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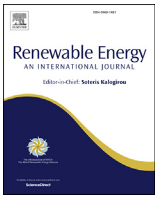

Environmental and exergetic sustainability assessment of power generation from biomass

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ABSTRACT

Power generation from biomass is mentioned as a means to make our society more sustainable as it decreases greenhouse gas emissions of fossil origin and reduces the dependency on finite energy carriers, such as coal, oil and natural gas. When assessing the sustainability of power generation from biomass, it is important to consider the supply chain of the used biofuel by conducting a life cycle assessment of the system. Besides regular sustainability assessments, such as the calculation of the environmental sustainability, attention should be paid to exergy losses, i.e. the loss of 'energy quality', caused by the system as a whole, because every process and activity is accompanied with the loss of exergy and because the amount of exergy on earth can only be replenished by capturing new exergy from solar and tidal energy. This research compares the use of livestock manure and verge grass for power generation by assessing the systems from an environmental as well as an exergetic life cycle point of view. The assessed systems are the following: combustion of bioethanol from the fermentation of verge grass, combustion of substitute natural gas from anaerobic digestion of cow and pig manure and combustion of substitute natural gas from supercritical water gasification of cow and pig manure. The environmental sustainability is assessed by calculating ReCiPe endpoint indicators and the exergetic sustainability is assessed by applying the relatively new Total Cumulative Exergy Loss (TCExL) method. The TCExL method considers all exergy losses caused by a technological system during its life cycle, i.e. the internal exergy loss caused by the conversion of materials and energy, the abatement of emissions and the exergy loss related to land use. In addition to comparing the three systems as well as both assessment methods, the influence of taking into account the system's by-products as 'avoided products' and via 'allocation' on the assessment results is investigated. The bioethanol system appears more sustainable from an environmental sustainability point of view, while the bioethanol and supercritical water gasification systems are preferred from an exergetic sustainability point of view. The indicator of the environmental sustainability assessment is highly influenced by the way of taking into account by-products, while the exergetic sustainability indicator is not.

1. Introduction

Renewable energy sources such as solar energy, wind energy and biomass are mentioned as a means to make our society more sustainable. They can be used to fulfil society's demand for energy carriers and to decrease the emission of carbon dioxide from fossil origin. Biomass is not only a source of energy, but also a material resource, i.e. a feedstock. When comparing different energy sources for power generation, it is important to assess these systems from a life cycle point of view, that is, to take into account the supply chain of the biomass and the construction, operation and decommissioning of the installations and equipment. By carrying out a life cycle assessment, problem-shifting between different life cycle

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phases and/or sustainability aspects is prevented [1]. Sustainability comprises the following three ‘pillars’: environmental, economic and social aspects [2]. This research is limited to the environmental aspect as data about the economic and social aspects of the assessed systems are not yet available.

Several methods have been developed to assess the environmental sustainability from a life cycle point of view. These methods convert the use of feedstocks, process emissions etc. into impact category indicators at a midpoint level, such as global warming potential, and/or into impact category indicators at an endpoint level, e.g. damage to human health and damage to ecosystem quality. Examples of these environmental indicators are the CML 2002 midpoint indicators [3], the Eco-indicator 99 endpoint indicator [4] and the ReCiPe indicators which comprise midpoint as well as endpoint indicators [5].

Besides the common environmental aspect of sustainability, it is also important to consider the degrading of the quality of energy, i.e. the exergy loss, caused by a (technological) system. Exergy, also known as the work potential of energy, is important because it is needed for every process and activity to take place, because every process and activity is accompanied with the loss of exergy, and because the amount of exergy on earth can only be replenished by capturing new exergy from solar and tidal energy. It is said that exergy and sustainability are related [6]. An advantage of exergy analysis compared to environmental sustainability assessment is that the mass and energy flows of a system can be considered based on their exergy value, thus without the need for classification or weighting factors. In scientific literature, life cycle assessment as well as exergy analysis are applied to assess systems such as hydrogen production [7] and food waste valorisation options [8]. However, these exergy analysis methods do not consider all exergy losses.

The Total Cumulative Exergy Loss (TCExL) indicator has been developed to take into account all exergy losses caused by a technological system during its life cycle [9,10], i.e. the internal exergy losses caused by the conversion of materials and energy, the treatment of emissions and the exergy loss related to land use. The TCExL method can be regarded as a combination of, or extension to, the exergy analysis methods known as Cumulative Exergy Consumption (CExC) [11], Cumulative Exergy Consumption and Abatement (CExCA) [12], Cumulative Exergy Extraction from the Natural Environment (CEENE) [13] and Exergetic Life Cycle Assessment (ELCA) [14]. It is said that the TCExL can be used as a fundamental indicator in the operationalization of the Brundtland definition of sustainability [15], as exergy is essential to meeting the needs of current and future generations [10].

Previously, e.g. Refs. [9,10,16], the TCExL method has been applied to assess and compare the following power generation systems: large-scale coal-fired power generation in combination with LNG evaporation, co-firing of coal and wood pellets, a wind farm and power generation by combustion of bioethanol originating from the fermentation of verge grass. Other examples of biomass types that could be used for power generation and/or the production of biogas are livestock manure and sewage sludge, e.g. Refs. [17–20]. As it would be interesting to assess and compare the environmental and exergetic sustainability of power generation from biomass, this research investigates the aforementioned verge grass system, the combustion of substitute natural gas obtained from anaerobic digestion of cow and pig manure and the combustion of substitute natural gas obtained from supercritical water gasification of cow and pig manure [21].

The applied assessment methods are the ReCiPe endpoint and TCExL methods. An important aspect when conducting a life cycle assessment is the comparability of the assessed systems, e.g. the way in which the production of by-products is taken into account. In scientific literature about life cycle assessment of biomass, several publications can be found that compare different ways of considering the by-products of processes, e.g. Refs. [22–25]. Allocation on an exergy basis is preferred to energetic and economic allocation because exergy is an absolute and thermodynamic indicator that does not vary with externalities [22]. On the other hand, allocation should be avoided according to the ISO standards for conducting an LCA and subdivision of multi-output processes or system enlargement should be applied instead [1,26]. The assessment of the three systems for power generation from biomass is also used to investigate to what extent the results of the environmental and exergetic sustainability assessment are influenced by the way of taking into account by-products, i.e. as avoided products (a variant of system enlargement) or via allocation on an exergy basis.

2. Sustainability assessment

As mentioned in the introduction, this research considers the environmental ‘pillar’ of sustainability and determines the exergetic sustainability of the technological systems as well. A difficulty with assessing the environmental sustainability is the need for models to convert aspects such as the use of feedstocks, process emissions, land use etc. into midpoint and endpoint indicators, while no consensus exists about all models that are used, e.g. regarding the environmental impact of emissions. Besides, environmental assessment methods make use of weighting factors, which makes environmental sustainability assessment methods less objective. The TCExL method has been developed to take into account as many components of sustainability as possible on the basis of fundamental scientific equations. By determining the total cumulative exergy loss caused by a technological system, the TCExL method indirectly considers the depletion and scarcity of resources as an increasing scarcity of a material implies a higher demand for energy carriers etc. to extract it, and thus a higher exergy loss is expected [16]. Although the economic and social pillars of sustainability are not taken into account in this research, they are considered indirectly via the amounts of feedstocks, products etc. which represent a certain amount of exergy. The methods used for assessing the environmental and exergetic sustainability are described in Sections 2.1 and 2.2, respectively. Section 2.3 discusses the comparability of the assessed systems.

2.1. *Environmental sustainability*

Regular environmental sustainability assessment methods consider the use of materials and energy by a technological system, its emissions to air, water and soil and the required transformation and occupation of land by this technological system. Several indicators have been developed, such as the CML 2002 indicators [3], the Eco-indicator 99 [4] and the ReCiPe midpoint and endpoint indicators [5], to indicate the environmental impact caused by technological systems. The CML 2002 method has been developed by the Institute of Environmental Sciences of the Leiden University (CML), Netherlands, as an operational guide to the 14040 series (Environmental management – Life Cycle Assessment) of the ISO standards. The CML 2002 method looks at the environmental impact along the cause-effect chain (e.g. of a toxic substance), hence it belongs to the midpoint methods. Examples of CML 2002 (midpoint) indicators are global warming potential (GWP), acidification potential and abiotic depletion potential. The Eco-indicator 99 method quantifies the environmental impact at the end of the cause-effect chain and therefore belongs to the endpoint methods. The Eco-indicator 99 method comprises the following three endpoint indicators: damage to human health, damage to

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ecosystem quality and damage to resources. The ReCiPe method is the result of harmonising the CML 2002 and Eco-indicator 99 methods with respect to modelling principles and choices into one method that offers the possibility of calculating midpoint as well as endpoint indicators. In this research, the environmental sustainability of the three systems is determined by calculating ReCiPe indicators, as this method is the result of a thorough cooperation between experts in the field of life cycle assessment and because it is a recent development in this field [10]. Examples of ReCiPe midpoint indicator categories are climate change, ozone depletion, freshwater eutrophication, human toxicity. The three ReCiPe endpoint indicators are named damage to human health, damage to ecosystem diversity and damage to resource availability. These three endpoint indicators are the result of conversion and aggregation of the relevant midpoint indicators as described in more detail by Goedkoop et al. [5]. For example, damage to human health is measured in disability-adjusted loss of life years, which is the sum of years of life lost and years of life disabled, and is influenced by ozone depletion etc. Climate change causes damage to human health as well as damage to ecosystem diversity. Consumption of fossil fuels damages resource availability and causes emissions which have an impact on human health and ecosystem diversity. The three endpoint indicators can be combined into one overall ReCiPe endpoint indicator via weighting. A disadvantage of the use of weighting factors is that these factors are disputable. However, the reason for calculating one overall ReCiPe endpoint indicator of each system is the need for one environmental sustainability indicator to compare the assessment results of the exergetic sustainability assessment with. The ReCiPe endpoint indicators have been calculated by using the life cycle assessment software tool named SimaPro (version 8.0) [27]. This software tool, developed by PRé consultants (Amersfoort, Netherlands), is used worldwide and facilitates the modelling of technological systems including their supply chains as it includes the ecoinvent database [28]. The ecoinvent database is maintained by the ecoinvent association (Zurich, Switzerland), previously known as the Swiss Centre for Life Cycle Inventories, and provides life cycle inventory data about the extraction, transport, processing and storage of energy carriers, chemicals, waste treatment etc. The SimaPro software includes several methods to calculate the environmental impact of technological systems as well, including the ReCiPe indicators. The uncertainties in these methods, e.g. with respect to environmental mechanisms and quantitative linkages between midpoint and endpoint categories, have been incorporated in ReCiPe in the form of the following three versions: the egalitarian (E), the hierarchist (H) and the individualist (I) perspectives. Of these perspectives, the egalitarian perspective is the most precautionary perspective, the individualist perspective is based on short-term interests and the hierarchist is a consensus model that is based on the most common policy principles [5]. The consensus model, more precise the ‘ReCiPe Endpoint (H) V1.11’ model, is used in this research because it is the default ReCiPe endpoint method and because no reason exists to deviate from the default settings. Besides these perspectives, the user can choose from several normalisation/weighting sets to calculate the overall endpoint indicator, i.e. the normalisation values of Europe or of the world, and the average weighting set or the weighting set belonging to the hierarchist perspective. Table 1 shows the weighting factors of the ReCiPe average and hierarchist weighting sets.

In this research, the normalisation/weighting set ‘Europe ReCiPe H/A’ is used, i.e. the normalisation values of Europe with the average weighting set, because the assessed systems are located in the Netherlands and because this is the recommended normalisation/weighting set. The ReCiPe scores are measured in (mega) points (MPt). The higher the ReCiPe endpoint indicator score, the lower the environmental sustainability is.

2.2. Exergetic sustainability

The TCExL (Total Cumulative Exergy Loss) method is applied to calculate the exergetic sustainability [10]. The TCExL indicator is the summation of the internal exergy loss caused by a technological system including its supply chains during the phases of construction, operation and decommissioning, the exergy loss caused by the abatement of its emissions and waste flows to an acceptable level, and the exergy loss related to land use by the system (1).

$$TCExL = Ex_{loss,internal} + Ex_{loss,abatement} + Ex_{loss,land\ use} \tag{1}$$

The higher the TCExL, the lower the exergetic sustainability of a system is. The data needed for calculating the TCExL originate from the SimaPro software as well as literature, as shown in Fig. 1 and explained below.

The internal exergy loss caused by the system is calculated from the Cumulative Exergy Demand (CExD, v1.04) reported by SimaPro [27,29], which is the exergy input, minus the amount of exergy represented by the products (electricity, by-products), emissions and waste flows of the system (2). The amounts of emissions and waste flows are also reported by SimaPro, while the exergy values of these emissions are calculated from the standard exergy values of components and other thermodynamic data, e.g. Ref. [30]. This is limited to the exergy values of the largest emissions, i.e. 99% by mass of all emissions, as it is undoable to calculate the exergy values of the more than 600 emissions reported by SimaPro.

$$Ex_{loss,internal} = CExD - Ex_{product(s)} - Ex_{emissions\ \&\ waste\ flows} \tag{2}$$

The amounts of emissions and waste flows reported by SimaPro are also used to calculate the exergy loss caused by abatement of carbon dioxide of fossil origin (5.9 MJ/kg [31,32]), sulphur dioxide (57 MJ/kg [14]), nitrogen oxides (16 MJ/kg [14]) and phosphate (18 MJ/kg [14]) emissions (3). The processes for the abatement of these emissions are explained in more detail in Refs. [10,14,16,31,32]. Data about the abatement exergy loss caused by other emissions have not yet been found in literature.

$$Ex_{loss,abatement} = \sum \left(emission_i \cdot ex_{loss,abatement,i}\right) \tag{3}$$

The exergy loss related to land use is determined from the types and amounts of land used by the system including its supply chains reported by SimaPro and a worldwide average exergy loss of 215 GJ per hectare per year (4). This number is calculated from the Net Primary Production (NPP) [33], which is the net amount of biomass produced when land is not occupied, and an average biomass

Table 1
Average and hierarchist weighting factors (%) available in SimaPro [5,27].

Impact category	Average weighting set	Hierarchist weighting set
Damage to human health	40	30
Damage to ecosystem diversity	40	40
Damage to resource availability	20	30

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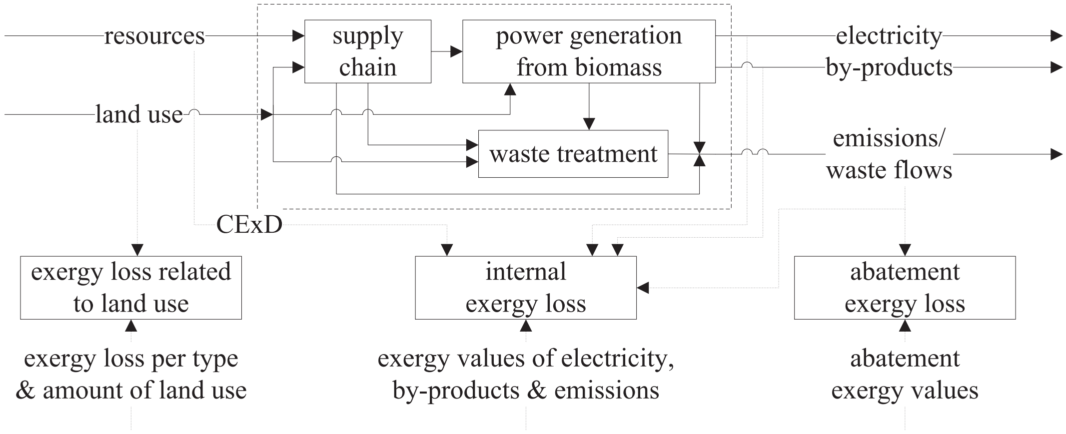

Fig. 1. Calculation of the components of the TCExL indicator.

exergy conversion factor of 42.9 MJ exergy per kg of carbon [34].

$$Ex_{loss,land\ use} = land\ use \cdot 215\ \mathrm{GJ/(ha \cdot yr)} \tag{4}$$

To prevent double-counting, the types of land use that are related to the growing of trees or another type of biomass are not taken into account when determining the exergy loss caused by land use. Neither are the types of land use related to marine ecosystems because of the negligible amount of solar energy that is captured [13]. This means that the land occupation types of which the name contains ‘benthos’, ‘fallow’, ‘forest’, ‘grassland’, ‘pasture and meadow’, ‘permanent crop’, ‘sclerophyllous’, ‘seabed’, ‘vegetation’, ‘water’ are not taken into account.

Equations (1) to (4) show that the TCExL increases when the internal exergy loss, the abatement exergy loss and/or the exergy loss related to land use increases. However, the internal exergy loss as well as the abatement exergy loss depend on the emissions of carbon dioxide of fossil origin, sulphur dioxide, nitrogen oxides and phosphate. An increase of these emissions causes a lower internal exergy loss and a higher abatement exergy loss. The TCExL method has been applied previously, e.g. Refs. [9,10,16], and the MS Excel spreadsheet used to calculate the TCExL scores from the amounts of inputs and outputs reported by SimaPro and the exergetic numbers mentioned before has been verified. The results of the TCExL calculations depend to a large extent on the CExD reported by SimaPro. The CExD indicators used by SimaPro originate from scientific research [29] and have been checked previously, e.g. Ref. [10]. The CExD reported by SimaPro also depends on the modelling of the systems in SimaPro. On the basis of the exergy input compared to the amount of exergy in the product of previously assessed energy systems, e.g. Refs. [9,10,16], the descriptions of the currently assessed systems and the assessment results, it is concluded that the results of this research are valid as well.

2.3. Comparability of the assessed systems

The three systems that are studied produce several by-products, such as proteins and grass fibres in the bioethanol system and several substitutes of mineral fertilizers in the anaerobic digestion (AD) and supercritical water gasification (SCWG) systems. When comparing systems, it is important that these systems produce the same product in the same amount (the functional unit) and that the production of by-products, the treatment of wastes and emissions and the use of materials, fuels, electricity and heat from the technosphere is accounted for. As the three systems are modelled in SimaPro, the use of materials, fuels etc. is taken into account via the aforementioned ecoinvent database that comes with SimaPro. The production of by-products can be solved in at least three ways. First, by enlarging the system so that all systems produce the same products and by-products in the same amounts. This method is known as ‘system enlargement’. Second, by regarding the by-products as avoided products and subtracting the (environmental impact of the) regular production processes for producing the same amount of these by-products as in the system under consideration. This method is a variant of the ‘system enlargement’ method and is called ‘avoided products’. The ‘avoided products’ method leads to a negative score of the environmental impact indicator in case the calculated environmental impact of the avoided products is larger than the calculated environmental impact of the product itself. Or, third, by allocating the impact of the process that produces several products between the product and by-product or by-products, which is named ‘allocation’. In this research, the allocation is based on the amount of exergy represented by the product and by-product flows of each multi-output process. This research also investigates the effect of applying the ‘avoided products’ and ‘allocation’ methods on the sustainability assessment results.

3. Description of the power generation systems

The assessed power generation systems are briefly described in the next three sections. The functional unit used in the comparison of the systems is the production of 1 PJ (Peta Joule, 10^{15} J) of electricity.

3.1. Combustion of bioethanol from verge grass via fermentation

The bioethanol system consists of the growing, mowing and transport of verge grass, followed by its fermentation into bioethanol and subsequently combusting the bioethanol in a combined-cycle power plant, as depicted in Fig. 2. The system is based on research by De Vries [35] and has a capacity of about 30 MW of electricity. Table 2 presents the main inputs and outputs of the system.

If the production of the grass fibres and protein by-products is taken into account via allocation, which is done on an exergy basis, 28, 31 and 41% of the impact of the fermentation process (including its supply chains) is allocated to the bioethanol product, grass fibres and protein by-products, respectively. The possibility of the existence of heavy metals etc. in the verge grass, originating from road traffic, has not been taken into account as it was not meant to conduct detailed environmental assessments of the systems.

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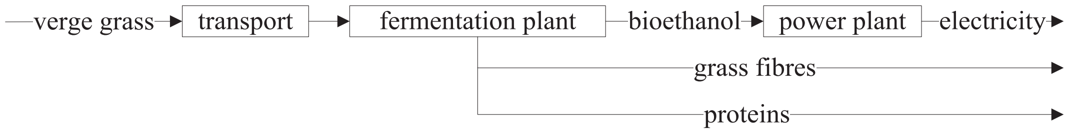

Fig. 2. Combustion of bioethanol from verge grass.

Table 2
Main inputs and outputs of the bioethanol system related to the production of 1 PJ of electricity.

Inputs	(kton)	Outputs	(kton)
Verge grass (40% dry matter)	490	Grass fibres	140
		Proteins	174

Table 3
Main inputs and outputs of the AD system related to the production of 1 PJ of electricity.

Inputs	(Mton)	Outputs	(kton)
Raw manure	3.3	Nitrogen (as N)	9.2
Water	3.3	Phosphate (as P_2O_5)	12
		Potassium (as K_2O)	23
		Sulphur (as S)	0.46

3.2. Combustion of biogas from raw manure via anaerobic digestion

The system that comprises the anaerobic digestion (AD) of raw manure and the subsequent production of biogas and electricity is based on the research by Gkranas [21]. Gkranas has conducted a thorough investigation of 12 different systems of anaerobic digestion and biogas production of which the system presented in this research, i.e. the system with digestate storage in a closed tank and upgrading the biogas by chemical absorption, resulted in the lowest carbon dioxide emissions. Anaerobic digestion is a well-established technology, but the decomposition efficiency is relatively low as approximately 50% of the organic matter is decomposed [21]. During anaerobic digestion, the raw manure is converted into biogas and digestate by microorganisms like acidogenic and acetogenic bacteria. The digestate contains nitrogen, potassium and phosphate components, which can be used as substitutes of mineral fertilizers in the agricultural sector. The biogas mainly consists of methane (approx. 60 vol%), carbon dioxide (approx. 35 vol%) and impurities such as hydrogen sulphide, nitrogen and ammonia. The system includes upgrading of the biogas to the substitute natural gas (SNG) conditions of the Dutch natural gas network. For reasons of comparability of the three systems of this research, the system investigated by Gkranas is adapted by omitting the injection of the produced SNG into the Dutch distribution gas grid and by adding the combustion of the produced SNG in a gas power plant. The resulting system is presented in Fig. 3. The main inputs and outputs of the system are presented in Table 3.

3.3. Combustion of biogas from raw manure via supercritical water gasification

The application of supercritical water gasification (SCWG) to produce biogas from raw manure and its subsequent upgrading and combustion has also been thoroughly investigated by Gkranas [21]. A major advantage of the SCWG system compared to the AD system is that most of the organic content of the raw manure decomposes, instead of the approximately 50% in the AD system. The SCWG system presented in this research is the system, of the four systems studied by Gkranas, that leads to the lowest carbon dioxide emission. I.e. the system in which the low pressure combustible gases from the SCWG and a part of the non-purified biogas are combusted in the furnace to produce the required heat and the resulting hydrogen is combusted in a fuel cell of the Proton Exchange Membrane type (PEM fuel cell) to produce the electricity needed for the furnace. In the SCWG system, the raw manure is compressed and heated to a pressure and temperature higher than the critical pressure and temperature of water (22.1 MPa and 647 K). The raw manure is converted into methane, carbon dioxide and hydrogen, which is followed by high pressure separation to separate the methane and hydrogen from the supercritical water containing dissolved carbon dioxide. Carbon dioxide and water are separated in a low pressure separator. The hydrogen is separated from the raw biogas by a membrane and is used as a feedstock in the PEM fuel cell. The raw biogas is purified to meet the requirements of substitute natural gas. For reasons of comparability of the three systems of this research, the system investigated by Gkranas is adapted, like the AD system, by omitting the injection of the produced SNG into the Dutch distribution gas grid and combusting the SNG in a gas power plant for power generation. The assessed SCWG system is depicted in Fig. 4 and Table 4 presents the main inputs and outputs of this system.

SCWG of raw manure is still under development. Besides the aforementioned high, ideally full, conversion of raw manure, the SCWG system has the advantage of a significantly shorter residence time than the AD system [21].

4. Results of the assessments

The bioethanol system and both raw manure systems have been assessed by calculating the environmental sustainability (ReCiPe

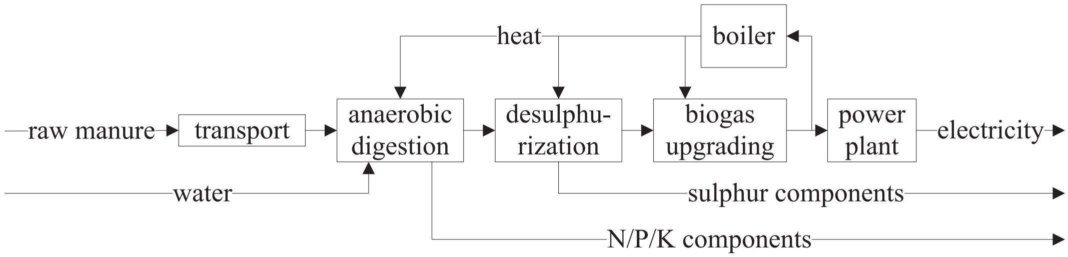

Fig. 3. Combustion of SNG from raw manure via anaerobic digestion.

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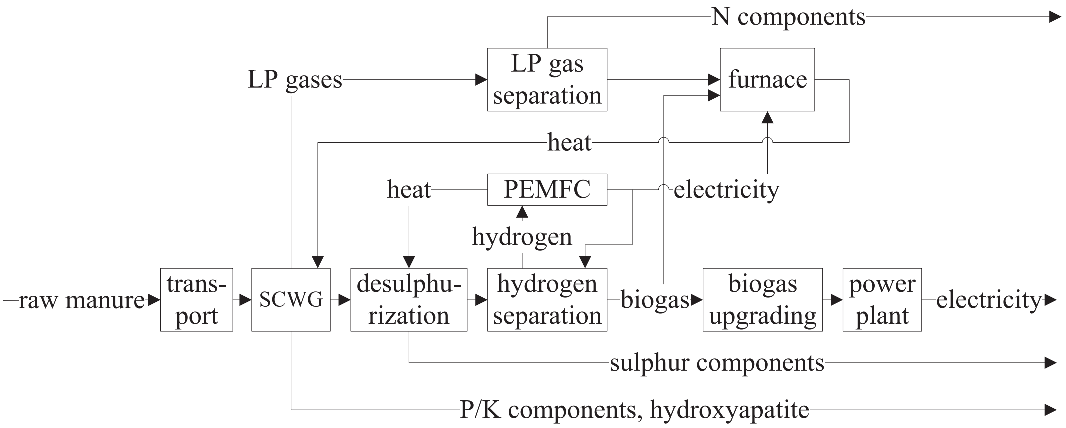

Fig. 4. Combustion of SNG from raw manure via supercritical water gasification.

Table 4
Main inputs and outputs of the SCWG system related to the production of 1 PJ of electricity.

Inputs	(Mton)	Outputs	(kton)
Raw manure	1.2	Nitrogen (as N)	8.0
		Phosphate (as P_2O_5)	1.3
		Potassium (as K_2O)	8.6
		Hydroxyapatite	7.6
		Sulphur (as S)	1.3

endpoint method) and the exergetic sustainability (TCExL, Total Cumulative Exergy Loss method) scores of these systems. On the basis of the results not only the systems can be compared but also the assessment methods themselves. Furthermore, it has been investigated what the influence on the results is of applying two different ways of making the three systems comparable, i.e. the 'avoided products' and 'allocation' methods.

The results of the assessment of the environmental sustainability of the three systems are presented in Tables 5 and 6 for the 'avoided products' and 'allocation' versions, respectively. The negative numbers in Table 5 are the result of subtracting the environmental impact of regular production processes for the production of the by-products (in the same amounts as produced by the system under consideration) from the environmental impact of this system.

Tables 5 and 6 show that the bioethanol system is preferred from an environmental sustainability point of view, i.e. −14 and 5.4 MPt, respectively. It is not clear which system performs second-best, as the AD system appears to perform only slightly better than the SCWG system according to the 'avoided products' way of making the systems comparable, but it is the opposite when applying the 'allocation' way as the ReCiPe score of the SCWG system is a little lower than the ReCiPe score of the AD system. Tables 5 and 6 also show that the total ReCiPe score resulting from applying 'avoided products' is very different from the 'allocation' version.

Tables 7 and 8 present the results of the exergetic sustainability assessment of the three systems for the 'avoided products' and 'allocation' versions, respectively. According to the 'avoided products' version of the results of the exergetic sustainability assessment (Table 7), the SCWG system causes the lowest TCExL (2.0 PJ), but the exergy loss caused by the bioethanol system is not much higher (3.6 PJ). On the other hand, the difference with the AD system is significant as the AD system causes 12 PJ of exergy loss, i.e. it is the system with the lowest exergetic sustainability. When applying 'allocation', the difference between the TCExL of the bioethanol (3.7 PJ) and SCWG (3.9 PJ) systems is small, with a slightly better performance of the bioethanol system. Again, the AD system is the system with the lowest exergetic sustainability. Thus, according to the results of the exergetic sustainability assessment, the AD system is the least-preferred system and it is not clear whether the bioethanol or the SCWG system is preferred. In addition, Tables 7 and 8 show that the TCExL scores are not much influenced by the way the production of by-products is taken into account.

The TCExL score of the AD and SCWG systems is to a large extent determined by the exergy value of the raw manure. This exergy value is calculated at 4.0 MJ per kg of raw manure as received and leads to an exergy input of 13 and 4.8 PJ for the AD and SCWG systems, respectively. Fig. 5 shows the influence of increasing and decreasing the exergy value of raw manure by 10% on the results. It is learnt from Tables 7 and 8 and Fig. 5 that the exergy value of the raw manure does not change the order of preference of the three systems as the SCWG remains the preferred system in the case of 'avoided products' and the SCWG and bioethanol scores remain comparable in the case of 'allocation'.

The results of the assessments can also be used to compare the environmental and exergetic sustainability assessment methods in another way. That is, when looking at the environmental and exergetic sustainability scores of each of the three assessed systems

Table 5
Results of the environmental sustainability assessment — avoided products.

Damage category[a] [MPt]	Bioethanol	Anaerobic digestion	Supercritical water gasification
Human Health	−1.5	0.26	0.62
Ecosystems	−17	−0.69	−0.18
Resources	4.1	−0.59	−0.59
Total ReCiPe score	−14	−1.0	−0.14

[a] The damage category numbers have already been weighted in accordance with the selected ReCiPe average weighting set, i.e. 40, 40 and 20%, respectively, and are measured in mega points (MPt).

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Table 6
Results of the environmental sustainability assessment – allocation.

Damage category[a] [MPt]	Bioethanol	Anaerobic digestion	Supercritical water gasification
Human Health	2.4	6.5	5.9
Ecosystems	1.1	2.2	2.5
Resources	1.9	3.0	2.6
Total ReCiPe score	5.4	12	11

[a] The damage category numbers have already been weighted in accordance with the selected ReCiPe average weighting set, i.e. 40, 40 and 20%, respectively, and are measured in mega points (MPt).

Table 7
Results of the exergetic sustainability assessment – avoided products.

[PJ]	Bioethanol	Anaerobic digestion	Supercritical water gasification
Exergy input	4.9	13	4.1
Exergy of the product	1.0	1.0	1.0
Exergy of emissions	1.0	0.60	0.91
Internal exergy loss[a]	2.9	12	2.2
Abatement exergy loss	0.61	−0.090	−0.27
Exergy loss land use	0.072	−0.062	0.0029
TCExL[b]	3.6	12	2.0

[a] The internal exergy loss is equal to the exergy input minus the exergy of the products and emissions/waste flows.
[b] The TCExL is the summation of the internal exergy loss, the abatement exergy loss and the exergy loss caused by land use.

Table 8
Results of the exergetic sustainability assessment – allocation.

[PJ]	Bioethanol	Anaerobic digestion	Supercritical water gasification
Exergy input	5.1	15	5.6
Exergy of the product	1.0	1.0	1.0
Exergy of emissions	0.67	0.73	1.0
Internal exergy loss[a]	3.4	13	3.6
Abatement exergy loss	0.28	0.42	0.21
Exergy loss land use	0.055	0.050	0.0069
TCExL[b]	3.7	14	3.9

[a] The internal exergy loss is equal to the exergy input minus the exergy of the products and emissions/waste flows.
[b] The TCExL is the summation of the internal exergy loss, the abatement exergy loss and the exergy loss caused by land use.

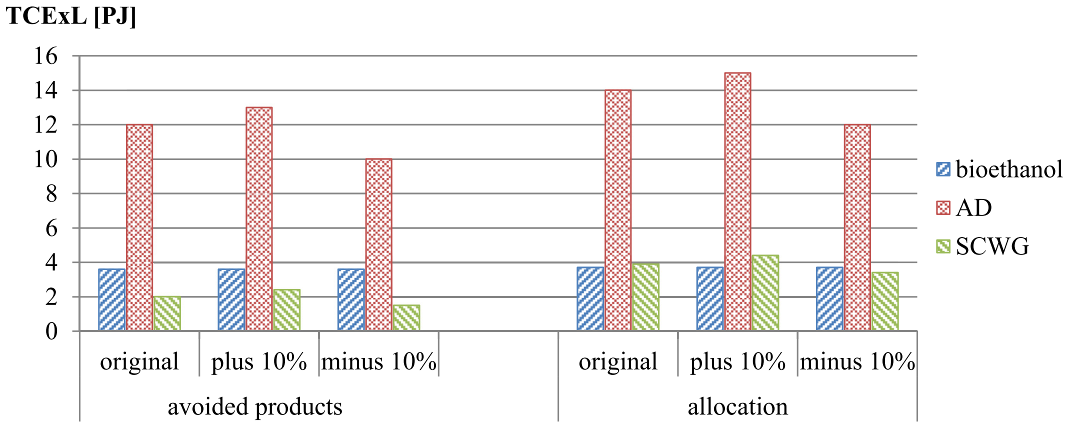

Fig. 5. The influence of increasing and decreasing the exergy value of raw manure by 10% on the TCExL scores of both raw manure systems.

(Tables 5–8), it is learnt that the scores of the environmental sustainability assessment are highly influenced by the way of making the systems comparable. E.g., the ReCiPe score of the bioethanol system equals −14 MPt in case of ‘avoided products’ and 5.4 MPt when applying ‘allocation’. On the other hand, the TCExL scores of the three systems remain mostly the same. Apparently, the results of the exergetic sustainability assessment are hardly influenced by the way of making the systems comparable.

In addition, the influence on the results of applying the ‘avoided products’ and ‘allocation’ methods can be investigated by comparing the environmental and exergetic sustainability assessment results of each of both ways of making the systems comparable, i.e. by comparing the results presented in Tables 5 and 7 and by doing the same with the results presented in Tables 6 and 8. When applying 'avoided products', the bioethanol system is clearly the system with the highest environmental sustainability, but the SCWG system shows the highest exergetic sustainability, although it performs only a little better than the bioethanol system. When applying 'allocation', the bioethanol system is the preferred system according to the environmental as well as the exergetic sustainability assessment results, although the difference between the exergetic sustainability of the bioethanol and SCWG systems is small. Thus, the 'avoided products' version leads to a larger difference between the environmental and exergetic sustainability assessment results than the 'allocation' version does.

5. Discussion and conclusions

On the basis of the results of the environmental sustainability assessment, it is concluded that the bioethanol system, which uses verge grass, performs better than both raw manure systems. Which system is second-best depends on the method used for making the systems comparable, as the 'avoided products' method indicates that the AD system performs a little better than the SCWG system and the 'allocation' method indicates the opposite. The SCWG system is still under development. Possibly, a more detailed assessment of both systems in the future will lead to a larger difference in the environmental sustainability of the systems. With regard to the bioethanol system, the large difference between the 'avoided products' and 'allocation' versions of the environmental sustainability assessment results is mainly caused by the scores in the impact category 'agricultural land occupation', which is understandable because of the origin of its grass fibres and proteins by-products. The large difference between the results of the 'avoided products' and 'allocation' versions of the AD and SCWG systems is caused by the scores in the impact categories 'fossil depletion', 'climate change human health' and 'climate change ecosystems'. Apparently, the scores in these impact categories are the most influenced by the production of the fertilizer by-products.

According to the results of the exergetic sustainability assessment, the AD system has the lowest sustainability. The SCWG system performs a little better than the bioethanol system when choosing 'avoided products', but results in almost the same TCExL scores when applying the 'allocation' method. The higher TCExL of the AD system is caused by the high exergy input from raw manure, which is considerably higher than in the SCWG system. Noticeable as well, is the influence of the abatement exergy loss on the TCExL scores of the bioethanol and SCWG systems. It would be interesting to assess the systems again when the abatement exergy loss of more emissions is available.

Looking at the results of the environmental as well as the exergetic sustainability assessment methods, the bioethanol system could be considered as the preferred system as it has the lowest score in three of the four cases, but the difference with the scores of the other systems is not always large.

When looking at the bioethanol and AD systems only, it is clear that the bioethanol system is the preferred system according to the environmental as well as the exergetic sustainability assessment results of this research. The development of the SCWG system will possibly lead to a system that performs clearly better than the AD system from an exergetic as well as an environmental sustainability point of view. Furthermore, aspects like the shorter residence time of the SCWG system compared to the AD system and the fact that raw manure is a more problematic waste stream than verge grass, because of the large amount and origin of raw manure, is not taken into account here.

When comparing the environmental and exergetic sustainability assessment results of each of the three systems, it is clear that the scores of the environmental sustainability assessment are highly influenced by the way of making the systems comparable, while the scores of the exergetic sustainability assessment are not. An advantage of the exergetic TCExL indicator over the environmental ReCiPe indicator is that the TCExL indicator is based on thermodynamic equations and does not need models for estimating the (environmental) impact. E.g., instead of using models for estimating the impact of emissions on the environment, it applies the abatement exergy loss caused by these emissions. This possibly explains the lower sensitivity of the exergetic sustainability assessment results to the way of making the systems comparable.

From the comparison of the environmental and exergetic sustainability assessment results in case of 'allocation', it is learnt that the results are a little more consistent than in the case of 'avoided products'. E.g., the order of preference remains the same with 'allocation' and differs with 'avoided products'. This is not in line with the preference for system enlargement, of which 'avoided products' is a variant, mentioned in the ISO standards for conducting an LCA, but it should also be noted that the differences between the environmental sustainability assessment scores of the three systems and between the exergetic sustainability assessment scores of the systems are not always large. And again, the ReCiPe scores are highly influenced by the way of making the systems comparable, while the TCExL scores are not.

6. Recommendations

It is recommended that researchers in the field of environmental sustainability pay close attention to the method they choose for making technological systems comparable as this research shows that the results of the environmental sustainability assessment are highly influenced by the method that is used, i.e. the 'allocation' or 'avoided products' way of making systems comparable. Furthermore, it is recommended that the TCExL method be implemented in life cycle assessment software tools to facilitate the calculation of TCExL indicators of technological systems, as it is important to pay attention to exergy losses. In this way, the calculation of the exergy loss caused by abatement of emissions of which not yet an abatement value is known is facilitated as well.

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Abbreviations

AD	Anaerobic Digestion
CEENE	Cumulative Exergy Extraction from the Natural Environment
CExC	Cumulative Exergy Consumption
CExCA	Cumulative Exergy Consumption and Abatement
CML	Institute of Environmental Sciences of the Leiden University, Netherlands
CExD	Cumulative Exergy Demand
E	Egalitarian (perspective)
ELCA	Exergetic Life Cycle Assessment
GWP	Global Warming Potential
H	Hierarchist (perspective)
I	Individualist (perspective)

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ISO	International Organization for Standardization
LCA	Life Cycle Assessment
NPP	Net Primary Production
PEM	Proton Exchange Membrane (fuel cell)
SCWG	Supercritical Water Gasification
SNG	Substitute Natural Gas
TCExL	Total Cumulative Exergy Loss

References

[1] G. Finnveden, M.Z. Hauschild, T. Ekvall, J. Guinée, R. Heijungs, S. Hellweg, A. Koehler, D. Pennington, S. Suh, Recent developments in life cycle assessment, J. Environ. Manag. 91 (2009) 1–21, http://dx.doi.org/10.1016/j.jenvman.2009.06.018.

[2] M. Teles dos Santos, S. Park, Exergy and sustainable development for chemical industry revisited, Comput. Aided Chem. Eng. 27 (C) (2009) 1923–1928, http://dx.doi.org/10.1016/S1570-7946(09)70711-4.

[3] J.B. Guinée, M. Gorrée, R. Heijungs, G. Huppes, R. Kleijn, A. De Koning, L. Van Oers, A. Wegener Sleeswijk, S. Suh, H.A. Udo de Haes, H. De Bruijn, R. Van Duin, M.A.J. Huijbregts, Handbook on Life Cycle Assessment. Operational Guide to the ISO Standards. I: LCA in Perspective. IIa: Guide. IIb: Operational Annex. III: Scientific Background, Kluwer Academic Publishers, Dordrecht, Netherlands, 2002.

[4] M. Goedkoop, R. Spriensma, The Eco-indicator 99. A Damage Oriented Method for Life Cycle Impact Assessment. Methodology Report and Annex, Pré Consultants, Amersfoort, Netherlands, 1999.

[5] M. Goedkoop, R. Heijungs, M. Huijbregts, A. De Schryver, J. Struijs, R. Van Zelm, ReCiPe 2008, A Life Cycle Impact Assessment Method which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level, Report I: Characterisation, Ministry of Housing, Spatial Planning and Environment, The Hague, Netherlands, 2009.

[6] I. Dincer, M.A. Rosen, Exergy: Energy, Environment and Sustainable Development, second ed., Elsevier Ltd., Amsterdam, Netherlands, 2013.

[7] D. Iribarren, A. Susmozas, F. Petrakopoulou, J. Dufour, Environmental and exergetic evaluation of hydrogen production via lignocellulosic biomass gasification, J. Clean. Prod. 69 (2014) 165–175, http://dx.doi.org/10.1016/j.jclepro.2014.01.068.

[8] T. Vandermeersch, R.A.F. Alvarenga, P. Ragaert, J. Dewulf, Environmental sustainability assessment of food waste valorization options, Resour. Conservation Recycl. 87 (2014) 57–64, http://dx.doi.org/10.1016/j.resconrec.2014.03.008.

[9] L. Stougie, H.J. Van der Kooi, Possibilities and consequences of the Total Cumulative Exergy Loss method in improving the sustainability of power generation, Energy Convers. Manag. 107 (1) (2016) 60–66, http://dx.doi.org/10.1016/j.enconman.2015.09.039.

[10] L. Stougie, Exergy and Sustainability – Insights into the Value of Exergy Analysis in Sustainability Assessment of Technological Systems [dissertation], Delft University of Technology, Delft, Netherlands, 2014.

[11] J. Szargut, D. Morris, F. Steward, Exergy Analysis of Thermal, Chemical, and Metallurgical Processes, Hemisphere Publ. Corp, New York, 1988.

[12] J. Dewulf, H. Van Langenhove, J. Dirckx, Exergy analysis in the assessment of the sustainability of waste gas treatment systems, Sci. Total Environ. 273 (1–3) (2001) 41–52, http://dx.doi.org/10.1016/S0048-9697(00)00841-X.

[13] J. Dewulf, M. Bösch, B. De Meester, G. Van der Vorst, H. Van Langenhove, S. Hellweg, M. Huijbregts, Cumulative exergy extraction from the natural environment (CEENE): a comprehensive life cycle impact assessment method for resource accounting, Environ. Sci. Technol. 41 (24) (2007) 8477–8483, http://dx.doi.org/10.1021/es0711415.

[14] R.L. Cornelissen, Thermodynamics and Sustainable Development; the Use of Exergy Analysis and the Reduction of Irreversibility [dissertation], Twente University, Enschede, Netherlands, 1997.

[15] WCED, Our Common Future, Report of the World Commission on Environment and Development, Oxford University Press, New York, 1987.

[16] Stougie L., Valero Delgado A., Van der Kooi H.J., Sustainability assessment of power generation systems by applying exergy analysis and LCA methods. In: ECOS 2015: Proceedings of the 28th International Conference on Efficiency, Cost, Optimization, Simulation, and Environmental Impact of Energy Systems; 2015 Jun 29-Jul 3; Pau, France. ISBN: 978-2-9555539-0-9, paper No. 51121.

[17] E. Ghafoori, P.C. Flynn, M.D. Checkel, Global warming impact of electricity generation from beef cattle manure: a life cycle assessment study, Int. J. Green Energy 3 (3) (2006) 257–270, http://dx.doi.org/10.1080/01971520600704423.

[18] R. Tachibana, Y. Ozaki, K. Fujie, Material and energy flow analysis in sewage sludge incineration and composting treatment processes, J. Chem. Eng. Jpn. 44 (10) (2011) 798–802.

[19] F. Cansu Ertem, J. Martínez-Blanco, M. Finkbeiner, P. Neubauer, S. Junne, Life cycle assessment of flexibly fed biogas processes for an improved demand-oriented biogas supply, Bioresour. Technol. 219 (2016) 536–544, http://dx.doi.org/10.1016/j.biortech.2016.07.123.

[20] D. Tonini, L. Hamelin, T.F. Astrup, Environmental implications of the use of agro-industrial residues for biorefineries: application of a deterministic model for indirect land-use changes, GCB Bioenergy 8 (4) (2016) 690–706, http://dx.doi.org/10.1111/gcbb.12290.

[21] G. Gkranas, Sustainability Analysis of a New Biomass Gasification System to Produce Substitute Natural Gas Based on Manure [MSc thesis], Delft University of Technology, Delft, Netherlands, 2015.

[22] K. Jana, S. De, Environmental impact of an agro-waste based polygeneration without and with CO2 storage: life cycle assessment approach, Bioresour. Technol. 216 (2016) 931–940, http://dx.doi.org/10.1016/j.biortech.2016.06.039.

[23] S. González-García, C. Lacoste, T. Aicher, G. Feijoo, L. Lijó, M.T. Moreira, Environmental sustainability of bark valorisation into biofoam and syngas, J. Clean. Prod. 125 (2016) 33–43, http://dx.doi.org/10.1016/j.jclepro.2016.03.024.

[24] C. Hennig, M. Gawor, Bioenergy production and use: comparative analysis of the economic and environmental effects, Energy Convers. Manag. 63 (2012) 130–137, http://dx.doi.org/10.1016/j.enconman.2012.03.031.

[25] F. Cherubini, A.H. Strømman, S. Ulgiati, Influence of allocation methods on the environmental performance of biorefinery products—a case study, Resour. Conservation Recycl. 55 (2011) 1070–1077, http://dx.doi.org/10.1016/j.resconrec.2011.06.001.

[26] S.E. Taelman, S. De Meester, W. Van Dijk, V. Da Silva, J. Dewulf, Environmental sustainability analysis of a protein-rich livestock feed ingredient in The Netherlands: microalgae production versus soybean import, Resour. Conservation Recycl. 101 (2015) 61–72, http://dx.doi.org/10.1016/j.resconrec.2015.05.013.

[27] Pré Consultants, Amersfoort, Netherlands. SimaPro LCA software – Available at: https://www.pre-sustainability.com/simapro (Accessed 11 February 2016).

[28] Ecoinvent Centre (Swiss Centre for Life-Cycle Inventories) St-Gallen, Switzerland. Ecoinvent database – Available at: http://www.ecoinvent.org (Accessed 11 February 2016).

[29] M.E. Bösch, S. Hellweg, M.A.J. Huijbregts, R. Frischknecht, Applying cumulative exergy demand (CExD) indicators to the ecoinvent database, Int. J. Life Cycle Assess. 12 (3) (2007) 181–190, http://dx.doi.org/10.1065/lca2006.11.282.

[30] J. Szargut, Appendix 1. Standard Chemical Exergy, Egzergia. Poradnik Obliczania I Stosowania, Gliwice: Widawnictwo Politechniki Shlaskej, 2007.

[31] J. Dewulf, H. Van Langenhove, J. Mulder, M.M.D. Van den Berg, H.J. Van der Kooi, J. De Swaan Arons, Illustrations towards quantifying the sustainability of technology, Green Chem. 2 (2000) 108–114, http://dx.doi.org/10.1039/B000015I.

[32] G. Van der Vorst, J. Dewulf, H. Van Langenhove, Developing sustainable technology: metrics from thermodynamics, in: B.R. Bakshi, T. Gutowski, D. Sekulic (Eds.), Thermodynamics and the Destruction of Resources, Cambridge University Press, Cambridge, 2011, pp. 249–264.

[33] H. Haberl, K.H. Erb, F. Krausmann, V. Gaube, A. Bondeau, C. Plutzar, S. Gingrich, W. Lucht, M. Fischer-Kowalski, Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems, Proc. Natl. Acad. Sci. 104 (31) (2007) 12942–12947.

[34] R.A. Alvarenga, J. Dewulf, H. Van Langenhove, M.A. Huijbregts, Exergy-based accounting for land as a natural resource in life cycle assessment, Int. J. Life Cycle Assess. 18 (5) (2013) 939–947, http://dx.doi.org/10.1007/s11367-013-0555-7.

[35] S.S. De Vries, Thermodynamic and Economic Principles and the Assessment of Bioenergy [dissertation], Delft University of Technology, Delft, Netherlands, 1999.

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