed (consequential LCA is outside the goal and scope of the article). In particular, the authors analyzed eight methods based on the following three approaches: relationships beyond the system boundaries (three methods), physical relationships (two methods), other relationships (three methods). In order to test the methods proposed, a case study was analyzed. A real Combined Heat and Power (CHP) plant installed in a dairy, placed in Lombardy Region (Northern Italy), was studied to provide results using the different approaches and methods to manage multifunctionality. In detail, a single-fuel CHP facility, a reciprocating internal combustion engine that consumes natural gas to produce electricity, steam, and hot water, was analyzed.

After a brief description of each method, the authors assessed for the case study described above, the fractions of fuel consumed between co-products (electricity and heat) applying the different methods proposed, intending to compare the results for evaluating the best effective choice. Besides, the paper provides a guide to address multifunctionality in combined heat and power plants.

In order to carry out the analysis, both the thermodynamic efficiency and effectiveness were assessed, and a graphical flow chart was provided.

2. Methodology

The work reviewed the multifunctional solutions applied in scientific publications for Combined Heat and Power (CHP) plant. The review was conducted using the following research queries on the web-platform Scopus (Elsevier B.V, 2020): “Allocation methods in cogeneration”, “Allocation methods”, “Allocation approaches”, “Combine heat and power plant”, “CHP”, “Life Cycle Assessment” and consulting the reports “Life cycle inventories of energy systems: results for current systems in Switzerland and other UCTE countries” and “Allocation: Combined heat and power” (Dones et al., 2007; Heck, 2007) both available in Ecoinvent 3.5 database (Wernet et al., 2016).

a. Literature review

Ten papers were selected in total to cover the hierarchy indicated in the ISO 14044 (ISO, 2006) to manage multifunctionality in CHP plants: expanding the product system and allocation (dividing the unit process excluded). Among all eight methods examined in this paper, three used relationships beyond the system boundaries (Incremental Electricity Centered Reference IECR, Incremental Heat Centered Reference IHCR, and Separate Production Reference SPR), two used physical relationships (Exergy and Energy content), and three used other relationships (Electricity, Heat, and Price). Beretta et al. (2012) provides one alternative method under the relationships beyond the system boundaries, the Self-Tuned Average-Local Productions Reference (STALPR), not discussed in this work. The method is similar to SPR, but in this case the primary energy factors should not be fixed by authorities but self-determined according to the energy production scenario of the area of interest.

The scientific papers selected for this work are summarized in Table 1. The percentages for electricity (first value) and heat (second value – steam and or hot water) are given for fuel consumption and emissions in each cell. The methods (Table 1) have the following principles. The *IECR* and *IHCR* assign the entire cogeneration savings benefit to heat or electricity production, respectively, giving a very little share of fuel consumption and/or emissions to heat (for IECR) and electricity (for IHCR). The percentage relating to electricity is higher in both cases because the facility produces more electricity than heat. The two methods adopt the system substitution a variant of system expansion, satisfying the primary energy balance. It could lead to negative inventory flows (JRC, 2010).

The *SPR* method considers the fuel consumption and/or emissions required to produce the same amount of electricity and heat in separate production facilities, operating with the reference primary energy factors (fixed by authorities). This approach is also used by the International EPD System Program (Capello et al., 2019).

Table 1: summary of articles on multifunctional approaches and methods in cogeneration. Cells containing "eks" represent the lack of results not provided by authors or not clear values

Reference	**Approach and method to calculate allocation factors**							
	Relationships beyond the system boundaries			**Physical relationships**		**Using other relationships**		
	IECR	**IHCR**	**SPR**	**Exergy**	**Energy**	**Electricity**	**Heat**	**Price**
Beretta et al. (2012)	88% 12%	61% 39%	69% 31%	81% 19%				
Caserini et al. (2019)	X[1]							
Dones et al. (2007)				78% 22%	62% 38%	100% 0%	0% 100%	62% 38%
Heck (2007)				76% 24%	36% 64%	100% 0%	0% 100%	65% 35%
Jungmeier et al. (1998)	X[2]	X[2]		44% 56%	14% 86%	100% 0%	0% 100%	24%

Reference	Approach and method to calculate allocation factors							
	Relationships beyond the system boundaries			Physical relationships		Using other relationships		
	IECR	IHCR	SPR	Exergy	Energy	Electricity	Heat	Price
								76%
Karlsdottir et al. (2020)			73% 27%					
Karlsson et al. (2018)				70% 30%	67% 33%			20% 80%
Noussan (2018)	X[1]							
Olsson et al. (2015)			60% 40%	80% 20%	45% 55%	100% 0%	0% 100%	
Rosen (2008)	X	X	X	X	X			X

[1] System substitution applied in district heating systems.

[2] In this case the authors provide credit for electricity and heat. A negative value indicates an avoided fuel consumption. For example, the IHCR was calculated from a heavy oil-fired heating plant (thermal efficiency 80%), in which a significant reduction of emissions was obtained by replacing the plant (heavy oil-fired) and giving the produced electricity a negative emission. The authors for both methods did not provide the percentages.

According to the *Exergy* method, each type of energy produced by the facility brings with it an exergetic value equal to the minimum exergy to obtain it and also implies a quantity of exergy destroyed for irreversibility in its realization (second law of thermodynamics). The sum of these two exergies represents the "cost" - in exergetic terms - allocated to the energy produced in question (downstream of the energy system). In the CHP case, the method allocates entropy production for irreversibility based on the exergetic content of each type of energy produced (electricity, steam, and hot water). Whereas, the *Energy* method is based on the energy balance (first law of thermodynamics), obtained by dividing the energy content of the product by the overall energy used by the CHP plant (Gyftopoulos and Beretta, 2005).

The allocation methods *Electricity* and *Heat* consider as a by-product the heat or the electricity respectively. Thus for the *Electricity* method, heat is assessed as burden-free vice versa for *Heat*, electricity is assessed as burden-free. The allocation method called *Price* describes an economic allocation based on the market price of electricity and heat (in this article, referring to the purchase prices).

Table 2 provides equations related to fuel consumption (not on emissions) for the eight methods selected.

Table 2: methods analyzed in this paper. For acronyms see Table 3

Method	Electricity [A_W]	Steam [A_S]	Hot water [A_{HW}]
IECR	$\frac{f_{W,sep} * W}{(f_{W,sep} * W + f_{Q,CHP} * Q}$	$\frac{f_{Q,CHP} * Q_S}{(f_{W,sep} * W + f_{Q,CHP} * Q}$	$\frac{f_{Q,CHP} * Q_{HW}}{(f_{W,sep} * W + f_{Q,CHP}}$
IHCR	$\frac{f_{W,CHP} * W}{(f_{W,CHP} * W + f_{Q,sep} * Q}$	$\frac{f_{Q,sep} * Q_S}{(f_{W,CHP} * W + f_{Q,sep} * Q}$	$\frac{f_{Q,sep} * Q_{HW}}{(f_{W,CHP} * W + f_{Q,sep}}$
SPR	$\frac{f_{W,sep} * W}{(f_{W,sep} * W + f_{Q,sep} * Q)}$	$\frac{f_{Q,sep} * Q_S}{(f_{W,sep} * W + f_{Q,sep} * Q}$	$\frac{f_{Q,sep} * Q_{HW}}{(f_{W,sep} * W + f_{Q,sep}}$
Exergy	$\frac{Ex_W}{(Ex_W + Ex_S + Ex_{HW})}$	$\frac{Ex_S}{(Ex_W + Ex_S + Ex_{HW})}$	$\frac{Ex_{HW}}{(Ex_W + Ex_S + Ex_{HW}}$
Energy	$\frac{W}{(W + Q_S + Q_{HW})}$	$\frac{Q_S}{(W + Q_S + Q_{HW})}$	$\frac{Q_{HW}}{(W + Q_S + Q_{HW})}$
Electricity	100%	0%	0%
Heat	0%	$\left(\frac{Q_S}{Q_S + Q_{HW}}\right)$	$\left(\frac{Q_{HW}}{Q_S + Q_{HW}}\right)$
Price	$\frac{p_W * W}{(p_W * W + p_Q * Q)}$	$\frac{p_Q * Q_S}{(p_W * W + p_Q * Q)}$	$\frac{p_Q * Q_{HW}}{(p_W * W + p_Q * Q)}$

Table 3 shows the descriptions of variables presented in Table 2.

Table 3: variables showed in Table 2

Variable	Description
A_W, A_S, and A_{HW}	Allocation factors for electricity, steam, and hot water.
$f_{W,CHP}$ and $f_{Q,CHP}$	Primary energy factor for the cogenerated electricity and heat.
$f_{W,sep}$ and $f_{Q,sep}$	Primary energy factor for the separately produced electricity and heat.
p_W and p_Q	Unit price for purchased electricity and heat.
Ex_W, Ex_S, and Ex_{HW}	Exergy for electricity, steam, and hot water.
W, Q, Q_S, and Q_{HW}	Net electricity, heat (steam plus hot water), steam, and hot water production in CHP plant.

b. Case study

A real CHP plant installed in a dairy placed in Lombardy Region (Northern Italy) was taken as a case study to test the multifunctional approaches and methods described in section 2.1. The plant is a reciprocating internal combustion engine that consumes natural gas to produce electricity and heat in steam and hot water forms. The electrical and thermal nominal powers are approx. 2.7 MW (efficiency 44.3%) and 2.6 MW (efficiency 42.2%) respectively. The energy obtained by the CHP plant is used to produce cheeses (i.e., Grana Padano PDO and Provolone Valpadana PDO), treated milk, butter, and other dairy products. Figure 1 shows the flow chart of the energy system under analysis.

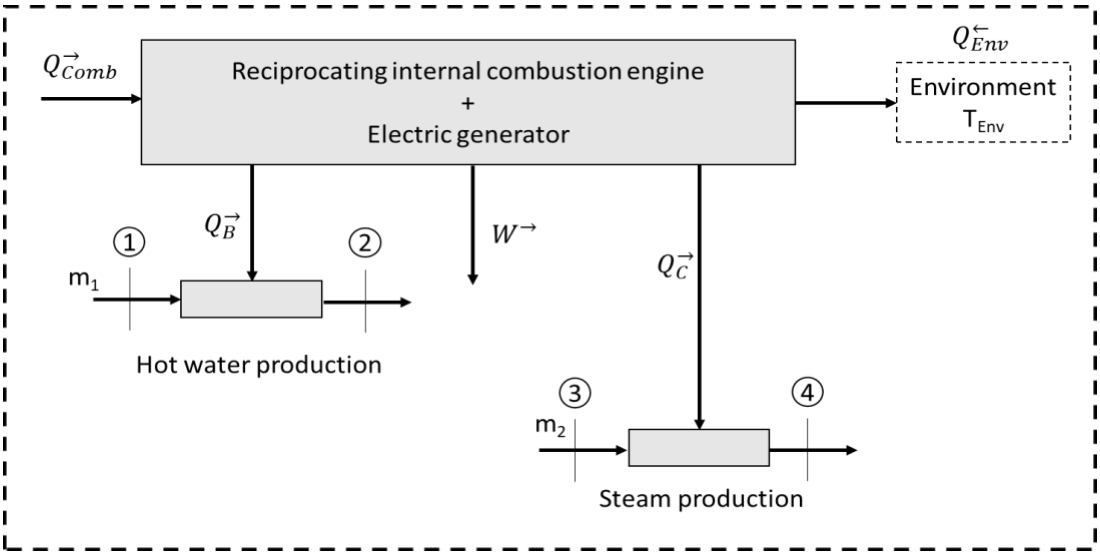

Figure 1: combined heat and power plant analyzed

During the year of analysis, the plant consumed 4 060 606 Nm^3 of natural gas, equal to 41 508 MWh ($Q_{Comb}^{\rightarrow}$), considering a Lower Heating Value (LHV) of 36.8 MJ per Nm^3 (Emmenegger et al., 2012). As a result, the CHP produced: 17 684 MWh ($W^{\rightarrow}$) of electricity, 11 064 MWh of heat :3 722 MWh ($Q_B^{\rightarrow}$) for hot water, and 7 342 MWh ($Q_C^{\rightarrow}$) for steam production. For the heat production (hot water and steam), the supply (T_{supply}^2, T_{supply}^4) and the return ($T_{return}^1 T_{return}^1$, T_{return}^3) temperatures are 363.2 K (90°C), 448.6 K (175.4°C), 338.2 K (65°C), and 363.2 K (90°C). Equations 1 and 2 provide the thermodynamic efficiency (69%) and effectiveness (49%) for the CHP plant under analysis.

$$\eta_I = \frac{W^{\rightarrow} + Q_B^{\rightarrow} + Q_C^{\rightarrow}}{Q_{Comb}^{\rightarrow}} \quad (1)$$

$$\eta_{II} = \frac{W^{\rightarrow} + Q_B^{\rightarrow} * \left(1 - \frac{T_{Env}}{T_B}\right) + Q_C^{\rightarrow} * \left(1 - \frac{T_{Env}}{T_C}\right)}{Q_{Comb}^{\rightarrow}} \quad (2)$$

Where T_{Env} is the temperature of the environment fixed equal to 288.15 K (15°C), T_B and T_C are log-mean temperatures equal to 350.0 K (76.8°C) and 401.1 K (128.0°C), provided by equation 3 (Gyftopoulos and Beretta, 2005).

$$T_{B\ or\ C} = \frac{T_{supply}^{2\ or\ 4} - T_{return}^{1\ or\ 3}}{ln\left(\frac{T_{supply}^{2\ or\ 4}}{T_{return}^{1\ or\ 3}}\right)} \quad (3)$$

3. Results and discussion

Applying the eight selected methods, chosen to allocate the amount of fuel consumed (and the relative potential environmental emissions) by the CHP plant, described in section 2, the results showed numerically in Table 4 and graphically in Figure 3 were obtained.

For the approach type relationships beyond the system boundaries, the primary energy factors provided by the Decree n. 176/2017 were used (Regione Lombardia, 2017). In detail, the primary energy values utilized for the separately produced electricity and heat are the following, 2.42 for $f_{W,sep}$ and 1.12 for $f_{Q,sep}$, considering a boiler efficiency equal to 94% based on LHV (Wernet et al., 2016) as reference. The primary energy factors for the cogenerated electricity and heat were assessed by equations 4 and 5, using the $f_{CHP,fuel}$ equal to 1.05 (primary energy factor for natural gas, input of the CHP plant).

$$f_{W,CHP} = \frac{f_{CHP,fuel} * Q_{Comb} - f_{Q,sep} * Q}{W} \qquad (4)$$

$$f_{Q,CHP} = \frac{f_{CHP,fuel} * Q_{Comb} - f_{W,sep} * W}{Q} \qquad (5)$$

Table 4: results obtained by different allocation method

Method	**Electricity**	**Steam**	**Hot water**
IECR	98%	1%	1%
IHCR	72%	19%	9%
SPR	78%	15%	7%
Exergy	87%	10%	3%
Energy	61%	26%	13%
Heat	0%	66%	34%
Electricity	100%	0%	0%
Price	77%	15%	8%

The data for the economic values used in the *Price* method were obtained from two reports provided by the Italian Regulatory Authority for Energy, Networks, and Environment (ARERA) and A2A S.p.A, both net of taxes. (Italian multi-utility that operates in energy, heat, networks, etc.). ARERA (2019) provides the purchase price for medium voltage electricity, non-domestic customers, stated equal to 140.00 € per MWh. A2A (2019), instead, provides the purchase price of heat for non-domestic consumers, stated equal to 65.00 € per MWh (value used for both steam and hot water).

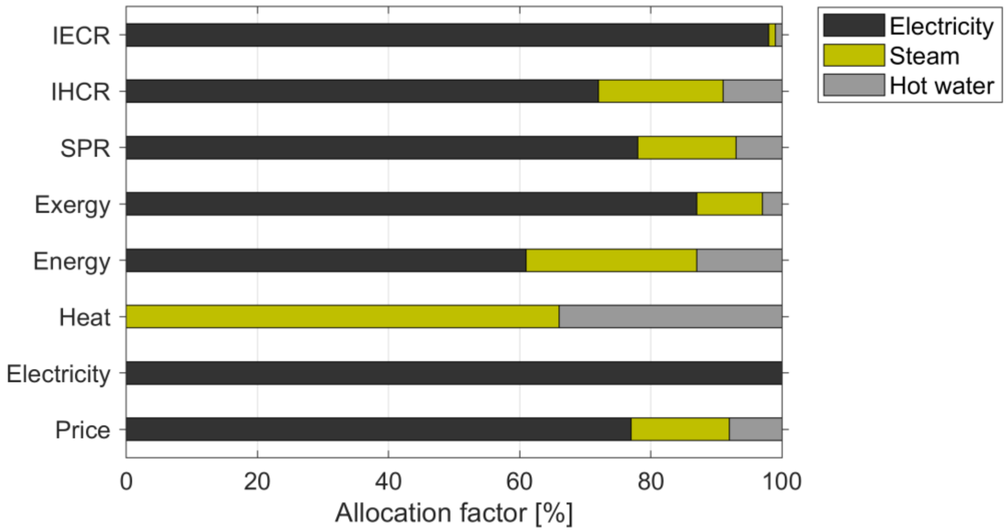

Figure 2: results obtained by different allocation methods

As expected, excluding the *Electricity* and *Heat* method, the fraction of fuel consumed to be allocated to electricity is the main contribution, ranging from 61% to 98%. On the other hand, steam and hot water ranging from 1% to 26% (steam) and from 1% to 13% (hot water).

Energy and *IECR* allocate the lowest and highest amount of fuel to electricity, equal to 61% and 98%, respectively.

Applying the ISO hierarchy approach (within the allocation – partitioning the inputs and outputs between the co-functions), the *SPR* method seems to be the most appropriate between the relationships beyond the system boundaries methods, in compliance with cogeneration regulations (Beretta et al., 2012). The *SPR* method splits the amount of fuel as follows: 78% to electricity, 15% to steam, 7% to hot water, resulting fairer than *IECR* and *IHCR* methods, both unbalanced in favor of heat or electricity. Surprisingly, this method appears to provide similar results to the economic method, *Price*. The results obtained by the *Price* method are the following: electricity (77%), steam (15%), and hot water (8%), approx. only 1% different from the SPR method.

Considering the results obtained, *IECR* and *Exergy* methods were in line with what was found by previous authors (Beretta et al., 2012; Dones et al., 2007; Heck, 2007; Olsson et al., 2015). Indeed for *IHCR*, *SPR*, *Energy*, and *Price*, the results achieved are slightly higher compared to Beretta et al. (2012), Dones et al. (2007), Heck (2007), Jungmeier et al. (1998), Karlsdottir et al. (2020), Karlsson et al. (2018), and Olsson et al. (2015).

Regarding the economic allocation, the achievement of different results is related to the geographical boundaries (other countries with different prices). This statement appears to apply not only to the economic allocation but also to the methods under the relationships beyond the system boundaries approach: countries have different primary energy factors, mainly due to different energy mix for electricity generation. Other variations are linked to the type of CHP plants analyzed: each type of energy system (i.e., turbogas, turbosteam, reciprocating internal combustion engines, etc.) has its efficiency and effectiveness.

4. Conclusions

This work aimed to review the methods applied in scientific articles, in compliance with ISO 14044 (ISO, 2006), to deal with multifunctionality in CHP plants. Subsequentially, to apply all the methods to a case study in order to test them. The results obtained were consistent with what was found by previous authors.

Even if the ISO proposes a hierarchy procedure to manage the amount of fuel among the different co-products (electricity and heat), therefore privileging the relationships beyond the system boundaries approach (closer to the expanding the product system), the other approaches can, however, be applied in some cases. Such as, *Price* and *Electricity* allocations can be used for CHP facilities that consume biogas, where the heat produced is used entirely to generate biogas and digestate within the biodigester (closed-loop). The Ecoinvent database (Wernet et al., 2016) provides for attributional dataset concerning CHP plants, allocation methods based on *Exergy* and *Price*.

Awaiting future standardization developments and considering that the *SPR* method is still under discussion (Beretta et al., 2012), it is suggested to evaluate the methods proposed through sensitivity analyses.

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