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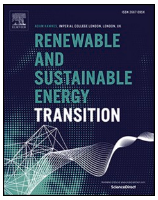

Full-length article

Allocation of carbon dioxide emissions to the by-products of combined heat and power plants: A methodological guidance

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ABSTRACT

Cogeneration has higher efficiency than separate heat and power generation. Since both are generated in a single process, it is necessary to allocate the emissions to by-products for comparing their environmental performance. Numerous methods exist resulting in very different allocations. There is no consensus regarding the method choice. The main objective of this article is the development and implementation of an evaluation scheme allowing the choice of an appropriate method for specific applications. This scheme consists of nine criteria in the categories "Applicability", "Environmental relevance", and "Systematic approach" allowing a rating. The Finnish method performs best for a standard use case resulting in emission factors of 322 g CO_2 / kWh_{el} and 192 g CO_2 / kWh_{th}. Both are associated with less emissions per unit then the electricity and district heating mix of Germany in 2020 that were 375 g CO_2 / kWh_{el} and 270 g CO_2 / kWh_{th}. Therefore, cogeneration electricity and heat could contribute to climate protection in the short- to mid-term. The implementation of two sensitivity analyses shows that the location and country-specific emission factors can have a great influence on the results and the contribution to climate protection. Depending on use case and individual importance of certain criteria the Energy, the Exergy or the Greenhouse Gas method can be preferable. Each scored with one point less than the Finnish method. In contrast to existing publications, this study supports decision-makers in transparently selecting an appropriate allocation method when assessing the products of cogeneration by considering different criteria.

1. Introduction

Combined heat and power (CHP) is defined as the simultaneous generation of electric and thermal energy within a single thermodynamic process [1]. This results in a higher overall efficiency than separate heat and power generation. Hence, CHP can reduce both primary energy demand and greenhouse gas (GHG) emissions [1,2]. Nevertheless, the reduction of primary energy depends on the total efficiency of the CHP plant. In this regard, high efficiency CHP plants as defined by the European Energy Efficiency Directive [3] are of special importance. Regarding the reduction of GHG emissions, CHP can play an important role for climate protection on a short- to mid-term level if low-emission energy sources such as natural gas or biomethane are used. However, the percentage share of renewable energies in the conventional electricity mix of countries worldwide is increasing. This leads to a shift in the contribution of CHP plants to climate protection, as grid electricity becomes less emission intensive over the time and the provision of heat is more and more electrified. Therefore, CHP emissions need to be compared to emissions related to grid electricity and district heating. Only when CHP entails the substitution of fossil fuels, the integration into the energy mix can be beneficial. In the future, it is necessary that CHP plants can be operated flexibly to contribute to balancing fluctuating power generation of renewable energy systems [4]. Life Cycle Assessment (LCA), Carbon footprint, and internal carbon dioxide (CO_2) budgeting for a CHP process require the emissions to be specifically allocated to both products. For these reasons, numerous methods for allocating CHP emissions exist. However, choosing the appropriate allocation method for a specific use case can be challenging and depending on the chosen method the results can vary greatly.

By examining and comparing twelve different allocation methods for CHP generation, this study provides a guidance for selecting an appropriate allocation method for specific use cases. To frame this study a literature review of existing allocation methods is carried out in Section

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Nomenclature

Abbreviations and Acronyms

CO_2	carbon dioxide
CHP	combined heat and power
DIN	German Institute for Standardization
EN	European Standard
EU	European Union
Ex	exergy
GHG	greenhouse gas
ISO	international Organization for Standardization
LCA	Life Cycle Assessment
pes	primary energy savings
spec. GHG	specific greenhouse gas emissions
VDI	the Association of German Engineers

Latin Symbols

C	costs
n	number of
T	temperature
W	energy quantity

Greek Symbols

η	efficiency
ϑ	power loss factor
ν	quality factor

Units

€	Euro
g	gram
K	Kelvin
kWh	kilowatt hour
t	tonne

Subscripts

a	ambient
C	Carnot
cold	cold medium
crit	criteria
dis	displacement mix
el	electricity
fin	Finnish method
hot	hot medium
i	considered category
in	input
LC	life cycle
loss	losses
m	thermodynamic mean
new	new value used
out	output
ref	reference technology
saved	emissions saved
SWE	Sweden
th	thermal energy
tot	total

2. In order to allow a profound and time efficient choice of the most suitable allocation method, an evaluation scheme is developed and introduced as methodology in Section 2 as well. The theory of the considered allocation methods is described in detail in Section 3 and applied to a case study and two sensitivity analyses that refer to that case study in Section 4. Afterwards, the evaluation scheme is applied to the different allocation methods and the results are presented in Section 5. Finally, these results are discussed in Section 6 and summarized in Section 7.

2. Material and methods

2.1. Data Basis

Methods for allocating GHG emissions are widely discussed throughout literature. In this context, the following twelve allocation methods are further considered in this study as these are the most referenced ones:

1. Energy method: Based on the efficiency of heat and electricity.
2. Efficiency method: Based on the efficiencies but in revers to the Energy method.
3. Electricity Reduction method: Considers a power loss factor.
4. Exergy method: Considers the energies qualities instead of their quantities.
5. Dresden method: Similar to the Exergy method but takes into account an additional quality factor.
6. Exergy Loss method: Considers the exergy losses occurring during the CHP process.
7. Substitution method: Based on a reference scenario in which the products are generated separately and can be divided into the Power Substitution method and the Heat Substitution method.
8. Remainder Value method: Similar to the Substitution method as the Heat Remainder Value method corresponds to the Power Substitution method and the Power Remainder Value method corresponds to the Heat Substitution method.
9. Displacement Mix method: A variation of the Heat Remainder Value / Power Substitution method whose reference scenario is the displacement mix.
10. Finnish method: Considers the primary energy savings compared to a reference scenario with separate generation.
11. GHG method: Similar to the Finnish method but considers the GHG emission savings instead of the primary energy savings.
12. Economic Values method: Takes into consideration an economic value, e.g., the costs, as allocating factor.

An overview of the relevant literature that refers to at least one of the considered allocation methods and the methods each study refers to is given in Table 1. Moreover, Table 1 presents in which publications one allocation method or an approach for selecting a method is recommended. Also, the research topic of each publication is given with reference to the allocation methods in Table 1.

This review shows that there has never been a study which considers and compares a broad variety of twelve different allocation methods before. Furthermore, there is no consensus on which allocation method to use and even no guidance for transparently selecting an appropriate allocation method for specific use cases. Therefore, the main objective of this study is to develop an evaluation scheme for transparently comparing allocation methods based on different criteria. Such an evaluation scheme illustrates the advantages and disadvantages of the allocation methods which allows the identification of further methods that may be best suited under consideration of individual preferences.

2.2. Evaluation scheme

To compare the considered allocation methods, the methods are applied to a case study. The necessary values are taken from the relevant literature or are based on own calculations and assumptions. Secondly, the allocation methods are evaluated using a newly developed evaluation scheme. In its main features, in particular, the evaluation based on a point scale, this scheme is based on a study from Forin et al. [28] but is adapted for comparing allocation methods. The scheme consists of three categories: Applicability, Environmental relevance, Systematic approach. Each category comprises a varying number of criteria. Within the different criteria scores are awarded in a range of zero to three. To evaluate all categories equally, weighting factors are introduced in accordance with Formula (1). $n_{crit,1}$ is the number of criteria in category 1 whereas $n_{crit,i}$ describes the number of criteria in the considered category i. This results in a weighting factor of one for the first category, of two for the second category and of four thirds for the third category.

$$\text{weighting factor} = n_{crit,1} / n_{crit,i} \tag{1}$$

The scoring within criterion 1.1 is based on the minimum, maximum, and mean number of required parameters that are five, eleven, and seven, respectively. Criterion 1.4 addresses the quality of the energy types. Evaluating a method better when it considers both quantity and quality is based on the assumption that from a physical point of view it is most reasonable to consider that heat can only be converted into work to a limited extent while electricity can be converted completely [9]. Criterion 3.1 considers the twenty-one publications described in Section 2.1 as reference number. If two thirds or more of the considered publications refer to a method, it is scored best. A method scores with one and a half points, if less than two thirds but one third or more refer to this method. If less than seven publications consider a method, it is rated the worst. Within criterion 3.3 all uncertain values were assigned an uncertainty of ± 5 %. The new results are compared to the original ones. After calculating the uncertainties of the possible combinations regarding one method, the median uncertainty for both electricity and heat are determined and weighted equally. This means that, if only one of the two values exceeded a limit of 5 % or 10 %, this is representative for the whole method. A detailed description of all criteria is given in Table 2.

3. Theory of allocation methods

Allocation methods can be divided into methods which are based on the provided amount of energy and methods which consider the separate production of power and heat [20]. The first category includes the Energy, the Efficiency, the Electricity Reduction, and the Exergy method [20]. The Dresden method builds on the Exergy method [25] and is therefore assigned to this category. The second category comprises the Exergy Loss, the Remainder Value, the Substitution, the Displacement Mix, and the Finnish method [20]. As a variation of the Finnish method [19], the GHG method belongs to this category as well. Besides those two categories, another category is identified that is not based on physical properties at all. This category comprises the allocation based on economic values as well as further methods, which assign a fixed proportion of emissions to power or to heat. The following sections explain the allocation methods in detail.

3.1. Methods based on the provided amount of energy

The Energy method is the most commonly used method for allocating GHG emissions to the products of a CHP plant due to its simplicity [12]. The uncomplicated calculation [18] evaluates the two by-products equally based on their proportion according to the overall CHP efficiency [7]. This means that the product with the higher efficiency and thus the higher share of output consequently has to account for the higher share of emissions [10]. The problem within the Energy method is that only the quantity and not the quality is considered [9]. Since the different working capacities of heat and power are not taken into account [20], the Energy method results in an advantageous evaluation of electricity generation [9].

The Efficiency method is very similar to the Energy method with the only difference that the allocation takes place in reverse [10]. This method assigns the efficiencies of heat and power to the respective other product [7]. This results in a higher share of emissions for the product with the lower efficiency [10]. Since heat has the higher efficiency, the advantageous evaluation of the electricity generation is mitigated compared to the Energy method.

The Electricity Reduction method is based on steam power plants with an extraction condensing turbine [20]. The heat extraction causes the electrical power to decrease which is considered by a power loss factor that consequently relates to the amount of energy diminished [8, 20]. This means that the calculation considers only the part of the thermal energy which could be used for further electricity generation if there were no heat extraction [5]. Since for the additional generation of heat an increased fuel demand is necessary this method is based on the polluter-pays principle [25].

The Exergy method not only considers the quantity but also the quality of the generated energies [26]. Therefore, exergy and energy are set in relation with each other [13]. The ratio of electricity is one whereas the ratio regarding heat is less [13]. This means that heat cannot be converted into work completely [9]. The exergy of heat can be determined by the Carnot factor meaning that the exergy amount depends on the surrounding conditions [7,9]. Altogether, this method allocates less emissions to heat than the Energy method [13].

The Dresden method is based on an exergetic calculation as well but takes into account a further quality factor that, in turn, considers specific losses [25]. Thus, the Dresden method allocates even less GHG emissions to heat than the Exergy method [25]. This method describes the evaluation of power losses in accordance with the extraction of heat as power is the target product [12,25].

3.2. Methods based on separate production

The Exergy Loss method compares the exergy losses of a CHP plant with a reference process [5]. Since the exergy of the required fuel increases with rising losses, this method illustrates the saved or additional consumption of fuel exergy due to the CHP plant [5]. Based on this, the primary energy and thus the specific GHG emissions can be allocated to the products [6]. As a result, the higher amount of GHG emissions is allocated to the product with the higher amount of exergy respectively to the product with fewer exergy losses [20].

The Remainder Value method allocates a specific amount of emissions to one of the two products and only the remaining emissions to the other product [6]. This method can be used if contractual requirements preset a specific amount of fuel energy for one product [5]. If there is no such contractual requirement, the emissions of a decoupled power or heat production are determined at first [20]. The remaining emissions are then allocated to the other product which is consequently allocated with the smaller amount of emissions [20].

The Substitution method is based on the assumption that an additional fuel demand is needed for the CHP process that is determined by the difference in fuel demand for a CHP plant and for a separate heat or power generation [6]. The emissions that are emitted during the separate production are allocated to the main product while the rest of the CHP emissions are allocated to the by-product [13,25]. Thus, this method underestimates the emissions allocated to the by-product [10]. Since the Substitution method is very similar to the Remainder Value method, Brautsch and Lechner equate the Power Remainder Value method with the Heat Substitution method and the Heat Remainder Value method with the Power Substitution method [20].

One version of the Power Substitution method is the Displacement Mix method that considers the displacement mix as reference scenario [10]. The displacement mix represents the energy plants that are displaced by the additional CHP electricity generation [10]. Therefore, those power plants must be identified that are displaced due to the CHP use [10]. By considering specific fuel utilization and emission factors, the total emission factor of the displacement mix can be determined

Table 1
Overview of relevant literature and the allocation methods considered by each publication.

Literature	[5]	[6]	[7]	[8]	[9]	[10]	[12]	[13]	[14]	[15]
Energy	×	×	×	×	×	×	×	×	×	×
Efficiency			×			×				
Electricity Reduction	×	×		×	×					
Exergy	×	×	×	×	×		×	×	×	×
Dresden							×			
Exergy Loss	×	×								
Substitution / Remainder Value	×	×	×	×		×		×	×	×
Displacement Mix										
Finnish		×	×			×				
Greenhouse Gas										
Economic Value								×	×	×
Further							×			×
Recommendation			Analysis of all possible methods			No method is preferable	Analysis of all possible methods			Selection should be based on scope and goal of the use case
Research topic	Allocation of emissions from CHP processes.	Calculation of target energy related emissions for energy conversion.	Provision of decision support for the cost breakdown of CHP processes.	Comparison of allocation methods summarizing that the chosen method can strongly influence the CO_2 intensity.	Identification of one allocation method which can be used consistently.	Comparison and application of allocation methods, referencing VDI guideline 4661 [11].	Identification of a best practice allocation method.	Analysis of emission allocation of a diesel-fired CHP plant.	Provision of an overview of CHP in Canada.	Investigation of allocation in the context of biorefinery systems.

[10].

The Finnish method compares the primary energy saved in a CHP plant to a reference system with separate production [20]. This reference system has to be based on state of the art technology so that no overestimation of the saved fuel occurs [10]. Harmonized reference values can be found in the Delegated Regulation (EU) 2015/2402 [29] and should be used in accordance with EU Directive 2012/27/EU [3]. Nevertheless, the obligation to use the same fuel as in the CHP system does not reflect the actual situation on site, such as the availability of renewable energies, which limits the validity of the corresponding results [30]. Although CHP efficiencies are lower than those of the reference system the fuel consumption, and thus the GHG emissions are decreasing [19]. The emissions are allocated to the products according to the amount of fuel consumption in the reference processes [6]. The Finnish method is the allocation method used by the German Federal Environmental Agency to balance CHP electricity and heat in the German electricity and district heating mix [31].

The GHG method is based on the same calculation concept as the Finnish method but takes into account GHG emissions instead of efficiencies [19]. Thus, it is possible to determine the emission savings of the CHP plant in the same way as the energy savings are determined within the Finnish method [19].

3.3. Methods based on non-physical properties

If CHP power and heat are sold separately, it can be reasonable to base the allocation method on economic values, such as the selling price of one product unit [13,24,32]. This method can reflect different qualities of similar products, if the economic value represents this quality [32].

Moreover, all emissions can be allocated to one product only. However, it should be noted that this method should not be used [19]. Further methods allocate 50 % of the emissions to each product [33] or represent contractual agreements between different parties [14], defining the amount of emissions allocated to each product.

3.4. Method comparison concerning specific GHG emissions

Table 3 presents the calculation rules for the considered methods. The equations are based on the explanations and the respective literature given in Sections 3.1 to 3.3. The methods that allocate GHG emissions based on fixed proportions are not considered as mathematical based allocations. The units of the parameters given in Table 3 can be found in Tables 4 and 5.

4. Case study

In the following, the elaborated allocation methods are applied in one case study and two sensitivity analysis. In the first sensitivity analysis, the efficiencies of the reference CHP plant are changed. In the second sensitivity analysis the CHP location is changed leading to a change of the specific GHG emissions of the electricity mix and its efficiency as well as of the efficiency of the displacement mix.

4.1. Reference system

The basis for the case study is a CHP plant with an installed capacity of 100 kW and 5,000 annual full load hours. Consequently, the CHP operates with 500,000 kWh natural gas as energy input W_{in} (Table 4). Due to the combustion of natural gas, the CHP plant emits 202 g CO_2 / kWh or, if the upstream chain is considered, 223 g CO_2 / kWh (Table 4). The electric efficiency η_{el} of the CHP is assumed to be 0.30 (Table 4), which is based on the values given by the German Federal Environmental Agency [4].

$$\eta_{th} = \eta_{tot} - \eta_{el} \tag{2}$$

In accordance with Formula (2), the thermal efficiency η_{th} is 0.55, which results from subtracting the electric efficiency η_{el} from the total efficiency η_{tot}, which corresponds to 0.85 [4]. Considering these efficiencies and the energy input, the natural gas combustion results in an electric energy output $W_{out,el}$ of 150,000 kWh and in a thermal output

[16]	[17]	[18]	[19]	[20]	[22]	[23]	[24]	[25]	[26]	[27]
×	×	×		×	×	×		×	×	×
			×	×				×	×	
				×						×
×	×	×		×	×	×		×	×	×
								×		×
				×				×		
		×	×	×				×		×
				×						
			×	×	×			×		
			×							
×		×				×	×			×
×	×				×					×
		Exergy method	Finnish method	Finnish method	Further	Economic Values				
Comparison of different allocation methods.	Comparison of traditional allocation methods to the thermoeconomic allocation and an exergoenvironmental analysis illustrating their advantages and disadvantages.	Application of allocation methods on a standard use case.	Determination of specific emission factors for district heating in Germany.	Conduction of an ecologic and economic analysis to identify possibilities for increasing efficiency and profitability of CHP taking into account CHP directive 2004/8/EG [21].	Discussion of allocation methods in the context of a CHP plant in South Korea.	Provision of a recommendation considering emissions as well as costs.	General review of allocation, focusing on the Economic Values method.	Examination of the exergetic optimization of various municipal energy supply and purchase systems in terms of a possible CO_2 reduction.	Application of allocation methods on a case study within the paper industry.	Illustration of the limits and strengths of different allocation methods.

$W_{out,th}$ of 275,000 kWh.

Assuming that the CHP plant is located in an installation room with an ambient temperature T_a of 298.15 K, the supply temperature T_{hot} is 353.15 K according to Vogel et al. and the return temperature T_{cold} is constantly 333.15 K (Table 4) [35]. Considering these temperatures in the respective equations (Table 3) the result is a thermodynamic mean temperature T_m of 343.05 K and a Carnot factor η_C of 0.13. The Carnot factor is calculated based on the formula given in Table 3 [44]. Values for separate heat and power generation are displayed for comparison reasons. The electric reference system is the purchase of electricity based on the German electricity mix. A national electricity mix is chosen since it does not matter for climate change mitigation where exactly a

Table 2

Criteria for comparing allocation methods summarized in an evaluation scheme.

Criterion	Considered aspects	Score
1. Applicability (weighting factor: 1)		
1.1. Calculation effort	Number x of parameters required by a method	• $x \geq 9$ (0 points) • $9 > x \geq 7$ (1.5 points) • $7 > x$ (3 points)
1.2. Data availability	Availability of the required data	• Assumptions (0 points) • Calculations (1.5 points) • Measurements (3 points)
1.3. Availability of methodological guidelines	Availability of methodological guidelines and/or a standard	• No methodological guideline is available (0 points) • Methodological guideline is available (1.5 points) • Standard is available (3 points)
1.4. Consideration of energy quality	Consideration of the quality of the energy types in addition to their quantity	• Only quantity (0 points) • Quantity and quality (3 points)
2. Environmental relevance (weighting factor: 2)		
2.1. Consideration of environmental concerns	Consideration of aspects relevant for climate change within the allocation factor	• No inclusion (0 points) • Inclusion (3 points)
2.2. Scope of the considered aspects	Inclusion of life cycle stages	• Only processes during the use phase (0 points) • Also upstream and/or downstream processes (3 points)
3. Systematic approach (weighting factor: 4/3)		
3.1. Scientific soundness	The considered publications x refer to the method	• $x < 7$ (0 points) • $7 \leq x < 14$ (1.5 points) • $x \geq 14$ (3 points)
3.2. Plausibility of results	Occurrence of negative values	• Yes (0 points) • No (3 points)
3.3. Stability regarding uncertainties	Difference of the results when uncertain input data (± 5 %) are used	• At least one result deviates by more than 10 % (0 points) • At least one result deviates by 5 % to 10 % (1.5 points) • Both results deviate by less than 5 % (3 points)

Table 3
Comparison of the calculation rules of the allocation methods taken into consideration.

Allocation method	Calculation
Energy method	$\mathrm{spec.\ GHG_{el}} = \dfrac{\mathrm{spec.\ GHG_{in}} \times \frac{\eta_{el}}{\eta_{el}+\eta_{th}} \times \mathrm{W_{in}}}{\mathrm{W_{out,el}}}$ $\mathrm{spec.\ GHG_{th}} = \dfrac{\mathrm{spec.\ GHG_{in}} \times \frac{\eta_{th}}{\eta_{el}+\eta_{th}} \times \mathrm{W_{in}}}{\mathrm{W_{out,th}}}$
Efficiency method	$\mathrm{spec.\ GHG_{el}} = \dfrac{\mathrm{spec.\ GHG_{in}} \times \frac{\eta_{th}}{\eta_{el}+\eta_{th}} \times \mathrm{W_{in}}}{\mathrm{W_{out,el}}}$ $\mathrm{spec.\ GHG_{th}} = \dfrac{\mathrm{spec.\ GHG_{in}} \times \frac{\eta_{el}}{\eta_{el}+\eta_{th}} \times \mathrm{W_{in}}}{\mathrm{W_{out,th}}}$
Electricity Reduction method	$\mathrm{spec.\ GHG_{el}} = \dfrac{\mathrm{spec.\ GHG_{in}} \times \mathrm{W_{in}}}{\mathrm{W_{out,el}} + (\vartheta \times \mathrm{W_{out,th}})}$ $\mathrm{spec.\ GHG_{th}} = \vartheta \times \mathrm{spec.\ GHG_{el}}$
Exergy method	$\eta_C = 1 - \dfrac{\mathrm{T_a}}{\mathrm{T_m}}$ $\mathrm{T_m} = \dfrac{\mathrm{T_{cold}} - \mathrm{T_{hot}}}{\ln\frac{\mathrm{T_{cold}}}{\mathrm{T_{hot}}}}$ $\mathrm{spec.\ GHG_{el}} = \dfrac{\mathrm{spec.\ GHG_{in}} \times \frac{\eta_{el}}{\eta_{el}+(\eta_C \times \eta_{th})} \times \mathrm{W_{in}}}{\mathrm{W_{out,el}}}$ $\mathrm{spec.\ GHG_{th}} = \dfrac{\mathrm{spec.\ GHG_{in}} \times \frac{\eta_C \times \eta_{th}}{\eta_{el}+(\eta_C \times \eta_{th})} \times \mathrm{W_{in}}}{\mathrm{W_{out,th}}}$
Dresden method	$\mathrm{spec.\ GHG_{el}} = \dfrac{\mathrm{spec.\ GHG_{in}} \times \frac{\mathrm{W_{out,el}}}{\mathrm{W_{out,el}} + (\mathrm{W_{out,th}} \times \eta_C \times \nu)} \times \mathrm{W_{in}}}{\mathrm{W_{out,el}}}$ $\mathrm{spec.\ GHG_{th}} = \dfrac{\mathrm{spec.\ GHG_{in}} \times \frac{\mathrm{W_{out,th}} \times \eta_C \times \nu}{\mathrm{W_{out,el}} + (\mathrm{W_{out,th}} \times \eta_C \times \nu)} \times \mathrm{W_{in}}}{\mathrm{W_{out,th}}}$
Exergy Loss method	$\mathrm{spec.GHG_{el}} = \dfrac{\mathrm{spec.GHG_{in}} \times \frac{\mathrm{Ex_{el,ref}} - \mathrm{Ex_{loss,el}}}{\frac{\mathrm{Ex_{in}}}{\mathrm{W_{in}}} \times \mathrm{W_{out,el}}} \times \mathrm{W_{in}}}{\mathrm{W_{out,el}}}$ $\mathrm{spec.GHG_{th}} = \dfrac{\mathrm{spec.GHG_{in}} \times \frac{\mathrm{Ex_{th,ref}} - \mathrm{Ex_{loss,th,ref}}}{\frac{\mathrm{Ex_{in}}}{\mathrm{W_{in}}} \times \mathrm{W_{out,th}}} \times \mathrm{W_{in}}}{\mathrm{W_{out,th}}}$
Remainder Value and Substitution method	**Power Remainder Value / Heat Substitution** $\mathrm{spec.GHG_{el}} = \dfrac{\mathrm{spec.\ GHG_{in}} \times \mathrm{W_{in}} - \mathrm{spec.GHG_{th}} \times \mathrm{W_{out,th}}}{\mathrm{W_{out,el}}}$ $\mathrm{spec.GHG_{th}} = \dfrac{\mathrm{spec.\ GHG_{th,ref}}}{\eta_{th,ref}}$ **Heat Remainder Value / Power Substitution** $\mathrm{spec.GHG_{el}} = \dfrac{\mathrm{spec.\ GHG_{el,ref}}}{\eta_{el,ref}}$ $\mathrm{spec.GHG_{th}} = \dfrac{\mathrm{spec.\ GHG_{in}} \times \mathrm{W_{in}} - \mathrm{spec.GHG_{el}} \times \mathrm{W_{out,el}}}{\mathrm{W_{out,th}}}$
Displacement Mix method	$\mathrm{spec.GHG_{el}} = \dfrac{\mathrm{spec.\ GHG_{dis}}}{\eta_{dis}}$ $\mathrm{spec.GHG_{th}} = \dfrac{\mathrm{spec.\ GHG_{in}} \times \mathrm{W_{in}} - \mathrm{spec.GHG_{el}} \times \mathrm{W_{out,el}}}{\mathrm{W_{out,th}}}$
Finnish method	$\mathrm{pes} = 1 - \dfrac{1}{\frac{\eta_{el}}{\eta_{el,ref}} + \frac{\eta_{th}}{\eta_{th,ref}}}$ $\mathrm{spec.\ GHG_{el}} = \dfrac{\mathrm{spec.\ GHG_{in}} \times (1-\mathrm{pes}) \times \frac{\eta_{el}}{\eta_{el,ref}} \times \mathrm{W_{in}}}{\mathrm{W_{out,el}}}$ $\mathrm{spec.\ GHG_{th}} = \dfrac{\mathrm{spec.\ GHG_{in}} \times (1-\mathrm{pes}) \times \frac{\eta_{th}}{\eta_{th,ref}} \times \mathrm{W_{in}}}{\mathrm{W_{out,th}}}$
GHG method	$\mathrm{GHG_{saved}} = 1 - \dfrac{1}{\frac{\mathrm{spec.\ GHG_{el,fin}}}{\mathrm{spec.\ GHG_{el,ref}}} + \frac{\mathrm{spec.\ GHG_{th,fin}}}{\mathrm{spec.\ GHG_{th,ref}}}}$ $\mathrm{spec.GHG_{el}} = \dfrac{\mathrm{spec.GHG_{in,\ LC}} \times (1-\mathrm{GHG_{saved}}) \times \frac{\mathrm{spec.GHG_{el,fin}}}{\mathrm{spec.\ GHG_{el,ref}}} \times \mathrm{W_{in}}}{\mathrm{W_{out,el}}}$ $\mathrm{spec.GHG_{th}} = \dfrac{\mathrm{spec.GHG_{in,\ LC}} \times (1-\mathrm{GHG_{saved}}) \times \frac{\mathrm{spec.GHG_{th,fin}}}{\mathrm{spec.GHG_{th,ref}}} \times \mathrm{W_{in}}}{\mathrm{W_{out,th}}}$
Economic Values method	$\mathrm{spec.\ GHG_{el}} = \dfrac{\mathrm{spec.GHG_{in}} \times \frac{\mathrm{C_{el}} \times \mathrm{W_{out,el}}}{\mathrm{C_{el}} \times \mathrm{W_{out,el}} + \mathrm{C_{th}} \times \mathrm{W_{out,th}}} \times \mathrm{W_{in}}}{\mathrm{W_{out,el}}}$ $\mathrm{spec.\ GHG_{th}} = \dfrac{\mathrm{spec.GHG_{in}} \times \frac{\mathrm{C_{th}} \times \mathrm{W_{out,th}}}{\mathrm{C_{el}} \times \mathrm{W_{out,el}} + \mathrm{C_{th}} \times \mathrm{W_{out,th}}} \times \mathrm{W_{in}}}{\mathrm{W_{out,th}}}$

Table 4
Characteristics of the CHP plant used as basis of the case study.

Characteristic	Symbol	Value	Unit	Reference
energy input	$\mathrm{W_{in}}$	500,000.00	kWh	assumption
total efficiency	η_{tot}	0.85	-	assumption based on [4]
electric efficiency	η_{el}	0.30	-	assumption based on [4]
power loss factor	ϑ	0.175	-	[8]
quality factor	ν	0.800	-	[34]
ambient temperature	$\mathrm{T_a}$	298.15	K	assumption
temperature hot medium	$\mathrm{T_{hot}}$	353.15	K	[35]
temperature cold medium	$\mathrm{T_{cold}}$	333.15	K	[35]
emission factor combustion of natural gas	$\mathrm{spec.\ GHG_{in}}$	202	g CO_2/ kWh	[36]
emission factor combustion of natural gas (incl. upstream chain)	$\mathrm{spec.\ GHG_{in,LC}}$	223	g CO_2/ kWh	[36]
costs for electricity	$\mathrm{C_{el}}$	0.044	€/kWh	[35]
costs for heat	$\mathrm{C_{th}}$	0.050	€/kWh	[35]

Table 5
Characteristics of the reference systems.

Specific GHG emissions	Symbol	Value	Unit	Reference
efficiency German electricity mix	$\eta_{el,ref}$	0.53	-	[37]
efficiency steam boiler	$\eta_{th,ref}$	0.89	-	assumption based on [38]
efficiency German displacement mix	η_{dis}	0.42	-	own calculation based on [39,40]
emission factor German electricity mix	$\mathrm{spec.\ GHG_{el,ref}}$	375	g CO_2/ kWh	[41]
emission factor steam boiler	$\mathrm{spec.\ GHG_{th,ref}}$	222	g CO_2/ kWh	[42]
emission factor German displacement mix	$\mathrm{spec.\ GHG_{dis}}$	811	g CO_2/ kWh	[43]

reduction of GHG emissions occurs. The reference system for the heat generation is a steam boiler as it is currently widely used in Germany. The German electricity mix has an efficiency of roughly $\eta_{el,ref}$ of 0.50 (Table 5) and relates to CO_2 emissions of 375 g CO_2 / kWh in 2020 (Table 5). This value is calculated by dividing all direct emissions from electricity generation by the consumption of the net available electricity from German generation [41]. The considered emissions from CHP electricity are allocated using the Finnish method [41]. The efficiency of a steam boiler $\eta_{th,ref}$ is 0.89 (Table 5) while emitting 222 g CO_2 / kWh (Table 5).

As shown in Section 3.2, another reference system for generating electricity can be the displacement mix. According to a prediction from Falkenberg et al., this mix is associated with CO_2 emissions of 811 g CO_2 / kWh regarding a German CHP plant in 2020 (Table 5). Its efficiency η_{dis} is calculated as the weighted average of the single efficiencies of the displaced energy sources (lignite, hard coal, and natural gas). The weighting factor used is the percentage share of these energy sources within the displacement mix. Crude oil, which is a displaced energy source, is not considered due to its small share of only 1 %. Considering the data from Kleinertz et al. [39] and shown by the German Federal Environmental Agency [40] the result is an efficiency η_{dis} of 0.42 (Table 5).

To perform the allocation based on economic values, potential revenues for CHP electricity and heat are used (Table 4). Prices for electricity can vary between 0.06 and 0.028 € / kWh due to different remuneration situations [35]. In this study, the arithmetic mean was chosen for the allocation.

Fig. 1 presents the results of the different allocation methods for the described case study. As only CO_2 is considered as greenhouse gas, the specific as well as the absolute emissions allocated to electricity and heat are presented in g CO_2 per unit of electricity or heat and t CO_2, respectively. The results are presented in g CO_2 per kilowatt hour since the determined emission factors depend on the chosen unit of electricity or thermal energy. The usage of the Exergy Loss method requires deep knowledge and detailed examinations about the CHP plant and the considered reference processes [6]. Due to the high amount of work associated with this method, its use is assumed to be unrealistic. Thus, this method is not applied to this case study.

Fig. 1 illustrates that allocation methods, which are based on the provided amount of energy, have the tendency to allocate more specific CO_2 emissions to electricity than to heat. One exception is the Energy method, as it allocates the same amount of specific CO_2 emissions to both products. The case study shows that allocation methods that consider a reference technology tend to allocate a higher emission factor to electricity. An exception is the Power Remainder Value / Heat Substitution method. It can be noted that the difference between the emissions allocated to heat and those allocated to electricity is substantially smaller within the methods of the second category than within the methods of the first category. However, some exceptions exist, such as the Heat Remainder Value / Power Substitution method and the Displacement Mix method. This case study shows the systematic weakness of those methods to allocate negative emission factors to one product, in this case to heat. The Economic Values method allocates nearly the same specific CO_2 emissions to both products. However, this is mainly attributed to the fact that the difference between electricity and heat prices is only marginal (Table 4). Compared to the German electricity mix with an emission factor of 375 g CO_2 / kWh, four methods (the Energy, the Power Remainder Value / Heat Substitution, the Finnish, and the Economic Values method) evaluate CHP electricity better, since it causes less emissions per kilowatt hour.

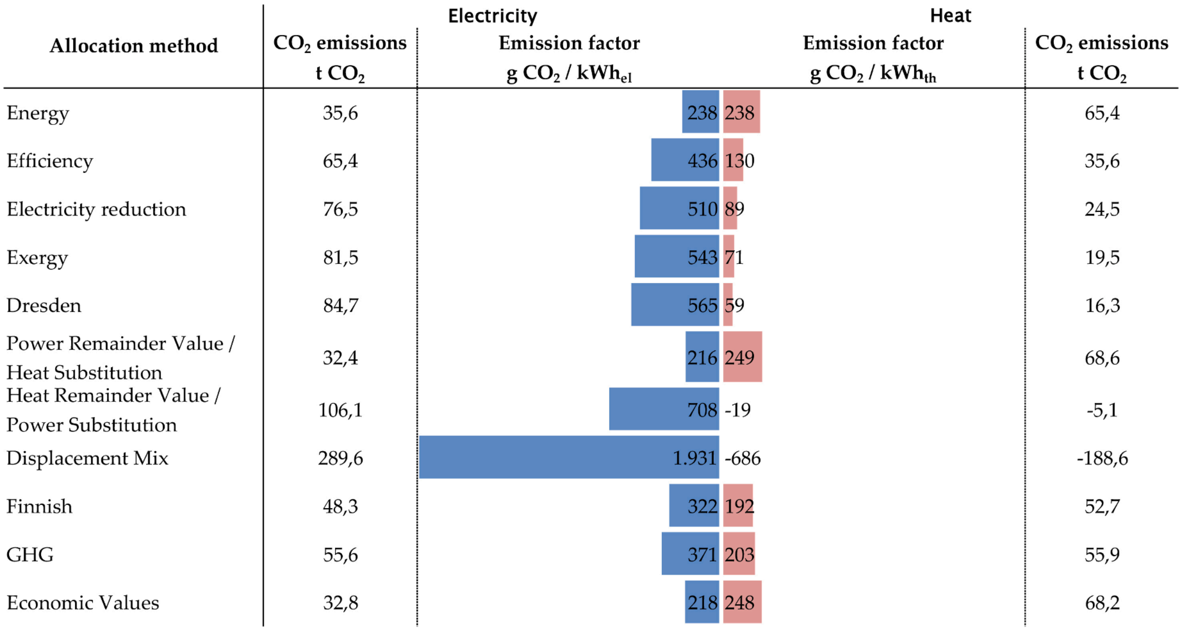
4.2. Sensitivity analysis with changed efficiencies

In the first sensitivity analysis the electric and the thermal efficiency of the reference CHP are changed. According to the Working Group for Economical and Environmentally Friendly Energy Consumption other possible efficiencies $\eta_{el,new}$ and $\eta_{th,new}$ are 0.41 and 0.46, respectively [45]. The changed efficiencies consequently lead to a change in the corresponding energy outputs. Therefore, the results of all the considered allocation methods change. Fig. 2 presents these results for the specific electricity and heat emission factors as well as the absolute emissions allocated to the by-products.

The differences between the allocated specific emissions for electricity and heat are closer to each other than in the case study. The exceptions are the Remainder Value as well as the Substitution method and the Displacement Mix method. The reason for this is that the new efficiencies for heat and electricity are closer to each other than in the case study. However, varying the efficiencies does not result in fundamental changes of the allocated specific emissions.

4.3. Sensitivity analysis with changed location

Within the second sensitivity analysis the location of the CHP is changed from Germany to Sweden. This country was chosen because of the significant difference to Germany concerning its electricity generation. The specific emissions of the Swedish electricity mix spec. $GHG_{el,ref,SWE}$ are 8.8 g CO_2 / kWh in 2020 [46] and those of the displacement mix spec. $GHG_{dis,SWE}$ are 1,036 g CO_2 / kWh [39]. The efficiency of the Swedish electricity mix $\eta_{el,ref,SWE}$ is 0.48 [47]. The Swedish displacement mix $\eta_{dis,SWE}$ has an efficiency of 0.43 on average (calculation



Allocation method	Electricity CO_2 emissions t CO_2	Electricity Emission factor g CO_2 / kWh_{el}	Heat Emission factor g CO_2 / kWh_{th}	Heat CO_2 emissions t CO_2
Energy	35,6	238	238	65,4
Efficiency	65,4	436	130	35,6
Electricity reduction	76,5	510	89	24,5
Exergy	81,5	543	71	19,5
Dresden	84,7	565	59	16,3
Power Remainder Value / Heat Substitution	32,4	216	249	68,6
Heat Remainder Value / Power Substitution	106,1	708	-19	-5,1
Displacement Mix	289,6	1.931	-686	-188,6
Finnish	48,3	322	192	52,7
GHG	55,6	371	203	55,9
Economic Values	32,8	218	248	68,2

Fig. 1. Results of the different allocation methods considering a natural gas fired CHP plant in Germany.

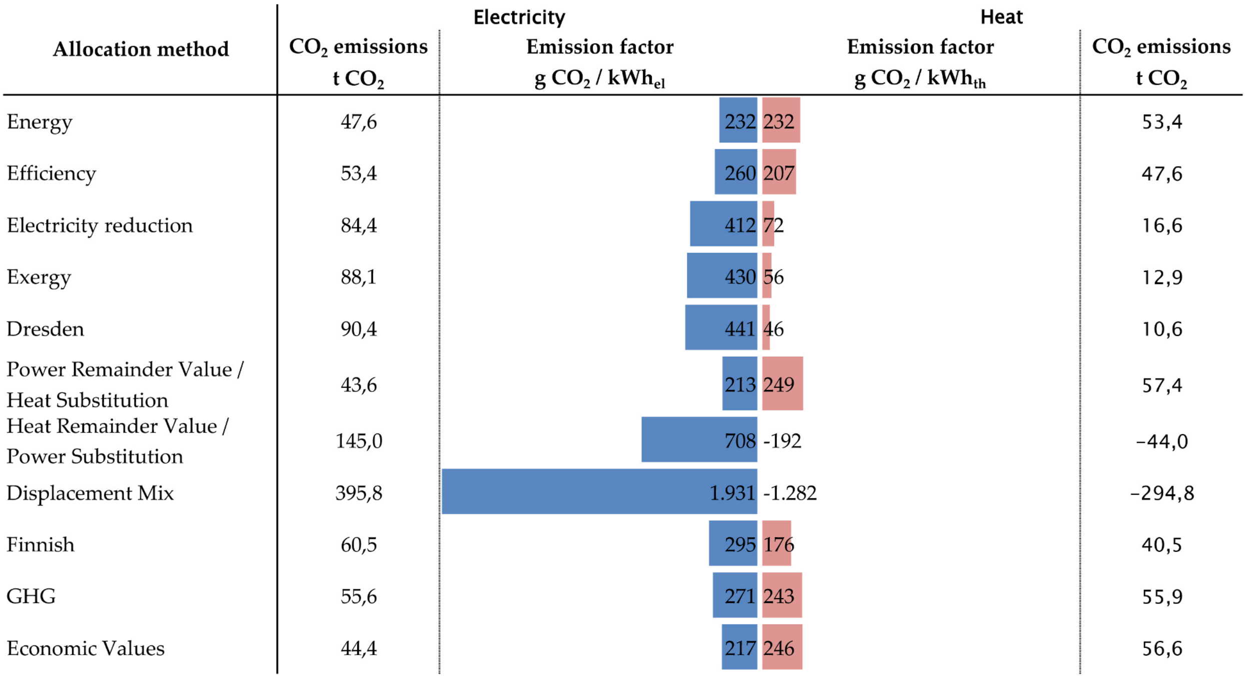


Fig. 2. Results of the allocation methods when changing the efficiencies of the referenced CHP plant.

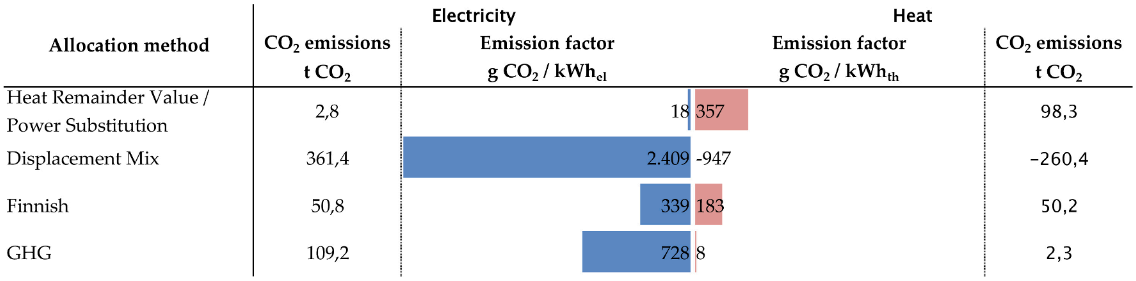


Fig. 3. Results of the four affected allocation methods when changing the location of the referenced CHP plant from Germany to Sweden.

analogous to Section 4.1) [39,48]. These adaptations lead to changes only within reference system-based allocation methods (Section 3.2). Changes, however, only occur in four of this five methods as the thermal reference system was not changed. Fig. 3 presents the results of the emission allocation to heat and electricity for those four allocation methods.

A comparison of Figs. 1,2 and 3 shows that changing the location to a country with an electricity mix with a higher share of energy sources with a small climate impact (e.g. renewable energies) has a higher influence on the results than changing the efficiencies of the CHP itself. Simultaneously, it must be considered that changing the location of the CHP plant affects only four of the eleven methods studied whereas changing the efficiencies affects all of them. The ratio of the allocated specific emissions within the Heat Remainder Value / Power Substitution method has changed as both results are now positive, and heat is attributed the higher emission factor. Concerning the other three methods, the differences between the allocated emission factors to heat and electricity became greater than for the reference CHP plant. This

Table 6
Application of the evaluation scheme to the considered allocation methods.

Criterion	1. Applicability (weighting factor: 1)				2. Environmental relevance (weighting factor: 2)		3. Systematic approach (weighting factor: 4/3)			∑
	1.1.	1.2.	1.3.	1.4.	2.1.	2.2.	3.1.	3.2.	3.3.	
Energy	3	1.5	3	0	0	0	3	3	3	19.5
Efficiency	3	1.5	1.5	0	0	0	0	3	1.5	12
Electricity Reduction	3	0	3	0	0	0	0	3	3	14
Exergy	0	1.5	3	3	0	0	3	3	3	19.5
Dresden	0	0	1.5	3	0	0	0	3	3	12.5
Remainder Value / Substitution	3	0	3	0	3	0	1.5	0	0	14
Displacement Mix	3	0	1.5	0	3	0	0	0	0	10.5
Finnish	1.5	0	3	0	3	0	1.5	3	3	20.5
GHG	0	0	1.5	0	3	3	0	3	1.5	19.5
Economic Values	3	3	1.5	0	0	0	1.5	3	3	17.5

reflects opposite results to the first sensitivity analysis.

5. Results

After applying the allocation methods in a case study, the methods are evaluated by using the evaluation scheme described in Section 2. The results are displayed in Table 6. Since the Exergy Loss method is not considered within the case study, this method is also not considered within the evaluation scheme.

After weighting the different criteria as described in Section 2, the Finnish method turns out to be the best allocation method regarding the considered criteria. This method achieves a total score of 20.5 points. The reason for this is that the Finnish method is not rated poorly in any of the three categories. The main weakness of this method is that a reference system for the separate production and thus corresponding data need to be assumed. Consequently, the results of this allocation method are strongly dependent on this reference system and on the associated efficiencies. Nevertheless, as represented by criterion 3.3. and as demonstrated in the two sensitivity analysis, the Finnish method is comparatively stable regarding such uncertainties.

The Energy method, the Exergy method, and the GHG method reach the second highest score with 19.5 points. The Energy and the Exergy method are evaluated equally concerning most criteria. A different scoring only occurs within two of the criteria considered in this study: Criterion 1.1. “Calculation effort” and criterion 1.4. “Consideration of energy quality”. On the one hand, the Energy method has a lower calculation effort than the Exergy method but, on the other hand, this method does not consider the quality of the different energies. Hence, these two methods are evaluated exactly reversed within those two criteria. Finally, this is the reason why the overall result is the same.

The reason that the GHG method is rated as good as the Energy and the Exergy method is the focus of this method on environmental concerns. The GHG method scores best regarding both criteria of the second category whereas the other two methods are rated with zero points. This method’s weaknesses can especially be found regarding the first category “Applicability”. The reasons for that are the comparatively high calculation effort, the need to assume required data, and that the quality of the energy types is not considered.

6. Discussion

As shown in the sensitivity analyses, the specific GHG emissions allocated to heat and electricity are strongly dependent on the allocation method chosen as well as on various parameters. Depending on the chosen allocation method, the allocated emission factors can differ extremely even under consideration of the same framework. Only if the allocated emission factor is lower than that of the electricity or the district heating mix of the considered region, using CHP heat or electricity can improve the emission factors of the respective mixes. Consequently, this can contribute to climate protection in the short- to medium-term and also in the long-term if low-emission energy sources such as biomethane or synthetic fuels are used as input. The emission factor of the German electricity mix in 2020 was 375 g CO_2 / kWh [41] and the average emission factor of the German district heating mix was 270 g CO_2 / kWh, if only fossil energy sources are considered [49]. Referring to the case study, using CHP electricity can improve the national electricity mix only when using the Energy, the Power Remainder Value / Heat Substitution, the Finnish, and the Economic Values method. An improvement of the district heating mix is given in any case. Considering that the German Federal Environmental Agency uses the Finnish method to allocate CHP emissions to electricity and heat [31], CHP electricity and heat can contribute to improve the respective national mixes. Nevertheless, especially the district heating emission factor can vary a lot from the presented average value, as it is strongly dependent on the energy source used. Especially if purchased renewable energies are considered it is important to analyze the differences between location-based and market-based emission factors [50].

Comparing the results of the sensitivity analyses to the results of the case study demonstrates that different allocation methods show a different degree of sensitivity to particular parameters. Concerning the chosen variations, changing the location on the one hand has a greater influence on the results than changing the efficiency. On the other hand, less methods are affected by changing the location. Considering the second sensitivity analysis it becomes evident that the location of the CHP plant plays an important role when evaluating a possible positive effect of CHP electricity and heat on corresponding national mixes. If for example the national electricity mix is already comparatively low, due to a high share of renewable energies, natural gas fired CHP plants probably do not have a positive effect on that mix. Nevertheless, a contribution of CHP heat or electricity to climate protection should always be evaluated only under consideration of the load profile of the CHP plant as well as the correspondingly displaced energy sources.

According to the Association of German Engineers, no allocation method is necessarily preferable over another [11]. However, as shown in Table 6, based on the specific criteria considered within this study, the Finnish method was found to be the best method for allocating GHG emissions in CHP processes. Thus, the result of the study presented here supports the chosen procedure of the German Federal Environmental Agency. Despite this, it is important to note that the difference between the Finnish method and the second-best methods – the Energy, the Exergy, and the GHG method – is only 1 point. Those three methods all achieved the same total score. Regarding the Energy and the Exergy method, this contrasts with the findings of other studies that prefer the Exergy over the Energy method [8,9,13,18,25]. As the Finnish method is only better regarding the chosen criteria, this does not mean that these methods are better or worse than each other. Depending on which criteria are considered and the weight of significance given to each criterion, different methods could in fact be found to be more favorable than others. For example, if environmental concerns are of great relevance, the GHG method might be the most appropriate method, although it has a higher calculation effort than the Finnish method (category 1. in Table 6). As another example, if proportionately simple calculations are desired, the Energy method could be most suitable. Finally, if the exact qualitative characteristics of the different energy forms are of great relevance, the Exergy method may be the best method to choose. This individual importance of certain criteria may be the reason why some studies, as mentioned before, prefer the Energy over the Exergy method. Evaluating the methods considering different criteria represents the benefit of the developed evaluation scheme: It demonstrates the specific advantages and disadvantages of different allocation methods even though those methods finally score similar or even the same. This in turn enables decision-makers to transparently decide which allocation method should be chosen in certain use cases.

Additionally, it is possible to add further criteria to the evaluation scheme, if those are relevant for an application case. Criterion 1.3. considers the usage of a method in a standard. As such a standard, DIN EN ISO 14044 – recognized in Germany (German Institute for Standardization – DIN), Europe (European Standard – EN) and internationally (International Organization for Standardization – ISO) – states that a system expansion is preferable to an allocation based on physical relations which in turn is preferable to an allocation based on non-physical relations [51]. Consequently, if standards are taken into account, a ranking could be considered within another criterion. Such additions could lead to different results which represent the individual importance of certain categories.

In the presented evaluation scheme, a weighting of the three different categories was carried out as those categories were assumed to be of equal importance. However, it is possible to weight the nine criteria equally instead of the three categories. Under this consideration, a different result occurs in which the Exergy method and the Energy method are scored the best. This corresponds to some publications, which prefer the Exergy method. Opposite, Brautsch and Lechner conclude that the Finnish method is the best allocation method [20] and the German Federal Environmental Agency chose this method to allocate CHP emissions to electricity and heat [31]. This gives further support and credence to the developed evaluation scheme and the corresponding results presented in this study.

7. Conclusion

This study compares twelve methods for allocating GHG emissions of CHP processes based on a newly developed evaluation scheme. In this scheme, nine different criteria within the categories “Applicability”, “Environmental relevance”, and “Systematic approach” were considered. The Finnish method ranks first. When applying this method to a standard use case, the result is that in 2020 the electricity generated in a gas-fired CHP plant corresponds to lower GHG emissions then the grid electricity mix of Germany. Therefore, CHP electricity could contribute to climate protection in the short- to mid-term in Germany as long as it is associated with lower GHG emissions than the conventional electricity mix. In order for CHP to contribute to national climate protection in the long-term, alternative low-emission fuels such as biomethane or synthetic fuels should be used. Yet, this has no influence on the applicability of the evaluation scheme since this is basically applicable to any CHP use case. Considering a higher electricity and lower thermal efficiency, the allocated emission factors differ slightly. Changing the location demonstrated that CHP plants in Sweden do not contribute to improve the conventional electricity mix due to the high share of low-emission energy sources in the Swedish electricity mix. Nevertheless, a contribution of CHP electricity and heat to climate protection should be evaluated considering the load profile of the CHP plant and the displaced energy sources.

Further, the GHG method, the Energy method and the Exergy method scored well. For this reason, these methods can be just as suitable as the Finnish method depending on the use case and the individual importance of certain criteria. That no allocation method can be defined as universal best method is supported by the findings of other studies. All in all, the evaluation scheme provides criteria for transparently choosing a suitable allocation method while also enabling individual adaptations easily.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rset.2023.100069.

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