

Article

## The Influence of Allocation on the Carbon Footprint of Electricity Production from Waste Gas, a Case Study for Blast Furnace Gas

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**Abstract:** Producing electricity from waste gas is an after treatment for waste gas while recovering the energy content. This paper addresses the methodology to calculate the effect that waste gas energy recovery has on lowering the impact of climate change. Greenhouse gases are emitted while burning the waste gas. However, a thorough study should include the production of the feedstock as well as the production of the infrastructure. A framework is developed to calculate the environmental impact of electricity production from waste gas with a life cycle approach. The present paper has a twofold purpose: to assess the climate change impact of generating electricity with blast furnace gas (BFG) as a waste gas from the steel industry; and to establish a sensitivity assessment of the environmental implications of different allocation rules.

**Keywords:** life cycle assessment; waste gas; blast furnace gas; allocation

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### 1. Introduction

When products or processes are developed and optimized it is important to include their environmental performance in the decision process. Life Cycle Assessment (LCA) is a methodology which allows

giving a complete and unbiased environmental impact of a product or service; it is, furthermore, the most prevailing methodology to do so. LCA assesses the overall environmental impact of a product or service by including all direct and indirect impacts of all life phases of the product or service from “cradle-to-grave” (mining of resources, production, distribution, use phase and end of life treatment). When computing the inventory data, the LCA practitioner sometimes needs to share the emissions from multi-output processes between their different products. This portioning operation is called allocation. In the ISO 14044:2006 standard [1], a procedure has been developed in order to guide the LCA practitioner to deal with a multi-output process. Methodological studies have identified procedures to deal with allocation [2–13]. All of them recognize the importance of allocation procedures on the end result and on the decision that will be based on the result of a LCA study. This paper assesses the carbon footprint of generating electricity with blast furnace gas (BFG) as a waste gas from the steel industry; and establishes a sensitivity assessment of the environmental implications of different allocation rules. The paper shows a carbon footprint calculation, which is a LCA exercise limited only to the emissions that have an effect on climate change. Carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) are taken into consideration in the model as they are the most important greenhouse gases. The study focuses on climate change only as it is among the most relevant impact categories for the energy and steel sector. However, the provided allocation procedures are general applicable and can be used to calculate impacts on other relevant impact categories such as human health, ecosystem quality and resource depletion. Moreover the allocation rules can be used in other multi-functional processes. The study includes emissions related to the building of the infrastructure, the fuel supply chain and the conversion emissions in the electricity plant. Some case studies have shown that allocation rules can have an influence on the calculated impact of bioenergy on the environment [14–28]. According to Cherubini *et al.* [29] allocation is important in the bio-energy context because bioenergy systems are often part of multifunctional processes. Electricity production from waste streams is also composed of multifunctional processes, making it worthwhile to investigate allocation procedures and their influences on the environment more in detail. The different allocation rules to produce electricity from waste gases are compared on the same functional unit (FU). The FU is a quantified description of the performance of a product system. The FU is used as a reference unit. It allows comparing two or several product systems on the basis of a common provided service. Every LCA study includes a FU that defines what is being studied and it is based on the goal and scope definitions. The use of a FU allows the comparison between other different LCA studies. As a consequence, all the end results of a LCA are related to the described FU and do not reflect the overall absolute impact of a product system. In this case, the production of 1 kWh of electricity has been chosen as the functional unit. In order to create a methodological framework for the practice of LCA on one hand and to ensure that all requirements of the methodologies are met, the International Standardization Organization (ISO) has published two standards, the ISO 14040:2006 [30] and the ISO 14044:2006 [1].

## 2. Theoretical Framework

Life Cycle Assessment is described as the evaluation of the material and energy flows alongside with their induced environmental stress throughout the life cycle of a product or service. This group of

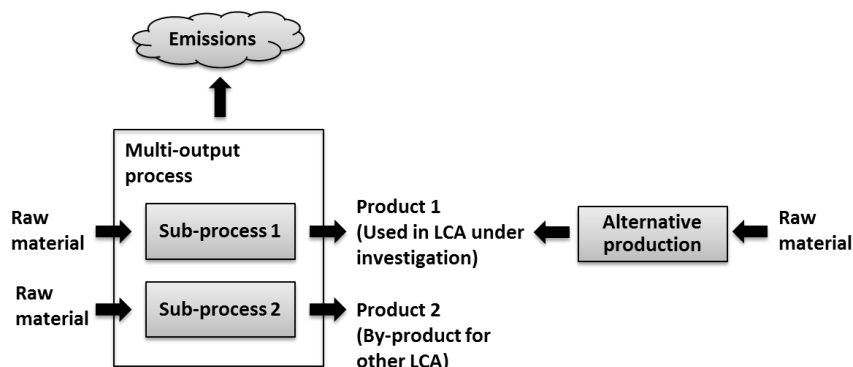
materials and energy pathways are called the elementary flows and are gathered in a life cycle inventory (LCI). The life cycle of a product is modeled as a system consisting of several other sub-systems; they resemble the activities throughout the different steps in the life cycle. The system is modeled from cradle-to-grave, which is from material production (cradle) to the final end-of-life treatment of the product (grave).

A LCI modeling problem arises when one of the functions of the product system is composed of a multifunctional process and the other is used in another product system. The LCI modeling problem that exists is the choice on how to divide or allocate the environmental impacts from the multifunctional process to the different product systems. The allocated share of the environmental burden of the multifunctional process to the product system under study significantly influences the result of the LCA. A large number of methodological approaches and solutions were developed in the past to deal with this issue of allocation. The ISO 14044:2006 norm includes a procedure to deal with the allocation problem in LCA [1]:

- Avoid allocation by dividing the multi-output processes in individual sub-processes and collect data for the sub-processes.
- Avoid allocation with an expansion of the system and attribute to the product-system a credit equivalent to the production of co-products elsewhere.
- However, when the allocation cannot be avoided, the inputs and outputs should be partitioned between the different co-products with respect to the physical and quantitative relationship between inputs/outputs and co-products.
- Sometimes, physical relationship could not be established between inputs/outputs and the co-products. In such a case, other relationship, e.g., the unit price might be used as a basis for allocation.

Figure 1 explains the allocation procedure [31]. The multi-output process delivers two jointly produced products, products 1 and 2. The problem that arises is how to allocate the emissions from the multi-output process between products 1 and 2. It is considered that product 1 is the product under investigation in the LCA. If the multi-output process consists out of two separate sub-processes (sub-processes 1 and 2) and if separated emission data exists, it is possible to avoid allocation by subdivision. Because of this specific procedure, the LCA of product 1 should take only the emissions from sub-process 1 into account. The allocation problem is eliminated if it is possible to subdivide the multi-output process in single-output processes. However, in many multi-output processes it is not possible to split-up the joint production as there is no physically separation of sub-processes. In this case, to avoid allocation, an expansion of the system can be an option. In system expansion the boundaries of the LCA are expanded in order to include processes that are influenced by the product under investigation. The multi-output process produces product 1 and hereby avoids the alternative production of product 1. The avoidance of the alternative production and its' related emissions can be credited to the multi-output process. When system expansion is not an option, the allocation of the emissions of the multi-output process can be based on relationships between the products 1 and 2 such as price, weight, volume, exergy and energy content. In this paper five different approaches are discussed to deal with the multifunctional process: system expansion, industry split-up, economic, exergetic and energetic allocation.

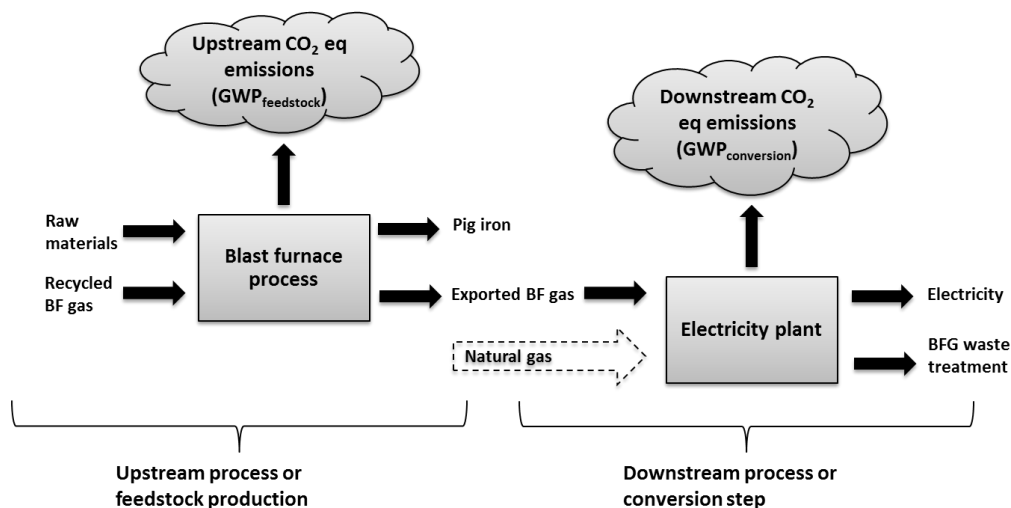
**Figure 1.** Overview of the allocation problem in multi-output processes.



### 3. The Blast Furnace Gas Case

When producing electricity from blast furnace gas, two allocation problems coexist; one related to the conversion process and one related to the feedstock production. During the conversion step (right part of Figure 2) the production of the electricity from blast furnace gas is seen as a multi-output process with two functions: producing electricity and treating the blast furnace gas, which is a waste from the steel industry. Which part of the downstream emissions should be allocated to the electricity production and which part should be allocated to the fact that the electricity plant is treating the waste gas from the steel industry? During the blast furnace process (left part of Figure 2) the question is how to allocate the upstream emissions between the two output products: the pig iron and the blast furnace gas. Combining the “feedstock” and the “conversion” allocation rules provide different sets of results. The blast furnace process uses coke, coal, blast furnace gas, coke oven gas, natural gas and iron ore to produce pig iron. The blast furnace gas, mainly composed of carbon monoxide, is an emission that occurs during this process. The blast furnace gas is recycled partly by the blast furnace process itself as it has an energetic value; the rest can be flared in order to oxidize the toxic carbon monoxide into non-toxic CO<sub>2</sub>. However, a different strategy is that instead of flaring the blast furnace gas, it can be diverted and used to produce electricity. Therefore the blast furnace gas replaces a share of natural gas.

**Figure 2.** Overview of the allocation problem that arises from producing electricity with blast furnace gas as a waste gas.



### 3.1. System Expansion

As the production of blast furnace gas is a consequence of the pig iron production, it is not possible to avoid allocation by splitting up the multi-output process in two separated sub-processes. However, it is still possible to avoid allocation via system expansion. When expanding the system it is possible to attribute credits to the product system (pig iron) equivalent to the production of the co-product (blast furnace gas) that is replacing the production of the alternative product (natural gas). As shown in Figure 2, the exported blast furnace gas is replacing natural gas. In studies dealing with system expansion of energy recuperation from waste streams it is mostly assumed that the waste stream is avoiding other energy sources [32–34]. In this sense, the production of pig iron should get a credit for offsetting the life cycle emissions originated while producing electricity from natural gas. The life cycle emissions for electricity generation from natural gas contain both the feedstock production, distribution and the conversion emissions generated by the burning of natural gas in an electricity plant. The life cycle impact of the pig iron includes all the upstream blast furnace emissions minus the production of the natural gas and all the downstream emissions during the conversion step in the electricity plant, without the emissions from producing an equivalent amount of electricity with natural gas. The blast furnace process is getting the benefit of recovering the energy content of the waste gas. The impact of producing electricity from blast furnace gas is equivalent to producing electricity from natural gas, in order to keep the whole system at an equivalent status.

### 3.2. Industry Split up

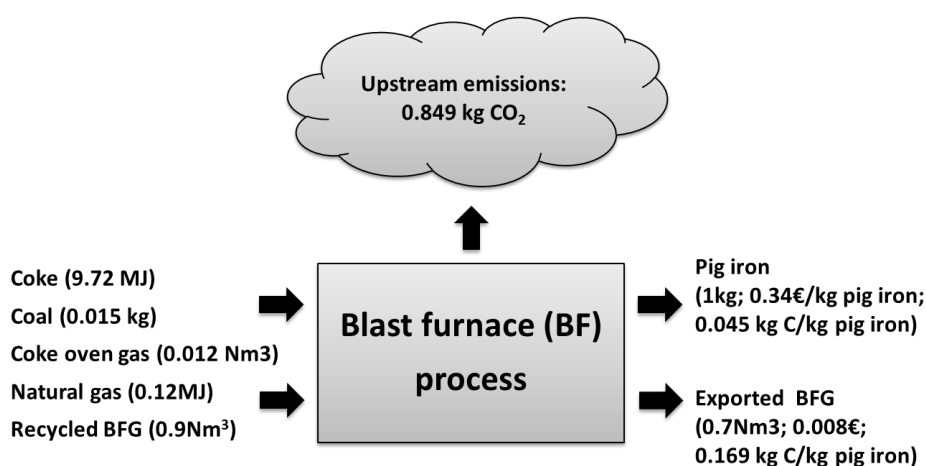
In the EU Emissions Trading System (EU-ETS) [35] waste gases are defined as gases derived from incomplete combustion or chemical reactions. Waste gases are not emitted without further combustion, because of the high content of incomplete or non-oxidized carbon that can be used in another process. The emissions occurring during the production of the waste gas are fully allocated to its producer (in this particular case the steel industry) according to the EU-ETS regulation. The consumer of the waste gas, the electricity producer, receives no additional allocation for the production of the feedstock (the blast furnace gas). Referring to Figure 2, the upstream emissions are fully allocated to the pig iron. The part of the blast furnace gas which is exported to the electricity plant, does not share the burden of the upstream emissions. On the other hand, if the waste gas is used to produce electricity the consumer of the waste gas is fully allocated with the conversion emissions occurring in the electricity plant. The downstream emissions from Figure 2 are fully allocated to the production of the electricity. The steel producer receives no emissions for the ‘waste treatment’ process, carried out by the electricity producer. Summarizing, the emissions from both industries are split up, the emissions occurring in each industry’s own processes are fully allocated to their intended output product. For the steel industry this is the production of pig iron, for the electricity producer this is the production of electricity. There is no transfer of up- or downstream responsibilities and related emissions.

### 3.3. Economic Allocation

Another way to allocate the upstream CO<sub>2</sub> emissions to the two co-products (pig iron and BFG) is by means of an economic allocation. As the electricity production is using the blast furnace gas as an

input, it can be argued that a partition of the upstream emissions should be allocated to the electricity producer. One way to allocate the CO<sub>2</sub> emissions is with a price based share. The economic allocation rule makes sense as the reason for the upstream emissions is ultimately the production of steel and the fact that the steel producers wants to create a financial profit. All the inputs and outputs involved in the production of 1 kg of pig iron are described in Figure 3. In the left side (input), the different energy carriers, materials and their respective amounts (involved in the production of 1 kg of pig iron) are given. On the right side (output), the emissions of CO, CO<sub>2</sub> and BFG induced by the production of 1 kg of pig iron are given. As it can be noticed, the production of 1kg of pig iron generates 1.6 Nm<sup>3</sup> of BFG. However 0.9 Nm<sup>3</sup> of BFG is recycled through the blast furnace and finally, only 0.7 Nm<sup>3</sup> of BFG are exported to the electricity producer [36].

**Figure 3.** The balance of a blast furnace process.



The unit price of BFG on the Belgian market is assumed to be 3.1 €/GJ and its Lower Heating Value (LHV) is 3.67 MJ/Nm<sup>3</sup>. The unit price of pig iron on the international market is assumed to be 465 \$/ton or 0.34 €/kg of pig iron [37]. The final price of the amount of BFG involved in the production of 1 kg of pig iron is then calculated. The net amount of BFG (Nm<sup>3</sup>) produced per kg of BFG is multiplied by the LHV (MJ/Nm<sup>3</sup>) of the BFG in order to obtain the energy content. Later, the energy content is then converted in GJ and multiplied by the unit price of the BFG (€/GJ). The economic allocation factors of the BFG and the pig iron are then calculated. The CO<sub>2</sub> emissions allocated to the BFG will represent 2.3% of the emissions of the blast furnace process, Equation (2):

$$Cost_{BFG} = \left(0.7 \text{ Nm}^3 \times \frac{\text{MJ}}{\text{Nm}^3} \times 1000\right) \times 3.1 \frac{\text{€}}{\text{GJ}} = 7.96 \times 10^{-3} \text{ €} \quad (1)$$

$$Factor_{BFG} = \frac{Cost_{BFG}}{(Cost_{BFG} + Cost_{Pig\ Iron})} = 0.023 = 2.3\% \quad (2)$$

### 3.4. Energetic Allocation

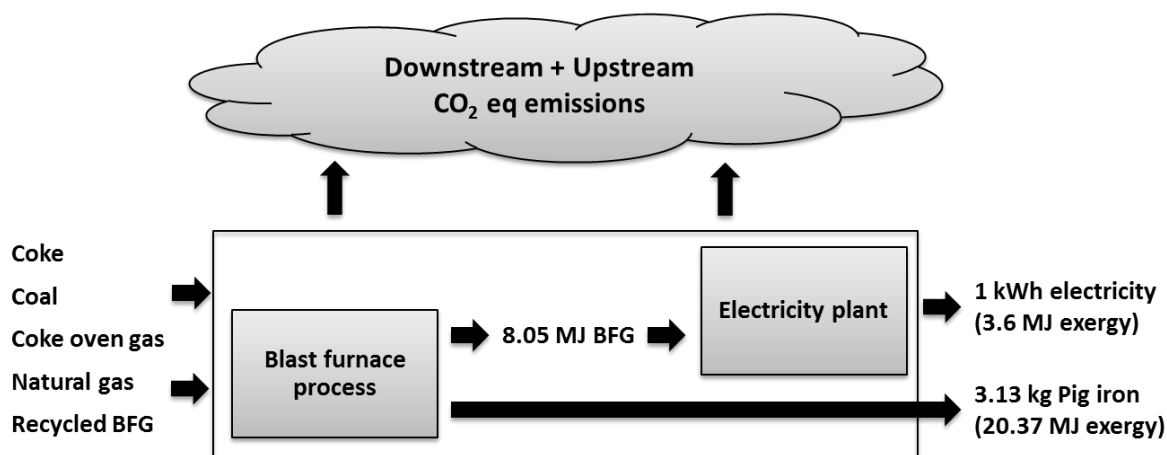
As BFG is a waste product from the steel industry, it can be argued that the steel industry should receive a part of the downstream emissions described in Figure 2. The steel industry forces the electricity producer to use carbon monoxide as a fuel. This “conversion” allocation method is based on the chemical reactions and the corresponding energy which is released during the two sequential

reactions: oxidizing C to CO (steel industry) and oxidizing CO to CO<sub>2</sub> (electricity producer). The final CO<sub>2</sub> emissions are created since the steel industry and the electricity producer both needed the oxidation energy in the two steps. The energetic allocation will divide the final CO<sub>2</sub> emissions according to the energy released in the two steps. During the first step, the steel industry uses the energy released during the oxidization of carbon in carbon monoxide, when carbon reacts to carbon monoxide, 110 kJ/mol is released. During the second part, the electricity producer uses the energy released when carbon monoxide is evolving further to carbon dioxide. During the reaction of carbon monoxide to carbon dioxide, 283 kJ/mol is released. The full reaction of carbon oxidizing to CO<sub>2</sub> releases 393 kJ/mol. A share of 72% ( $283 \div 393$ ) of the total energy originates from the oxidization process of CO to CO<sub>2</sub>. As a consequence, 72% of the carbon dioxide released during the combustion of CO in the electricity plant is allocated to the electricity production; the other part is allocated to the steel production as an impact associated for the “waste treatment”.

### 3.5. Exergetic Allocation

Another way to allocate the emissions is with an exergetic allocation rule. The exergetic allocation rule applies to the full system and includes both industries. The multi-functional process produces pig iron as well as electricity, see Figure 4. The total carbon emissions from the steel industry and the electricity producer will be divided taken the exergy of both products (pig iron and electricity) into consideration.

**Figure 4.** Overview of the exergetic allocation rule for pig iron and electricity produced in a blast furnace process.



To produce 1 kWh of electricity 8.05 MJ BFG is needed. To produce 1 kg of steel, 2.56 MJ of BFG ( $3.67 \text{ MJ/Nm}^3 \times 0.7 \text{ Nm}^3$ ) is exported to the electricity plant. This means that for every kWh electricity, 3.13 kg of pig iron is produced. The exergy of 1 kWh electricity is 3.6 MJ. According to Gasparatos 1 kg of pig iron corresponds to 6.57 MJ exergy [38]. When producing 1 kWh of electricity, 20.37 MJ pig iron is produced. The downstream and upstream carbon emissions are divided over the co-products taking the exergy content into consideration. This means that 85% of the total emissions are allocated to the production of pig iron and the remaining 15% of the emissions are allocated to the production of electricity.

## 4. Life Cycle Inventory

### 4.1. Conversion

The conversion CO<sub>2</sub> emissions are measured by the electricity producer, together with the fuel consumption and the electricity production. However, these emissions should be treated with caution as they also contain CO<sub>2</sub> emissions from the blast furnace process. All the CO<sub>2</sub> emissions which enter the electricity plant via the composition of the blast furnace gas are inert during the combustion and will not add energy to the process. This part of the CO<sub>2</sub> is therefore considered as 100% allocated to the blast furnace. The remaining CO<sub>2</sub> equivalent conversion emissions are 1.102 kg CO<sub>2</sub>eq/kWh for electricity produced with blast furnace gas and 0.358 kg CO<sub>2</sub>eq/kWh for the production of electricity with natural gas (these values were directly obtained from the electricity producer). The CO<sub>2</sub> equivalent emissions include both methane and nitrous oxide emissions, as these two pollutants have an effect on climate change. The conversion emissions from producing electricity with natural gas are gathered for the modeling of the “system expansion” case.

### 4.2. Impacts of the Construction of the Power Plants

For the impacts of the production and the decommissioning of the power plant, default EcoInvent data (Table 1) are considered for natural gas and blast furnace gas as they are combusted in the same plants. The EcoInvent datasets [39] on the power plant includes the land transformation and occupation, use of materials (concrete, steel, copper, plastics, *etc.* energy consumption, heat waste and the transport. In Table 1 the lifetime, the employment rate and the efficiency are taken into account in the calculation. The impact of these power plants originates essentially from the construction materials (gravel, cement, water, steel, explosives, *etc.*).

**Table 1.** EcoInvent assumptions on different power plant infrastructures [39].

Name	EcoInvent process	Amount/kWh	CO <sub>2</sub> /kWh
Blast furnace gas plant	Gas power plant, 100 MWe/RER/I U	$7.28 \times 10^{-11}$	$3.50 \times 10^{-4}$
Natural gas plant	Gas power plant, 100 MWe/RER/I U	$5.95 \times 10^{-4}$	$2.86 \times 10^{-4}$

### 4.3. Feedstock Production

#### 4.3.1. Blast Furnace Gas Production

The pig iron production process is used to model the feedstock production of BFG. All the inputs and outputs involved in the production of 1 kg of pig iron are considered. The production of pig iron is modeled with the Econinvent process “Pig iron, at plant/GLO U [kg] (#1132)”. As an input, we have the different energy carriers and materials as well as their amounts involved in the production of 1 kg of pig iron. The CO<sub>2</sub> emissions and BFG are the described output. As it can be noticed, the production of 1 kg of pig iron generates 1.6 Nm<sup>3</sup> of BFG. However, 0.9 Nm<sup>3</sup> of BFG is recycled in the blast furnace and, only 0.7 Nm<sup>3</sup> of BFG is exported to the electricity producer. The lower heating value is 3.67 MJ/Nm<sup>3</sup>[39]. When simultaneous producing 1 kg of pig iron and 0.7 Nm<sup>3</sup>BFG, 1.56 kg CO<sub>2</sub>eq is



emitted [39]. This means that for 1 MJ of BFG, 0.61 kg CO<sub>2</sub>eq is emitted in total according to Equation (3):

$$0.61 \frac{\text{kg CO}_2\text{eq}}{\text{MJ BFG}} = \frac{\left(1.56 \frac{\text{kg CO}_2\text{eq}}{\text{kg pig iron}}\right)}{\left(0.7 \frac{\text{Nm}^3\text{BFG}}{\text{kg pig iron}}\right)\left(3.67 \frac{\text{MJ BFG}}{\text{Nm}^3}\right)} \quad (3)$$

However, according to the economic allocation factor calculated with Equation (2), only 2.3% of the total CO<sub>2</sub> of the blast furnace process emissions should be allocated to the production of BFG, the rest should be allocated to the pig iron production. The impact on climate change of producing BFG is 0.014 kg CO<sub>2</sub>eq/MJ BFG, Equation (4). According to measurements done by the electricity producer, 8.05 MJ of BFG is needed to produce 1 kWh of electricity. This means that 0.112 kg CO<sub>2</sub>eq is emitted when producing the amount of BFG that is needed to generate 1 kWh of electricity, Equation (5):

$$0.014 \frac{\text{kg CO}_2\text{eq}}{\text{MJ BFG}} = 2.3\% \times 0.61 \frac{\text{kg CO}_2\text{eq}}{\text{MJ BFG}} \quad (4)$$

$$0.112 \frac{\text{kg CO}_2\text{eq}}{\text{kWh}} = 8.05 \frac{\text{MJ BFG}}{\text{kWh}} \times 0.014 \frac{\text{kg CO}_2\text{eq}}{\text{MJ BFG}} \quad (5)$$

#### 4.3.2. Natural Gas Supply Mix

For the natural gas production and transport, the Belgian situation is considered. The different type of natural gas per supplying country and their share in the Belgian mix are considered (Table 2). The country specific production and transport (to Europe) emissions are used to calculate the emissions of 1 MJ of a Belgian supply mix natural gas. A lower heating value (LHV) of 37 MJ/Nm<sup>3</sup> is considered.

The Qatari natural gas, which represents 17% of the Belgian supply mix, is modeled separately. In fact, it is supplied in a liquefied form and requires dedicated liquefaction and transport infrastructures. The liquefied natural gas (LNG) model includes the natural gas production, the liquefaction energy, the evaporation energy and the transport, see table 3. Since no specific inventory data from the natural gas extraction Qatar is available, the EcoInvent datasets corresponding to the extraction and the liquefaction of Algerian natural gas are applied. Transoceanic shipping over a distance of 6277 nautic miles is considered for the transport of the LNG between the Ras Laffan port in Qatar and Zeebrugge in Belgium. Once in Belgium, the LNG is evaporated in a decompression plant modeled according to the operation of an equivalent Italian plant [39]. The distribution of the natural gas to the end user after the evaporation is modeled according to the EcoInvent dataset including energy requirements, emissions and infrastructure of the high pressure distribution network in Belgium. The assessment of the different types of natural gas shows that the Qatari gas (LNG) is responsible of more than 51% of the overall GWP of the Belgian natural gas supply mix while it represents only 17% of the volume of the imports. This is due essentially to the liquefaction and the transport of the LNG which represents respectively 46% and 28% of the CO<sub>2</sub> emissions of the LNG.

**Table 2.** Natural gas supply mix in Belgium [40].

Country of origin	%	EcoInvent processes	kg CO <sub>2</sub> eq/MJ
Netherlands	35	Natural gas, production NL, at long-distance pipeline/RER U	$1.88 \times 10^{-3}$
Norway	35	Natural gas, production NO, at long-distance pipeline/RER U	$3.64 \times 10^{-3}$
UK	4	Natural gas, production GB, at long-distance pipeline/RER U	$1.20 \times 10^{-3}$
Qatar	17	see LNG model	$2.09 \times 10^{-2}$
Russia	3	Natural gas, production RU, at long-distance pipeline/RER U	$2.17 \times 10^{-2}$
Other	6	Natural gas, at long-distance pipeline/RER U	$1.03 \times 10^{-2}$

**Table 3.** Production, transport and evaporation data of 1 MJ of the LNG.

EcoInvent processes	Amount	Units
Production		
Natural gas, at production onshore/DZ U	$2.70 \times 10^{-2}$	m <sup>3</sup>
Liquefaction		
Natural gas, burned in gas motor, for storage/DZ U	$1.56 \times 10^{-1}$	MJ
Production plant, natural gas/GLO/I U	$2.13 \times 10^{-14}$	P
Transport		
Transport, liquefied natural gas, freight ship/OCE U	$2.44 \times 10^{-1}$	tkm
Evaporation		
Water, salt, ocean	$1.73 \times 10^{-5}$	m <sup>3</sup>
Natural gas, burned in gas turbine, for compressor station/DZ U	$1.51 \times 10^{-2}$	MJ
Production plant, natural gas/GLO/I U	$2.13 \times 10^{-14}$	P
Distribution		
Natural gas, burned in industrial furnace >100kW/RER U	$1.67 \times 10^{-3}$	MJ
Electricity, medium voltage, at grid/BE U	$7.14 \times 10^{-5}$	kWh
Pipeline, natural gas, high pressure distribution network/CH/I U	$7.95 \times 10^{-10}$	km
Transport, natural gas, pipeline, long distance/RER U	$7.67 \times 10^{-3}$	tkm

## 5. Result: Carbon Footprint of Electricity from Blast Furnace Gas

The Life Cycle Inventory Assessment (LCIA) can be summarized in Table 4, with the results of the manufacturing of the electricity plant, production of the feedstock and the conversion emissions occurring during the generation of the electricity. The table gives the CO<sub>2</sub>eq emissions per produced kWh for the different life phases of electricity production with BFG and natural gas.

**Table 4.** Climate change impact (kg CO<sub>2</sub>eq/kWh) of the different life phase of electricity generation from BFG and natural gas.

In kg CO <sub>2</sub> eq/kWh	BFG	Natural Gas
Plant infrastructure (GWP <sub>plant</sub> )	0.0004	0.0003
Feedstock (GWP <sub>feedstock</sub> )	0.112	0.050
Conversion (GWP <sub>conversion</sub> )	1.102	0.358
Total (GWP <sub>elec</sub> )	1.215	0.408

The “feedstock” and the “conversion” emissions can be allocated with the different rules provided above. First of all, the chosen sets of allocation rules are discussed. The climate change impact is

expressed as the global warming potential (GWP) with kg CO<sub>2</sub> equivalents as the unit. All emissions relevant for climate change are translated in kg CO<sub>2</sub> equivalents. The impact on climate change of producing electricity will include the feedstock production, the conversion and the production of the plant itself, see Equation (6). The main question is about which allocation factors to consider for the feedstock and the conversion step. To calculate the total impact on climate change of producing electricity, following formula is used:

$$GWP_{elec,BFG} = GWP_{feedstock} + GWP_{conversion} + GWP_{plant} \quad (6)$$

where  $GWP_{elec,BFG}$  is the GWP of producing electricity from blast furnace gas;  $GWP_{feedstock}$  is the GWP of the blast furnace process;  $GWP_{conversion}$  is total conversions emissions from the electricity plant;  $GWP_{plant}$  is GWP for the production of the electricity plant.

### 5.1. System Expansion

In the system expansion approach, Equation (7), the impact of generating electricity from BFG is the same as generating electricity from natural gas. The production of the pig iron is credited for offsetting the life cycle emissions that would have occurred when producing electricity from natural gas. The life cycle emissions for electricity generation from natural gas contain the feedstock production, distribution and the conversion emissions when burning the natural gas in an electricity plant, as shown in the third column of Table 4. The impact of generating electricity from BFG is:

$$GWP_{elec,BFG} = GWP_{elec,NG} = GWP_{feedstock} + GWP_{conversion} + GWP_{plant} = 0.050 + 0.358 + 0.0003 = 0.408 \text{ kg CO}_2\text{eq/kWh} \quad (7)$$

### 5.2. Industry Split up

In the ‘industry split up’ allocation set, the feedstock production is entirely allocated to the pig iron production. The BFG is therefore an emission-free feedstock. However, the conversion emissions occurring in the electricity plant are fully allocated to the production of electricity. The inert CO<sub>2</sub> that was produced in the blast furnace gas process and that is part of the composition of the BFG, is 100% allocated to the pig iron production:

$$GWP_{elec,BFG} = GWP_{feedstock} + GWP_{conversion} + GWP_{plant} = 0 + 1.102 + 0.0004 = 1.102 \text{ kg CO}_2\text{eq/kWh} \quad (8)$$

### 5.3. Energetic Allocation

In the energetic allocation rule the feedstock production is entirely allocated to the pig iron production. The BFG is again, an emission-free feedstock. The conversion emissions are only partially allocated to the production of electricity, based on the chemical reactions and the corresponding energy which is released during the reaction, 72% of the net conversion emissions are allocated to the electricity generation from BFG:

$$GWP_{elec,BFG} = GWP_{feedstock} + 0.72 \times GWP_{conversion} + GWP_{plant} = 0 + 0.72 \times 1.102 + 0.0004 = 0.794 \text{ kg CO}_2\text{eq/kWh} \quad (9)$$

#### 5.4. Economic Allocation

With an economic allocation approach, the feedstock production is divided between the blast furnace process and the electricity production process with an economic allocation rule. Only 2.29% of the total emissions produced in the blast furnace are taken into account, which is 0.112 kg CO<sub>2</sub>eq/kWh. The BFG is therefore not anymore an emission-free feedstock. The conversion emissions are partially allocated to the production of electricity, based on the energetic allocation rule:

$$\begin{aligned} GWP_{elec,BFG} &= GWP_{feedstock} + 0.72 \times GWP_{conversion} + GWP_{plant} = \\ &0.112 + 72\% \times 1.102 + 0.0004 = 0.906 \text{ kg CO}_2\text{eq/kWh} \end{aligned} \quad (10)$$

#### 5.5. Exergetic Allocation

With the exergetic allocation rule 85% of the total carbon emissions produced in the blast furnace and the electricity plant are allocated to the pig iron production. Only 15% of the total emissions are allocated to the electricity production.

The blast furnace emits 1.56 kg CO<sub>2</sub>eq/kg pig iron. The production of 3.13 kg of pig iron corresponds with the amount of BFG needed for 1 kWh and emits a total of 4.88 kg CO<sub>2</sub>eq. The total conversion emissions are 2.12 kg CO<sub>2</sub>/kWh, including all the CO<sub>2</sub> emissions which enter the electricity plant via the composition of the blast furnace gas: The previous allocation rules these emissions were allocated for 100% to the blast furnace.

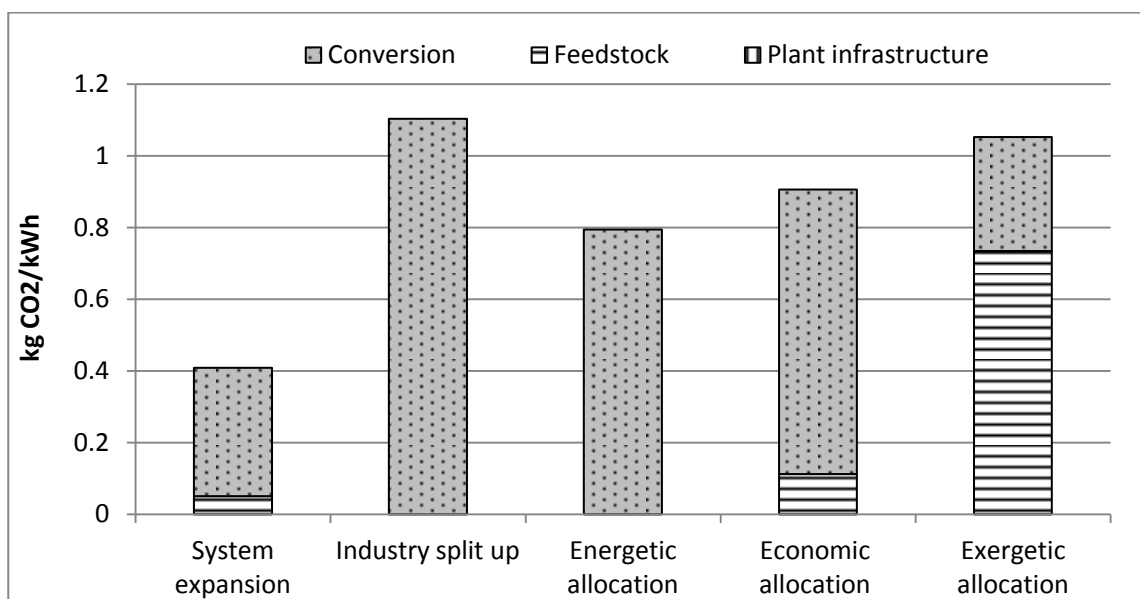
$$\begin{aligned} GWP_{elec,BFG} &= 15\% \times (GWP_{blast\ furnace} + GWP_{total\ conversion} + GWP_{plant}) \\ &= 15\% \times (4.88 + 2.12 + 0.0004) \\ &= 1.05 \text{ kg CO}_2\text{/kWh} \end{aligned} \quad (11)$$

## 6. Conclusions

As LCA is a decision support tool, allocation rules should be explicitly addressed in the reporting. The chosen allocation rule will have an impact on the end result. This should be pointed out by the LCA practitioner to the decision makers. A sensitivity assessment using different sets of allocation rules is an indispensable tool for decision makers to assess the possible environmental impact of a multifunctional process. In Figure 5, the average GWP of producing electricity with BFG as a waste gas from the steel industry is shown, under several different scenarios. Five different approaches to deal with the allocation problem are addressed: system expansion, industry split up, energetic allocation, economic allocation and exergetic allocation. The average GWP varies between 0.794 kg CO<sub>2</sub>eq/kWh (energetic allocation), 0.906 kg CO<sub>2</sub>eq/kWh (economic allocation) 1.05 CO<sub>2</sub>eq/kWh (exergetic allocation) and 1.102 kg CO<sub>2</sub>eq/kWh (industry split up). The approach, in which the system is expanded to include the avoided use of natural gas, has the lowest average GWP (0.408 kg CO<sub>2</sub>eq/kWh) as this approach allocated the burden of using BFG to the steel industry. Different allocation procedures assist different decisions. When it comes to taking consequences of a decision into consideration, system expansion is the most appropriate procedure as it includes the environmental impact of the avoided production. In the industry split up and the energetic allocation set, it is considered that BFG is an emission free feedstock at production level. In the economic allocation method the production of the

feedstock is allocated partly to the electricity production. The industry split up is the allocation rule provided by EU-ETS document [35], this is an easy-to-understand method that separates the different industries. However, it fails to provide insights on the benefits of using a waste gas for electricity generation. Another significant issue is that the electricity producer is obliged to burn the BFG and this obligation is not taken into consideration when calculating the carbon footprint with an industry split up allocation rule. The economic allocation rule provides a better understanding of the environmental impact induced by consumption. Products, such as steel and electricity, are produced to make an economic profit; therefore it makes sense to include an economic perspective when dividing environmental impacts of multifunctional processes. The exergetic allocation provides an approach in which two co-products (pig iron and electricity), with a different functionality, are compared on the same unit. An exergetic allocation is able to evaluate material and energy resource depletion.

**Figure 5.** Average impact on climate change for the production of 1 kWh with blast furnace gas with the different allocation rules.



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