Life cycle analysis of horticultural products:

Memo on handling multi-functionality of combined heat and power systems

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Introduction

This memo has been prepared as a methodological exploration on the issues of multi-functionality of Combined Heat and Power (CHP) systems. It is viewed in the context of the development of a methodology for calculating the environmental footprints of horticultural products, the Hortifootprint Category Rules (HFCR, see Helmes et al, 2020). The goal of this HFCR is to provide a harmonised methodology after which consistent LCA studies can be performed for the European horticultural sector. The development of the methodology is following as much as possible the most recent guidance for developing Product Environmental Category Rules (PEFCR) published by the European Commission (Zampori and Pant, 2019).

The development of the HFCR was initiated by Royal FloraHolland, Dutch Fresh Produce Centre and Wageningen Economic Research, with co-financing from the Dutch Fund for Horticulture & Propagation Materials, ABN AMRO Bank N.V., the Dutch sector organisation for greenhouse horticulture (Glastuinbouw Nederland), MPS, Rabobank, Foundation Benefits of Nature and in co-production with experts from Blonk Consultants and PRé Sustainability.

At the start of the project, several topics were identified where additional guidance was needed for the horticulture sector as well as the guidance currently available in the PEF. The following methodological challenges were identified:

- handling multifunctionality of combined heat and power systems used during cultivation;
- modelling nitrogen and phosphorus emissions;
- modelling of pesticides emissions;
- modelling of capital goods.

This memo is one of four elaborating on methodological challenges.

A combined heat and power (CHP) system can provide heat and electricity for a horticultural greenhouse producer. The producer can sell part of the electricity to the grid and can capture the CO_2 from the flue gas to enrich the air inside the greenhouse for the crops or ornamental plants. There are several ways of handling the multi-functionality of the CHP system used in horticulture and there is a strong disagreement between the approaches of standards, databases and research literature. Despite disagreement on this topic from sector experts, this memo provides a rationale on how to handle multi-functionality of CHP systems in environmental footprints of horticultural products for the development of the product environmental footprint methodology for horticultural products.

Firstly, we subdivided the horticultural system into the heat and electricity production subsystem, the carbon dioxide capture and purification subsystem and the cultivation system. We then considered system expansion: this method is relevant for scenarios where one heating technology replaces another. However, this involves modelling and assumptions, which is not feasible in single-product environmental footprint assessments (without extensive data collection). Physical allocation is also rejected as chemical properties are not possible and the relationship between physical properties and the emissions of a CHP system is disputable. Five other relationships are considered: 1) 100% to electricity is not appropriate: heat from a CHP system would have a disproportionally lower impact than greener alternatives. So, this is rejected. 2) 100% to heat is not fully correct as it would suggest that a CHP system is less efficient than a natural gas boiler. So, this is rejected. 3) Exergy based allocation has the advantage that it is consistent with background data, but it is not applicable to the horticultural situation, because the exergy of heat does not represent the application of heat used in a greenhouse. So, this is rejected. 4) Energy-based allocation is applicable and makes sense. 5) Economic allocation makes some sense from a theoretical point of view. The main issue here is that it is practically problematic to apply, resulting in inconsistency and uncertainty. So, this is not recommended.

In conclusion, the most applicable and sensible method for the co-production of heat and electricity from CHP systems in single product environmental footprint assessments is energy allocation. It must also be stressed however that the application of energy allocation does not offer sufficient information for taking scientifically sound conclusions on a technology switch from the use of CHP to other heating technologies or vice versa.

Background

A Combined Heat and Power (CHP) system provides heat and electricity for industries, consumers and horticulture. The use of CHP systems in Dutch horticulture has become common practice in the past decades, replacing natural gas boilers to heat the glasshouses. The electrical capacity of CHP systems in Dutch horticulture was about 500 MW in 2003 and increased to about 2500 MW in 2012. Currently it has decreased to about 2400 MW due to a decreasing area under greenhouses, a less favourable electricity market (spark spread) and increasing use of more sustainable solutions, such as geothermal energy, biofuels, residual heat from power plants and solar; about 62% of the area under Dutch glasshouses is still heated with CHP systems in 2017, when the total energy use in the sector was about 100 PJ (Van der Velden and Smit, 2018). Besides the advantage of efficiently producing electricity, another useful feature of a CHP is that a flue gas cleaner is often connected, which provides purified carbon dioxide to stimulate faster carbon dioxide uptake and hence the growth rate of the plants. Growers who do not have a CHP or boiler and a flue gas cleaner need to buy the CO_2 from other sources, such as CO_2-cyclinders or from pipelines. The heat and purified carbon dioxide from a CHP are used in the greenhouses. A part of the electricity is supplied to the grid and part is used in the greenhouse, especially when the greenhouse is intensively lit.

To determine the environmental impact of the heat, electricity and carbon dioxide used in the greenhouses, there are different methods. The most commonly discussed methods are system expansion, and exergy, energy or price allocation. System expansion means that one of the co-products is considered as the main (determining) product and the others are considered as by-products, where an increasing production of the main product leads to substitution of production of the by-products elsewhere with other production technologies. For example, if electricity is considered as the main product, the heat and the CO_2 from the CHP would substitute heat from a natural gas boiler and CO_2 in cylinders produced in a chemical factory. The environmental impact of the increased electricity production is then the total impact minus the impact of the substituted production. The impact of the heat and the CO_2 from the CHP is then considered equal to the impact of the substituted production technologies. This could be done similarly when considering heat as the main product, where the electricity substitutes electricity production in for example natural gas or coal-fired power plants or the current local consumption mix. System expansion often involves disputable assumptions: it is not always clear which is the determining co-product and which production technologies are substituted. It is also not always the goal of an LCA to study the impact of a change.

To study the impact of a product as it is, the total impact is allocated to the co-products. This can be done based on a physical characteristic, such as mass, exergy or energy, prices or any other idea that experts find reasonable. The choice for system expansion or one of the other allocation methods results in different outcomes. For example, Torrellas et al. (2012), Olsson et al. (2015), Rosen et al. (2008), and Tereshchenko and Nord (2015) compared the outcomes of applying 2 to 7 different methods for handling multi-functionality in CHP. So, it is important to select the method carefully, aligned with the objectives of the study and based on reasonable discussion.

In practice, there are many different preferences. Important background life cycle inventory databases generally apply exergy allocation (for example, Moreno Ruiz et al., 2016; Kupfer et al., 2018), while LCA standards prescribe system expansion (European Commission, 2018; FAO, 2015; BSI, 2011), and peer-reviewed scientific papers have many different preferences. For example, Torrellas et al. (2011) consider heat as the main product when applying system expansion substituting the current national grid mix and use the energy-content when applying allocation, while they do not discuss nor decide which of the two options are preferred in which situation. Olsson et al. (2015) on the contrary conclude that heat should be considered as a by-product after analysing different system expansion scenarios. Rosen et al. (2008) analysed different allocation options and concluded that the exergy-based method is in their view the most meaningful and accurate of the methods. Guest et al. (2011) also prefer exergy allocation. Frischknecht (2000) argues that system expansion is just a special case of allocation and should have a lower priority in the standards. Kelly et al. (2014) applied two methods: one method is equal to system expansion with electricity as the main product and one method allocates one third to electricity and two thirds to heat. Lansche and Müller (2012) implemented a method where both electricity and heat are substituted when biogas is introduced as a replacement of fossil fuels. Aldrich et al. (2011) propose a method which allocates according to the relative inefficiencies of the components that are specific for electricity and heat.

Given the disagreement in practice and the complexity of the issue, a thorough discussion is described in this note to provide a solid rationale and decision on how to handle multi-functionality of Combined Heat and Power (CHP) systems in environmental footprints of horticultural products for the development of the product environmental footprint methodology for horticultural products.

Selection procedure

There are three steps to follow for selecting the method according to ISO14044:2006 (ISO, 2006). Other standards, such as the PEFCR Guidance (European Commission, 2018) all refer to the same procedure, which we summarise as follows:

- Step 1: avoid allocation by
  - dividing the unit process into sub-processes or
  - system expansion with avoided impact outside the production system (for example avoided electricity production in coal-fired plants, natural gas-fired plants, nuclear energy, wind, solar or a mix).
- Step 2: allocate to co-products (not to wastes) in a way that reflects the underlying physical relationships (e.g. the mass or volume of different products transported in the same truck or ship often determines the impact of the transport).
- Step 3: allocate to co-products (not to waste) in a way that reflects the other relationships (e.g. economic, physical characteristics or-, preference).

The ISO standard also requires that "Allocation procedures shall be uniformly applied to similar inputs and outputs of the system under consideration". Moreover, the ISO standard demands consistency of the method with the goal and scope through a consistency check.

As there is little further guidance given in LCA standards on how to determine whether a step is valid for a certain situation, we propose to follow the following criteria:

- The method must be applicable to all sizes of CHP systems; so, also for CHP systems that supply heat and carbon dioxide to many horticultural enterprises (in line with the ISO requirement).
- The method must be meaningful for all outputs of the CHP system (electricity, heat and purified carbon dioxide); so, the results of applying the chosen method not only need to give meaningful answers to the research questions for the horticultural product(s) as defined in the goal and scope, but also for each of the outputs of the CHP system (if not already included).
- Operators must be able to apply the method easily and unambiguously.
- The method does not need to support assessments of the impact of horticultural products produced in greenhouses heated by CHP systems compared to the impact of horticultural products produced in greenhouses heated by other technologies, such as geothermal energy systems, natural gas boilers, etc.., as this approach does not fully take into account of the background emission and result in a simplification of the overall systems. Indeed while CHP are actively producer of electricity as part of the heating process, geothermal systems are net consumers of electricity from the grid. The assessment of the latter will thus be affected by the overall performance of the electricity system which is not fully considered in this approach.

Step 1: dividing or expanding the system

Subdividing the system

The first part of the first step in the selection procedure is subdividing the system. There are several aspects of subdividing the CHP production system:

1. Electricity and horticultural products leave the horticultural company, where the on-site energy production can be separated from the use of the energy in the crop cultivation.
2. The energy production activity produces heat, electricity and purified CO_2, while heat and electricity come from a CHP system that emits flue gases containing CO_2. The purified CO_2 comes from a flue gas cleaner, which captures and uses the flue gases from the CHP system.
3. The CHP system producing electricity and heat cannot be separated further, because it is one unit process performed by one piece of equipment and the quantities of process inputs (mainly natural gas) cannot be specified for the individual outputs (electricity and heat).

So, subdividing processes until it is not feasible anymore, results in three separate unit processes: 1) the cultivation activities, 2) the CHP system and 3) the flue gas cleaning system (Figure 1).

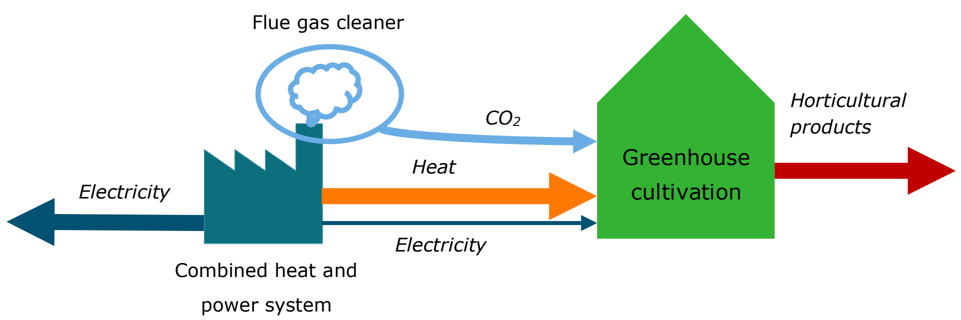

Figure 1 *Graphical representation of the heated greenhouse processes, subdivided into three unit process and the product flows*

The CHP system runs with the purpose to produce heat and electricity, during which CO_2 is released. CO_2 is also released and captured from processes with the purpose of producing chemicals such as hydrogen. In all cases and on all scales, CO_2 is an emission. It is not a waste, residue or by-product that is recycled.

If CO_2 is captured in a flue gas cleaner, this is considered as a negative emission. If the CO_2 is then applied in greenhouse cultivation, it is emitted from the greenhouse and from the plant material. Emissions from the greenhouse arise because a part of the CO_2 is not directly captured by the plants. Emissions from the plant material arise whenever it decays, in the greenhouse, during crop residue processing, at the consumer, and at the post-consumer waste treatment. These are all delayed fossil CO_2 emissions that were initially produced during heat and power production. The storage of the CO_2 applied for fertilisation is short (<1 year) and is therefore not taken into account in the emissions inventory.[1]

This subdivision has the following consequences:

- Horticultural products are produced during cultivation activities.[2]
- Electricity and heat are co-products of the CHP unit system.
- Electricity, heat and purified CO_2 are considered as inputs to the cultivation activities.
- The CO_2 is considered as an emission from the CHP system.

If this procedure is not followed, we will have complications in the system expansion and allocation options. In case of system expansion, we are likely to consider the purified CO_2 as a by-product that substitutes CO_2 production elsewhere, but there it can also be produced in multi-functionality. In case of allocation, there is no physical parameter that could be used besides exergy (which method we will later dispute) and it is difficult to determine a price of the CO_2 as it is directly used by the owner of the CHP system. Moreover, not subdividing does not solve the problem of the delayed CO_2 emissions. So, from a practical point of view, we propose the subdivision in any situation. The only multi-functionality issue that then remains is in the CHP system. For this, the next steps in the hierarchy of the ISO 14044 standard are considered (ISO, 2006).

System expansion is considered

System expansion is a way to deal with multi-functionality, but lower in the ISO hierarchy than subdivision, hence less preferred. Several important reference documents prescribe system expansion for CHP systems: the LEAP feed guidance (FAO, 2015), the PAS2050 (BSI, 2011), the Dutch protocol for reporting and monitoring the primary energy use and production in the Dutch horticultural sector (Van der Velden and Smit, 2017), and the PEFCR Guidance (European Commission, 2018).

The LEAP guidance (to which the PEFCR Guidance refers to for handling multi-functionality in agricultural modelling), refers to CHP as an example '... where operations generate an output that unambiguously avoids external production'. In that case, the rule is 'apply system expansion by estimating avoided emissions. (e.g. energy delivered to grid)'. This would be the case where CHP systems are used in horticulture and surplus electricity is supplied to the grid.

The Carbon Footprint Specification PAS2050, which is an important reference here as it contains a supplement for horticultural products, also states: 'where a process results in the co-production of electricity that is exported to a larger electricity transmission system, the avoided emissions resulting from this co-production of electricity would be based on the average GHG emissions intensity of grid electricity.'

The PEFCR Guidance states: '*If electricity is produced in excess of the amount consumed on-site within the defined system boundary and is sold to, for example, the electricity grid, this system can*

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[1] This approach is consistent for CO_2 sourced from outside the horticultural enterprise: the impact of the CO_2 emissions is attributed to the producing party.

[2] If multiple types of products are produced, there is a multi-functionality problem. This will not be discussed here, but in the (draft) standard on horticultural products.

be seen as a multifunctional situation. The system will provide two functions (e.g. product + electricity) and the following rules shall be followed:

- *If possible, apply subdivision.*
- *Subdivision applies both to separate electricity productions or to a common electricity production where you can allocate based on electricity amounts the upstream and direct emissions to your own consumption and to the share you sell out of your company (e.g. if a company has a wind mill on its production site and export 30% of the produced electricity, emissions related to 70% of produced electricity should be accounted in the PEF study.*
- *If not possible, direct substitution shall be used. The country-specific residual consumption electricity mix shall be used as substitution* (for some countries, this option is a best case rather than a worst case.)*.*
- *Subdivision is considered as not possible when upstream impacts or direct emissions are closely related to the product itself*[3]*.*

The reasons why direct substitution of electricity is considered possible in case of co-generation of heat and electricity are, in our interpretation, the following:

- Electricity is a uniform product, which can be transported without much loss or environmental cost. So, in practice one type of electricity production can easily be substituted by another.
- The *country-specific residual consumption electricity mix* is to be used so a debate on which type of electricity production is the marginal production is avoided. For example, if coal-fired power is chosen, this would be a very large bonus for the CHP's heat, but does this actually happen? If natural gas-fired power is chosen, this could mean that the co-produced heat from the power plants is also avoided. So, this must then also be taken into account.
- The substitution method is in theory an accurate description of what would happen when more heat is produced by a CHP and electricity demand stays the same: less electricity will be produced elsewhere.

However, there are several important complications:

- For produced heat in natural gas-fired power plants, the same reasoning could be applied to choose for substituting the heat when the impact of electricity is assessed. So, it is arguable to consider heat as the determining coproduct and electricity as the by-product. Some researchers even argue that heat should be considered as a by-product (e.g. Kelly et al., 2014, and Olsson et al., 2015). Moreover, in the case of large-scale natural gas fired-power plants, the excess heat is generally considered as a by-product. So, in general, neither heat nor electricity can be considered as the determining product.
- The PEFCR Guidance (European Commission, 2018) was at the time of writing not clear on how the allocation rules are applied in the datasets for electricity production in power plants, where heat can also be produced and delivered to customers. The PEFCR Guidance states that the 'country-specific residual grid mix, consumption mix' shall be used (available at http://lcdn.thinkstep.com/Node/). The dataset clearly states it is based on an attributional LCI method principle; exergy allocation is applied to heat and power from CHP systems. This is a serious inconsistency in the PEFCR Guidance.
- This would mean that the data for the electricity grid mix has to be adapted, because this would otherwise create a loop: the electricity from one CHP would avoid electricity from another CHP. Then the reduction in co-produced heat of the second CHP needs to be compensated. This could be solved by assuming the heat avoids heat from a natural gas boiler. This would mean that the impact of the heat from the initial CHP, which avoids electricity from another CHP would be the same as the impact of heat from a natural gas boiler. Another solution could be to consider the electricity grid mix without electricity from CHP systems. Both solutions are however not possible in environmental footprinting because the PEFCR Guidance requires the use of default electricity data which cannot be adapted, and in which allocation is applied in contradiction to the rules. So, consistency is then not possible, inconsistently applying system expansion will lead to incorrect results.

[3] The Circular Footprint Formula of the PEFCR Guidance (European Commission, 2018) could also be interpreted as an indirect suggestion to apply system expansion in the CHP case, because system expansion is to be applied where electricity is recovered from waste incineration.

- It is still debatable to always use the current *country-specific residual consumption electricity mix*. When we compare the use of a CHP system and innovative technologies, such as geothermal energy, we also want to know what the environmental footprint of the product produced with the CHP system will be in the near future. It is expected that in the coming years the consumption mix will include relatively more wind and solar energy. So, with the same inputs and outputs, the climate change impact of the product produced with heat from a CHP system will then be greater when applying system expansion. The impact of products produced with geothermal energy on the other hand will stay the same. Such an analysis could show under which conditions a switch from CHP to another heating technology would have a reducing environmental impact.
- The European Commission argue in the Renewable Energy Directive (EC, 2009) that where "Co-products from the production and use of fuels should be taken into account in the calculation of greenhouse gas emissions." and that "The substitution method is appropriate for the purposes of policy analysis, but not for the regulation of individual economic operators...". The PEFCR Guidance contradicts this statement.

So, the fact that these standards prescribe system expansion is on the one hand a logical choice. It has a higher priority and seems much more possible than in almost all other multi-functionality situations. On the other hand, it results in practical complications and contradictions. In the case of comparing the impact of horticultural products produced in greenhouses heated by CHP systems and other technologies, system expansion is the most suitable method, but it involves advanced modelling and scenario analysis. This type of analysis is practically not feasible for product environmental footprinting, where a straightforward and unambiguous methodology is essential. The conflict is that the PEFCR Guidance (Zampori and Pant, 2019) aims at reaching consistency and comparability between single product studies and at the same time takes the 'what if' question of increasing or reducing the use of CHP into account. Unfortunately, these two objectives cannot be combined in the case of CHP system use in horticulture.

Therefore, we conclude that system expansion is not applicable for single product environmental footprint assessments of horticultural products.

Step 2: allocate based on physical relationships

Step 2 is to allocate based on physical relationships. However, this step is disputable in the case of CHP (Frischknecht, 2000):
- Chemical properties are not possible, because both co-products stem from the natural gas.
- Physical properties are disputable: energy and exergy content are important physical characteristics of electricity and heat, but neither one of them directly influences the emissions characteristics of a CHP system. For example, a lower electricity-to-heat energy ratio (less electricity and more heat per unit of natural gas) may result in lower efficiency of converting the natural gas energy content; in that case, the reduction in electricity energy does not affect the emissions; so, only when the efficiency would be the same with any electricity-to-heat ratio, a physical relationship could be observed.

Note that allocation based on physical properties is often associated with this step, while there is not always a causal relationship between the properties and the environmental impact. An example where there is a relationship is the co-production of different crops or ornamental plants in a greenhouse, where we can assume that the grower makes sure that the surface of the greenhouse is fully occupied. The impact of heating the greenhouse is directly related to the surface area occupied by a crop or ornamental plant, which makes it an appropriate physical parameter for allocation based on a physical relationship. Such relationships can be found in the case of combined production, where there is no physical relationship between the co-products. In joint production, on the other hand, there is a physical relationship between the co-products, which makes the identification of a physical relationship between the co-products and the impact not possible. Examples are co-products of oilseed crushing, grain milling, sugar production, beer production or dairy production.

Step 3: allocate based on other relationships

In this step, any arbitrary physical or economic parameter can be chosen. The most commonly mentioned parameters are energy, exergy and price, but one could also choose to allocate 100% to either electricity or heat, arguing that either the electricity or the heat is the main product (note that this is not the same as the determining product) and the other is a low valued by-product. Other methods have been proposed, but they are complex and require data that is not available (Aldrich et al., 2011).

100% to electricity is considered, but is not appropriate
Allocating 100% to electricity could be described as a system expansion scenario, where the electricity from the CHP system substitutes electricity from a natural gas-fired power plant with the same efficiency as the CHP system, but where the residual heat is not utilised. In theory this sounds reasonable, but in practice this means that using a boiler or a geothermal source to heat the greenhouse has a disproportionately higher impact, arguing that they would keep the situation with high heat losses from the power plants in place. Therefore, this method is considered inappropriate and is rejected.

100% to heat is considered, but is not sensible
Allocating 100% to heat is not fully correct: heat from a CHP could be substituted with heat from a boiler, but a boiler efficiently converts natural gas into heat. So, no scenario can be described to justify this allocation method and hence it is not sensible and is rejected.

Exergy-based allocation is considered, but is not applicable
The exergy values of the co-products could be considered as an alternative to allocate. Exergy is a theoretical concept based on physical properties. It is used in the case of heat and electricity from CHP systems in the LCDN Thinkstep database (Kupfer et al., 2018) to which the PEFCR Guidance refers, and the ecoinvent database (Wernet et al., 2016), because the developers view exergy, the potential amount of work that can be delivered, as the true value of energy products (Moreno Ruiz et al., 2016). This view is in line with the papers of Rosen (2006; 2008), who strongly advocated the use of exergy allocation for CHP.

This way of allocation is valid for steam turbines producing electricity. However, this is not valid for use of heat in biological production. The exergy of electricity is equal to the energy, and the exergy of heat is the maximum possible conversion to work, resulting in a much lower value per MJ energy than the exergy value of electricity (about 0.2 MJ/MJ). This assumes that a CHP system is supplying heat and electricity to provide work (e.g. push a locomotive or drive a generator), while heat is often not valued for its conversion to work, but as thermal energy. Heat is used simply as a heat source in greenhouses as well as in industrial applications and city heating. So, in these cases the exergy of heat does not represent the value that it obtains from the input (natural gas) to provide the purpose, which makes exergy-allocation not applicable to CHP systems used in horticulture and itis therefore rejected.

Energy-based allocation is applicable
Electricity and heat are measured in energy (MJ), which is the main physical characteristic reflecting the function of natural gas and electricity (Table 1). There is also a clear relationship between the energy content of the natural gas input (upper heating value) and the energy of the electricity and the heat produced. The energy allocation method is therefore considered applicable and also sensible[4].

[4] In the very scarce peer-reviewed scientific literature on the CHP multi-functionality issue in horticulture Torrellas et al. (2012) prefer energy allocation over system expansion (though only arguing that it results in a better comparison between Dutch, Hungarian and Spanish tomatoes).

Economic allocation is a theoretically reasonable, but practically not recommended
The economic value of the co-products is often seen as an alternative to allocate. However, in the case of CHP systems in the horticultural context, the heat is not sold to the market but used by the owner. This means that we cannot directly determine the economic value of these co-products.

- Based on statistics from CBS (2020) averaged over 2013-2019 the supply prices of electricity in the class 2 000 to 20 000 MWh is €0.076 per kWh.
- The price of heat is variable depending on location, infrastructure and demand (Raaphorst & Benninga 2019).
- Nevertheless, the approach is not consistent with the market prices of electricity.
- Trying to calculate the variable cost price of electricity from combusting natural gas where only electricity is produced, is not an option either, because such systems would be highly inefficient.

So, at the moment we do not have any other solution that to assume the theoretical cost price of heat is a good estimate for the theoretical market price of heat from a CHP system. With this assumption, electricity is a more important product than heat (Table 1). In that sense it seems more valid to apply substitution to heat than to electricity, but the allocation percentage of heat is still high, which shows that applying substitution to heat is also not the obvious method to choose. Economic allocation therefore appears to be a reasonable choice. However, economic allocation based on the (always changing) market price of electricity and the (always changing) natural gas based cost price of heat as a proxy for the market price is inconsistent and uncertain. Similarly, Guest et al. (2011) reject economic allocation for CHP systems 'due to the localized and often vertically integrated nature of the district heating industry'. Moreover, the PEFCR Guidance (European Commission, 2018) states: 'In case of economic allocation is used, the allocation factors shall be fixed and provided in the PEFCR'. This assumes that the ratios of the outputs are fixed. So, from a practical point of view, economic allocation is not recommended.

Table 1 *An example of the economic, energy and exergy allocation fractions of a CHP system (reference unit is 1 m^3 input of natural gas with a LHV of 31.65MJ/m^3)*

Co-products	Electricity	Heat	Total
Unit	kWh	MJ	
Amount	3.5	15.2	
Efficiency	40%	48%	
Price (€)	0.076	0.013	
Revenue (€)	0.27	0.20	0.46
Economic allocation	57%	43%	1
Energy content (MJ)	3.6	1	
Energy production (MJ)	12.6	15.2	24.3
Energy allocation (MJ)	52%	63%	
Exergy value (MJ)	3.6	0.2	
Exergy production (MJ)	12.6	3.04	15.7
Exergy allocation	80%	19%	

Discussion

An LCA was undertaken for heat from a small CHP system using the various methods for handling the co-production of heat and electricity, for heat from a geothermal system, and for heat from a natural gas boiler. It was assumed that 48% of the lower heating value of natural gas is converted into heat and 40% into electricity. For the natural gas boiler, it was assumed that 90% of the lower heating value is converted into heat. The results are shown in Figure 2. Heat from CHP with energy allocation has a slightly greater impact than heat from a natural gas boiler and is similar to the method in which electricity is regarded as the main product, because the natural gas boiler has slightly more efficiency. If heat is seen as the main product (avoided electricity), that would mean that geothermal energy has a greater impact than the CHP. Geothermal energy has a slightly smaller impact than heat from a CHP with exergy allocation. Price allocation results in an impact lower than with energy allocation and higher than with exergy allocation, but it has not been possible to determine prices reliably and consistently, 100% to heat and 100% to electricity are not real options, but represent the extremes.

When a single product study is carried out on a horticultural product for the production of which a CHP system is used and this is compared to the results with another single product study where geothermal energy is used, the latter seems much less impactful (comparing energy allocation and geothermal heat in Figure 2). This could lead to a different conclusion than when applying system expansion in a comparative study, depending on the most likely electricity market scenario. So, the aim of increasing comparability between single product studies of the PEF Guide is out of reach for horticultural products, at least in cases where CHP systems are used.

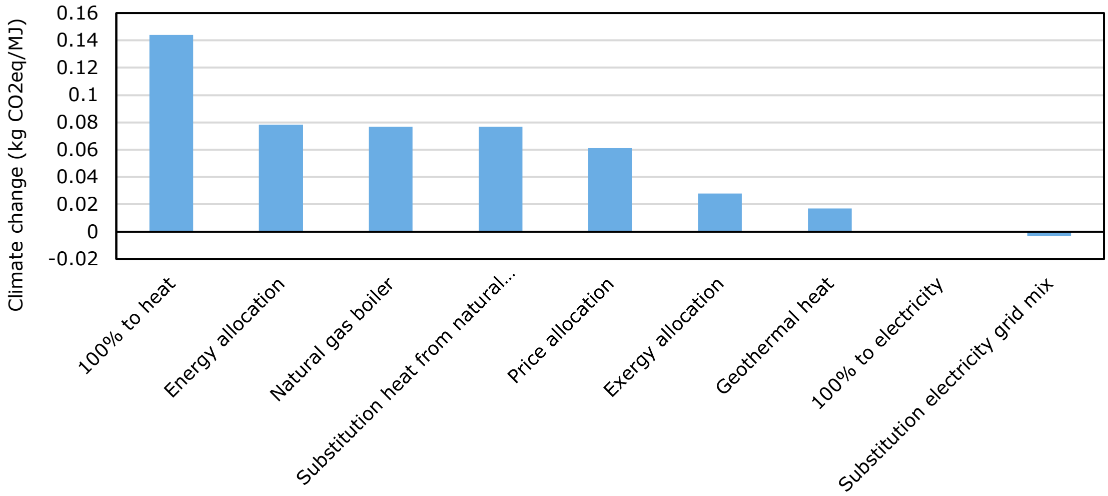

Figure 2 *Climate change impact of heat from a CHP system for heating a greenhouse using various methods for handling the multi-functionality*

Conclusion

Following the ISO 14044 (ISO, 2006), we explored several ways of handling the multi-functionality of the CHP system used in horticulture for the development of a product environmental footprint methodology of horticultural products.

- The first part of the first step is to consider subdivision: we decided to consider the heat and electricity production as one unit process, the carbon dioxide capture and purification as one unit process and the cultivation as one unit process.
- The second part of the first step is to consider system expansion: this method is relevant for scenarios where one heating technology replaces the other. However, this involves modelling and assumptions, which is not feasible in single product environmental footprint assessments.
- The second step for single product studies is to consider physical allocation: chemical properties are not possible and the relationship between physical properties and the emissions of a CHP system is disputable.
- The third step for single products studies is to choose any other relationship:
  - 100% to electricity is not appropriate: heat from a CHP system would have a disproportionally lower impact than greener alternatives. So, this is rejected.
  - 100% to heat is not fully correct as it would suggest that a CHP system is less efficient than a natural gas boiler. So, this is rejected.
  - Exergy-based allocation has the advantage that it is consistent with background data, but it is not applicable to the horticultural situation, because the exergy of heat does not represent the application of heat used in a greenhouse. So, this is rejected.
  - Energy-based allocation is applicable and makes sense.
  - Economic allocation makes some sense from a theoretical point of view. The main issue here is that it is practically problematic to apply, resulting in inconsistency and uncertainty. So, this is not recommended.

So, the most applicable and sensible method for the co-production of heat and electricity from CHP systems in single product environmental footprint assessments is energy allocation[5]. For the time being, we recommend accepting inconsistent allocation approaches in foreground modelling and background databases (energy- and exergy- based respectively) as it is not feasible to adapt this in standard LCA software and the mandatory background data for PEF compliant studies are not allowed to be modified by the users. However, we recommend that the data owners to seriously consider the arguments discussed here and apply energy allocation instead of exergy allocation in the following update, even though this means that earlier LCA results and conclusions of LCA practitioners need to be reconsidered.

It must also be stressed that the application of energy allocation does not offer sufficient information for taking scientifically sound conclusions on a switch from the use of CHP to other heating technologies or vice versa. To be able to assess the environmental impact of such a switch it is advisable to apply system expansion consistently throughout the lifecycle, taking into account various scenarios of future developments in the electricity market.

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[5] The produced CO_2 do not get any impact attributed at this stage, because it is an emission. The environmental impact of purification and transport of CO_2 is entirely allocated later on to CO_2 production and delivery.

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