Sustainability Assessment of Power Generation Systems by Applying Exergy Analysis and LCA Methods

Stougie, Lydia; van der Kooi, Hedzer; Valero Delgado, A.

Publication date
2015

Document Version
Accepted author manuscript

Published in
Proceedings of ECOS 2015

Citation (APA)
Stougie, L., van der Kooi, H., & Valero Delgado, A. (2015). Sustainability Assessment of Power Generation Systems by Applying Exergy Analysis and LCA Methods. In *Proceedings of ECOS 2015: 28th International Conference on Efficiency, Cost, Optimization, Simulation, and Environmental Impact of Energy Systems* Article 51121

SUSTAINABILITY ASSESSMENT OF POWER GENERATION SYSTEMS BY APPLYING EXERGY ANALYSIS AND LCA METHODS

***Lydia Stougie*[a], *Alicia Valero Delgado*[b], *Hedzer van der Kooi*[c]**

[a] *Delft University of Technology, Delft, Netherlands, l.stougie@tudelft.nl (CA),*
[b] *Research Centre for Energy Resources and Consumption, Zaragoza, Spain, aliciavd@unizar.es,*
[c] *Delft University of Technology, Delft, Netherlands, jvdkooi@casema.nl*

Abstract:

The selection of power generation systems is important when striving for a more sustainable society. However, the results of environmental, economic and social sustainability assessments are subject to new insights into the calculation methods and to changing needs, economic conditions and societal preferences. Researchers active in the field of exergy and sustainability claim that exergy losses and sustainability are related. The Total Cumulative Exergy Loss method and the exergy replacement costs of minerals are used to assess and compare power generation systems that make use of fossil and renewable energy carriers. These power generation systems are the following: an ultra-supercritical coal power plant, a power plant that co-fires coal and biomass, a wind farm, and a combined cycle power plant that uses bioethanol originating from the fermentation of verge grass. Furthermore, environmental, economic and social sustainability assessment methods are applied to assess the four power generation systems as well. On the basis of the results of the assessments, it is concluded that the wind farm system is preferred from the environmental, social and exergetic sustainability points of view, but not from the economic sustainability viewpoint. The advantage of the exergetic sustainability assessment method is that its results are not influenced by choices like whether verge grass should be considered a waste product or not. The influence of the exergy replacement costs on the results of the exergetic assessment is small, because less than 5 per cent of the exergy input of the systems during construction, operation and commission is of mineral origin. When looking at the infrastructural part of the systems only, the influence of the exergy replacement costs is larger because about 25 to 40 per cent of the exergy input is of mineral origin.

Keywords:

Sustainability, Power Generation, Total Cumulative Exergy Loss, Exergy Replacement Costs, Environmental, Economic and Social Sustainability.

1. Introduction

In general, sustainability is assessed from a life cycle point of view and subdivided into an environmental, an economic and a social sustainability component. The problem with these regular sustainability assessment methods is that the results of the assessments change over time because of e.g. new insights into the models that are used for calculating the environmental impact, indirect costs and market influences in the case of economic assessments and the availability and non-quantitative nature of social data. Another shortcoming of regular sustainability assessment methods is that exergy losses are not taken into account, while researchers in the field of exergy and sustainability claim that exergy losses and sustainability are related, e.g. [1]. This research describes the assessment of the sustainability of four power generation systems by applying regular non-exergetic sustainability assessment methods as well as an exergy analysis method that combines the recently developed Total Cumulative Exergy Loss method [2,3] and the exergy replacement costs of minerals [4,5]. The reason for including exergy replacement costs is that these costs not only take into account the chemical exergy value of minerals but also value the ore grade of the mines as a measure of their overall quality. Domínguez et al. [6] already demonstrated that 'the chemical exergy component is not always a good accounting tool and should not be used in isolation'. The power generation systems that are assessed are the following: an ultra-supercritical coal power plant, a power plant that co-fires coal and biomass, a wind farm, and a combined cycle power plant

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. Paper No. 51121.

that uses bioethanol originating from the fermentation of verge grass. On the basis of the results of the assessments, conclusions are drawn about the sustainability of the four power generation systems and the value of exergy analysis in sustainability assessment of power generation systems.

2. Sustainability assessment

The environmental, economic and social components of sustainability are combined in the Life Cycle Sustainability Assessment (LCSA) method, e.g. [7], but this method is still under development and faces some difficulties, e.g. the qualitative nature of many social indicators and the weighting of the three components of sustainability. Furthermore, combining the three components into one number leads to the possibility that one component compensates for another component, which is known as ‘weak sustainability’. Therefore, it was decided to take into account the three components of sustainability separately. Also, a method is known that combines life cycle assessment and exergy analysis, i.e. the exergoenvironmental analysis [8], but this method allocates the results of an environmental life cycle assessment to the individual components of a process or system by applying exergy analysis, which is different from the goal of this research.

In this research, the sustainability of the four power generation systems is assessed by applying the non-exergetic environmental, economic and social sustainability assessment methods and the exergy analysis method described in sections 2.1 to 2.4, respectively. From comparing the results of applying the assessment methods to the four systems and ranking of the systems per assessment method, conclusions can be drawn with regard to the value of exergy analysis in sustainability assessment. For example, what it means for the environmental sustainability if a system is chosen that is preferred from an exergetic point of view. The non-exergetic sustainability assessment methods have been introduced before, e.g. [2], and have been selected on the basis of a thorough literature research into sustainability assessment of technological systems because of their common use and/or usability in this research. The exergy analysis method is a combination of the recently developed Total Cumulative Exergy Loss method [2,3] and the exergy replacement costs of minerals [4,5].

2.1. Environmental sustainability

An environmental Life Cycle Assessment (LCA) method that results in ReCiPe endpoint indicators is used to assess the environmental sustainability of the four systems. This ReCiPe method is a combination of the CML 2002 and Eco-indicator 99 methods and was presented in 2008 as the result of a thorough cooperation between experts in the field of LCA [9]. The ReCiPe method facilitates the calculation of midpoint indicators as well as endpoint indicators. These endpoint indicators are calculated from the midpoint indicators by applying models, which introduces uncertainty (e.g. [10]), but because of the need for a single environmental sustainability indicator per assessed system it has been decided to use endpoint indicators. In this research, the SimaPro Software tool version 8.0.4.26 [11] in combination with the ecoinvent database version 2.2 [12] is used to calculate these endpoint indicators. The default normalisation/weighting set, i.e. ‘ReCiPe Endpoint (H) V1.04’ and ‘Europe ReCiPe H/A’ of SimaPro is used to calculate the ReCiPe endpoint indicators. The higher the ReCiPe endpoint indicator score, the lower the environmental sustainability is.

2.2. Economic sustainability

The economic sustainability of the systems is assessed by calculating their Present Worth Ratio (PWR). This PWR not only takes into account the Net Present Value (NPV) but also the investment costs of the installations, and is defined as the NPV of the revenues and costs during the lifetime of the installation over the NPV of these investment costs. A higher PWR score indicates a more likely investment. The costs and revenues associated with fuels, raw materials, products, utilities, maintenance etc. have been included in the NPV. The following economic data have been used in this research. The lifetime of the installations after construction is assumed to be 20 years and the applied discount rate equals 8 per cent. The price used for coal is €2.65 per GJ and the price of electricity is €60 per MWh. The brief descriptions of the systems include the yearly revenues used for calculating the PWR, thus without taking into account the capital costs.

2.3. Social sustainability

The social sustainability assessment method applied in this research was introduced in 2011 [13] as an alternative to the standard method for determining the social sustainability that is under development [14,15], and because it would be too time-consuming and costly to gather site-specific social data. The method makes use of the Inequality-adjusted Human Development Index (IHDI) of countries reported by the UNDP [16], the number of man-hours spent in the different stages of the production chains and the country of origin of the employees. The IHDI indicators have been used because they are reported for a large number of countries and because they take into account the inequality between the people living in a country as well. The overall IHDI of a system ($IHDI_{overall}$) is calculated from the percentage of man-hours per country relative to the total number of man-hours ($perc.man.hrs_i$) and the IHDIs of the countries the employees originate from as follows (1).

$$IHDI_{overall} = \sum_{i=1}^{i=n} perc.man.hrs_i \cdot IHDI_i / 100 \qquad (1)$$

2.4. Exergetic sustainability

The exergetic sustainability is assessed by applying the Total Cumulative Exergy Loss (TCExL) method [2,3] in combination with the exergy replacement costs of minerals [4]. The TCExL method is described in Section 2.4.1 and determines the exergy loss caused by a technological system including its supply chains during the phases of construction, operation and decommissioning. Although it is common practice to call an assessment a life cycle assessment if the aforementioned three life cycle phases are included, it is only a true life cycle assessment if technological installations for the transformation of the outputs to the required inputs are included in the assessment, i.e. if it is a ‘cradle to cradle’ system instead of a ‘cradle to grave’ system. The TCExL method can be applied to all kinds of technological systems and thus to ‘cradle to cradle’ as well as to ‘cradle to grave’ systems. The systems of this research are of the ‘cradle to grave’ type and therefore the TCExL method is combined with the exergy replacement costs of minerals described in Section 2.4.2 to include the ‘grave to cradle’ part of the systems as well (Section 2.4.3).

2.4.1. Total Cumulative Exergy Loss (TCExL) method

The Total Cumulative Exergy Loss (TCExL) method [2,3] was introduced in 2012 (under its previous name Cumulative Exergy Loss (CExL) method) [17] as an alternative to existing exergy analysis methods. The TCExL is the summation of the internal exergy loss caused by a technological system, the internal exergy loss caused by abatement of the resulting waste flows and emissions to an acceptable level and the exergy loss accompanied with the land used by the system. The TCExL method can be regarded as a combination of, or extension to, the exergy analysis methods known as Cumulative Exergy Consumption (CExC) [18], Cumulative Exergy Consumption and Abatement (CExCA) [19], Cumulative Exergy Extraction from the Natural Environment (CEENE) [20] and Exergetic Life Cycle Assessment (ELCA) [21]. The main difference between methods that calculate the (total cumulative) exergy loss (e.g. the TCExL method) and methods that calculate the total exergy consumption (e.g. CExC and Exergetic Cost/Exergy Cost methods [22]) is that the latter include the amount of exergy of the resulting products and by-products as well. In other words, the Exergetic Cost or Exergy Cost is larger than the amount of exergy that is lost.

The internal exergy loss is equal to the difference between the total input and output of exergy of the system during the phases of construction, operation and decommissioning. This difference is calculated from the Cumulative Exergy Demand (CExD, [23]) reported by SimaPro/ecoinvent minus the amount of exergy represented by the products, emissions and waste flows of the system. Hereto, the exergy values of mass flows have been calculated from the standard exergy values of substances and other thermodynamic data, e.g. [24]. As it was undoable to calculate the exergy values of all, i.e. more than 600, emissions reported by SimaPro, it was decided to calculate the exergy values of the largest emissions until at least the exergy values were known of the emissions that contribute 99% by mass of all emissions.

The abatement exergy loss is calculated from the amounts of waste flows and emissions reported by SimaPro/ecoinvent multiplied by the abatement exergy values of these components. The abatement exergy values of the emissions are used because the exergy values of the emissions themselves are no measure of the environmental impact of these emissions. The abatement exergy values applied in this research are limited to the abatement exergy values of carbon dioxide, sulphur dioxide, nitrogen oxides and phosphates as abatement exergy values of other components have not yet been found in literature. The abatement exergy value of 5.9 MJ/kg for carbon dioxide is based on CO_2 recovery via ethanolamine absorption and stripping followed by compression to 80 atm. for underground storage [25,26]. The 57 MJ/kg for sulphur dioxide is based on 90% removal of SO_2 in a flue gas desulphurisation unit of a coal-fired power plant with limestone and subsequent conversion to gypsum [21]. The 16 MJ/kg for nitrogen oxides is based 80% removal in a $DeNO_x$ unit of a coal-fired power plant as well [21] and the 18 MJ/kg for phosphates is the value for 99% removal [21].

The exergy loss accompanied with land use equals the amount of exergy that the ecosystem cannot capture from sunlight because of land occupation by installations, equipment etc. that are part of the assessed system. A worldwide average exergy loss of 215 GJ per hectare per year is calculated from the Net Primary Production [27], i.e. the net amount of biomass produced when this land is not occupied, and an average biomass exergy conversion factor of 42.9 MJ exergy per kg of carbon [28]. SimaPro/ecoinvent distinguishes between different types of land occupation. 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 in determining the exergy loss caused by land use. In addition, the types of land use related to marine ecosystems are not considered because of the very small amount of solar energy that is captured [20]. Summarising, the land occupation types that are not taken into account are all types of which the name contains ‘benthos’, ‘forest’, ‘pasture and meadow’, ‘permanent crop’, ‘sclerophyllous’, ‘seabed’, ‘vegetation’ or ‘water’. Biomass like trees or grass that is used as an input to a technological system is taken into account via the CExD calculated of that system.

2.4.2. Exergy replacement costs of minerals

The assessment of minerals is accomplished through the so-called exergy replacement costs. These costs represent the exergy that would be needed, applying current available technology, to replace the minerals into their original conditions after they have been dispersed at the end of their use phase [5]. The baseline used for calculating the exergy replacement costs is a model of an average dispersed crust, named Thanatia, which is a planet that describes a possible state of the earth where all available resources have been consumed and dispersed [29]. Thanatia can be used as a boundary limit to the calculations since the model includes a list of minerals with their respective concentrations in the crust which constitutes the lower limit of the ore grades. Every mineral deposit has exergy, the greater the difference between the concentration of the mineral in the dispersed crust and in the mine, the greater its exergy. The exergy needed to extract any given mineral increases exponentially as the concentration in the mine decreases, i.e. when the ore grade and the size of the particle decreases, the exergy needed to recover the mineral from the rock tends towards infinity. Exergy replacement costs are associated to the type of mineral analysed, the ore grade of the deposit and the energy intensity of the mining and beneficiation process. The scarcer a mineral, the higher the associated exergy replacement costs are. Consequently, scarcer minerals such as gold and mercury have a higher weight in the accounting process than common minerals such as limestone and phosphate rock. This way, exergy replacement costs can be used as a quality weighting factor for minerals based on thermodynamics.

2.4.3. Combination of the TCExL method and exergy replacement costs of minerals

The TCExL method can be combined with the exergy replacement costs by substituting the CExD values of minerals with the exergy replacement costs of these minerals followed by calculating the total exergy input of the system (by hand) from the amounts of resources used by the system reported by SimaPro/ecoinvent and the CExD values or exergy replacement costs (in case of minerals) of these resources.

3. Description of the power generation systems

The four power generation systems that are assessed in this research are briefly described in the next four sections. The functional unit used in the comparison of the systems is the production of 1 PJ of electricity. In case the systems produce by-products as well, this is accounted for via allocation of the inputs, emissions etc. to the product and by-products on an exergy basis.

The assessment includes the extraction and/or growing, processing and transport of coal, wood pellets and other inputs as well as the treatment of the wastes and emissions according to the processes modelled in SimaPro/ecoinvent. The assessment includes the phases of construction, operation (including maintenance) and decommissioning of the installations and equipment.

3.1. Coal-fired power plant

The coal-fired power plant system (Fig 1.) is based on the new ‘Maasvlakte Power Plant No.3’ in Rotterdam, Netherlands, and is an adaptation of the ‘waste heat’ system previously presented as part of the LNG case study [2,3]. The coal-fired power plant system considers the power plant only, i.e. neither the production of H-gas, which is a mixture of evaporated LNG and nitrogen that is used by large-scale gas consumers in the Netherlands, nor the exchange of waste heat of the coal power plant with the LNG terminal and the LNG terminal itself are part of the system anymore. Furthermore, the carbon dioxide is not captured.

The power plant has a capacity of 1070 MWe, it uses ultra-supercritical steam of about 600 °C and 300 bars and has an electrical efficiency of about 47 per cent [30]. The coal consumption for the production of 1 PJ of electricity is 0.11 Mton. The emissions to air consist of 0.24 Mton of CO_2, 51 ton of NO_x and 0.41 ton of SO_x. Other emissions have not been included in the assessment as they are missing in the description of the power plant ([30]) and because it was not meant to conduct detailed environmental assessments of the systems. In addition, 0.81 PJ of waste heat is emitted to the ocean and 13 kton of slags/ashes result.

The investment costs and yearly revenues excluding capital costs of the system allocated to the production of 1 PJ of electricity are €66 million and €6.0 million per year, respectively.

The man-hours needed for exploration/processing, deep sea transport of coal and operation of the power plant have been calculated at $2\cdot10^5$, $7\cdot10^4$ and $2\cdot10^4$ man-hours per Mton of coal, respectively.

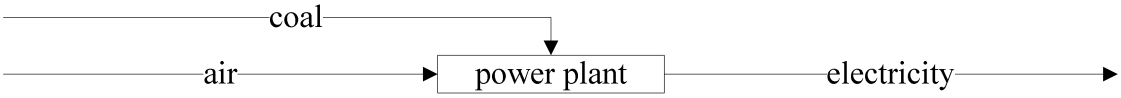

Fig. 1. Coal-fired power plant.

3.2. Co-firing of coal and wood pellets

The Amercentrale power plant in Geertruidenberg, Netherlands [31] is the power plant the co-firing system (Fig. 2) is based on. This power plant co-fires 87 kton of coal and 37 kton of trees (transformed into wood pellets) per PJ of electricity. The wood pellets are produced in the Georgia Biomass plant in the US [32] and then transported to the Netherlands. The coal power plant produces heat as well. On the basis of the exergy values of both products, 96% of the inputs, emissions etc. of the power plant is allocated to the generated electricity. The power plant emits 0.15 Mton of fossil CO_2, 0.042 Mton of biogenic CO_2, 0.12 kton of NO_x, 37 ton of SO_2 and 3.5 ton of PM10 per PJ of electricity. Like in the coal-fired power plant system, other emissions have not been included in the assessment.

The investment costs and yearly revenues of the system allocated to the production of 1 PJ of electricity are €47 million and €8.0 million per year, respectively.

The man-hours needed for exploration/processing and deep sea transport of coal as well as for operating the power plant are the same as in the previous system. The man-hours needed for the processing of trees to wood pellets and subsequent deep sea transport have been calculated at $2 \cdot 10^5$ and $3 \cdot 10^5$ man-hours per Mton of wood pellets, respectively.

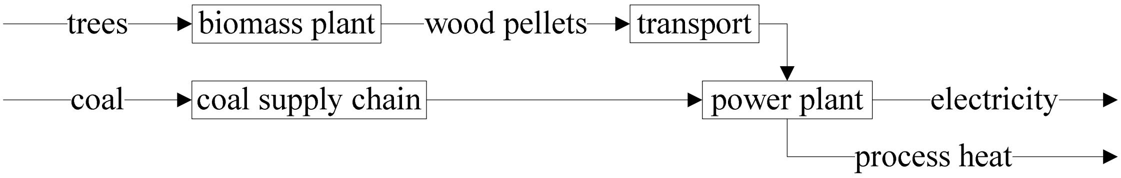

Fig. 2. Co-firing of coal and wood pellets.

3.3. Wind farm

The wind farm system is modelled after the wind farm that is under construction in the Noordoostpolder area in the Netherlands [33]. This system is slightly different from the wind farm system presented before ([2]) in the sense that now the Siemens SWT3.0 instead of the Siemens SWT3.6 is modelled as the off-shore wind turbine, which corresponds with the type of off-shore wind turbine that will be used in this area. The wind farm has a capacity of about 5 PJ of electricity per year and needs 2.4 PJ of wind energy per PJ of electricity. Back-up systems to deal with the discontinuity in electricity production caused by too low or too high wind speeds have not been taken into account in this research. As an alternative to back-up power plants, energy storage facilities are investigated by researchers world-wide.

The investment costs allocated to 1 PJ of electricity amount to €198 million. The yearly revenues excluding capital costs and excluding subsidy are €8.7 million per year and the subsidy to be received during the first 15 years of operation is calculated at €12 million per year.

It was assumed that all employees active during construction, operation and decommissioning of the wind farm system originate from the Netherlands, therefore the man-hours have not been calculated.

3.4. Combustion of bioethanol from verge grass

This bioethanol system (Fig. 3) consists of the growing, mowing and transport of verge grass, followed by its fermentation to bioethanol and subsequently combusting the bioethanol in a combined-cycle power plant. This system has a capacity of about 30 MW of electricity and is based on the research by De Vries [34].

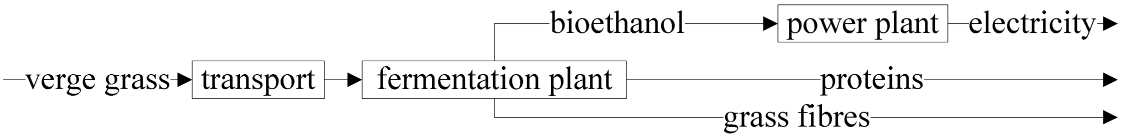

Fig. 3. Combustion of bioethanol from verge grass.

The grass fibres and protein by-products of the fermentation processes are taken into account via allocation on an exergy basis, i.e. 28, 31 and 41 per cent of the impact of the fermentation process including its supply chains is allocated to the bioethanol product and 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.

The investment costs allocated to 1 PJ of electricity equal €86 million. Assuming that €15 per ton of verge grass (40% dry matter) is received for its processing, the yearly revenues excluding capital costs amount to €21 million.

Like in the wind farm system, it is assumed that all employees originate from the Netherlands.

4. Results of the assessments

The results of applying the environmental, economic and social sustainability assessment methods to the four systems are presented in Tables 1 to 3, respectively. The ReCiPe total score of the environmental assessment is subdivided into its three damage categories. The damage category human health contributes 32 to 44 per cent of the total ReCiPe score. The categories ecosystems and resources contribute about 25 and 35 per cent, respectively, but with the exception of the wind farm system where both categories contribute 12 and 56 per cent respectively. The total ReCiPe score of the wind farm system is small compared to the other systems, which is understandable because wind energy needs not to be transported and does not lead to flue gases etc. The environmental sustainability of the bioethanol system largely depends on the fact whether the verge grass input is considered a waste product, i.e. it uses ‘no’ land to grow, or not. If the land needed to grow the grass is taken into account, the ReCiPe score increases from 8.0 to 34 MPt. Furthermore, the results of the bioethanol system largely depend on the allocation of the impact of the fermentation process to the three products, i.e. the bio-ethanol product and the grass fibres and protein by-products, as 99% of the ReCiPe score, including infrastructure processes, is determined by the fermentation process including its supply chains.

Table 1. Results of the environmental sustainability assessment.

Damage category [MPt]	Coal power plant	Co-firing	Wind farm	Bioethanol
Human Health[1]	9.6	7.2	0.25	3.3
Ecosystems[1]	5.0	5.4	0.093	1.7
Resources[1]	7.2	6.2	0.44	3.0
Total ReCiPe score	22	19	0.78	8.0

[1] The damage category numbers have already been weighted in accordance with the selected ReCiPe average weighting set.

According to the results of the economic sustainability assessment in Table 2, the Bioethanol system is the most sustainable from an economic point of view. The reason for the high PWR compared to the other systems is that in the bioethanol system money is received for the processing of the feedstock, i.e. verge grass. The wind farm system has a negative PWR, indicating that this system is not profitable at the prices used.

Table 2. Results of the economic sustainability assessment.

	Coal power plant	Co-firing	Wind farm	Bioethanol
NPV [10^6 €]	8	17	-23	94
Investment costs [10^6 €][1]	57	40	184	80
PWR [-]	7.2	6.2	0.44	3.0
PWR	0.13	0.42	-0.12	1.2

[1] Net Present Value of the investment costs.

The results of the social sustainability assessment are shown in Table 3. The wind farm and bioethanol systems have the highest social sustainability because it is assumed that all employees originate from the Netherlands (Sections 3.3 and 3.4). The coal power plant system has a lower social sustainability than the co-firing system because the employees of the coal supply chain are from a country with a lower IHDI than the employees of the wood pellet supply chain.

Table 3. Results of the social sustainability assessment.

	Coal power plant	Co-firing	Wind farm	Bioethanol
$IHDI_{overall}$ [-]	0.633	0.639	0.857	0.857

Table 4 presents the results of the exergetic sustainability assessment. The exergy input is a combination of the CExD and exergy replacement costs of minerals (Section 2.4.3). The wind farm system has the highest exergetic sustainability. The three other systems, which involve combustion of the fuel input, have about the same exergetic sustainability. The exergy input of the wind farm system is much lower because in SimaPro/ecoinvent only the wind energy captured by the wind turbine is considered as an input. Allocation of all wind flowing towards the wind turbines would result in an exergy input and TCExL that is 2.2 PJ higher, but then again the wind farm system has the highest exergetic sustainability.

Table 4. Results of the exergetic sustainability assessment.

[PJ]	Coal power plant	Co-firing	Wind farm	Bioethanol
Exergy input[1]	3.1	3.5	1.2	5.1
Exergy of the product	1.0	1.0	1.0	1.0
Exergy of emissions	0.38	0.38	0.026	0.91
Internal exergy loss[2]	1.7	2.1	0.18	3.1
Abatement exergy	1.5	1.0	0.051	0.48
Exergy loss land use	0.040	0.0051	0.00087	0.023
TCExL[2]	3.3	3.2	0.23	3.6

[1] The exergy input is a combination of the CExD and exergy replacement costs of minerals.

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

When looking in more detail at the exergy input, it appears that the influence of the exergy replacement costs of minerals is quite small, which is understandable because the used amount of mineral inputs is small compared to the input of fossil and renewable inputs during the operation phase. Table 5 gives an overview of the origin of the inputs that contribute at least 1 per cent to the exergy input of the systems as a whole, thus including infrastructure processes, and the origin of the inputs that contribute at least 1 per cent to the exergy input of the infrastructural part of the systems.

Table 5. Overview of the origin of the inputs that contribute at least 1% to the exergy input of the systems and the origin of the inputs that contribute at least 1% to the infrastructural part of the systems.

[% of total exergy input]	Coal power plant	Co-firing	Wind farm	Bioethanol
Whole system, i.e. including infrastructure processes				
Mineral	0.0	0.0	3.9	0.0
Renewable	0.0	23	89	74
Fossil	95	74	4.9	22
Total	95	97	98	96
Infrastructural part of the system[1]				
Mineral	21	25	41	28
Renewable	19	15	8.4	8.6
Fossil	57	55	47	60
Total	97	95	96	97

[1] Calculated from the inputs of the system including infrastructure processes and the inputs of the system excluding infrastructure processes.

Table 6 provides an overview of the results of the environmental, economic, social and exergetic sustainability assessments. The wind farm system is preferred from an environmental and exergetic point of view and is one of the systems with the highest social sustainability, but has the lowest economic sustainability. The difference in the exergetic sustainability of the three other systems is too small to draw conclusions about which system is second-best. Although it seems that the bioethanol system is the least preferred from an exergetic point of view, while it is the second-best from an environmental point of view. However, the environmental sustainability largely depends on the fact whether the verge grass input is considered a waste product, i.e. it uses ‘no’ land to grow, or not. The latter would result in a ReCiPe score of 34 instead of 8.0 MPt, but would not lead to a different exergetic sustainability.

Table 6. Results of the environmental, economic, social and exergetic sustainability assessments.

	Coal power plant	Co-firing	Wind farm	Bioethanol
ReCiPe [MPt]	22	19	0.78	8.0
PWR [-]	0.13	0.42	-0.12	1.2
$\mathrm{IHDI}_{\mathrm{overall}}$ [-]	0.63	0.64	0.86	0.86
TCExL [PJ]	3.3	3.2	0.23	3.6

5. Discussion and conclusions

On the basis of the results of the assessments, it is concluded that the wind farm is preferred from the environmental, social and exergetic sustainability points of view, but not from the economic sustainability viewpoint. However, back-up systems to deal with the discontinuity in electricity production by the wind farm (caused by too low or too high wind speeds) have not been taken into account, but it is expected that the wind farm is still preferable from the environmental and exergetic sustainability points of view because of the large difference with the scores of the other systems. It must also be noted that the results of the environmental sustainability assessment are less certain because of the choice of ReCiPe endpoint instead of ReCiPe midpoint indicators, but the need for a single environmental sustainability indicator per assessed system resulted in the choice of endpoint indicators.

The coal power plant and the co-firing system apply similar technologies, i.e. the combustion of coal and/or biomass, to generate power. According to the results of the assessments, the co-firing system performs better than the coal power plant does. The results of the environmental and economic sustainability assessment of the bioethanol system largely depend on choices with regard to considering verge grass a waste product or not. Besides, the environmental and exergetic sustainability assessment results of the bioethanol system are largely influenced by the allocation of the impact of the fermentation process including its supply chains to the bioethanol product and grass fibres and protein by-products as well, but the applied allocation on the basis of the exergy values of the products is considered appropriate in this research. The social sustainability of the bioethanol system is not influenced by the allocation as it has been assumed that all employees originate from the Netherlands.

The advantage of the exergetic sustainability assessment method is that its results are not influenced by choices regarding an input being a waste product or not, and other uncertainties like market prices and the like. The exergetic assessment method takes into account all exergy losses caused by a system during its life cycle and leads to results that do not change over time.

The influence of the exergy replacement costs of minerals on the results of the exergetic assessment appears small, because less than 5 per cent of the exergy input of the systems during construction, operation and commission is of mineral origin. When looking at the infrastructural part of the systems only, the influence of the exergy replacement costs is larger because about 25 to 40 per cent of the exergy input is of mineral origin.

6. Recommendations

It is recommended that the TCExL method and the exergy replacement costs of minerals be implemented in life cycle assessment software tools and that abatement exergy values of more components be calculated.

References

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

[2] Stougie L., Van der Kooi H.J., Possibilities and consequences of the total cumulative exergy loss method in improving the sustainability of power generation. In: Zevenhoven R., editor. ECOS 2014: Proceedings of the 27th International Conference on Efficiency, Cost, Optimization, Simulation, and Environmental Impact of Energy Systems; 2014 Jun 15-19; Turku, Finland, Åbo Akademi University, Thermal and Flow Engineering Laboratory: 1519-28.

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

[4] Valero A., Valero A., Thermodynamic rarity and the loss of mineral wealth. In: Zevenhoven R., editor. ECOS 2014: Proceedings of the 27th International Conference on Efficiency, Cost, Optimization, Simulation, and Environmental Impact of Energy Systems; 2014 Jun 15-19; Turku, Finland, Åbo Akademi University, Thermal and Flow Engineering Laboratory: 307-18.

[5] Valero A., Valero A., From grave to cradle. A thermodynamic approach for accounting for abiotic resource depletion. Journal of Industrial Ecology 2013;17(1):43-52.

[6] Domínguez A., Valero A.,Valero, A. Exergy accounting applied to metallurgical systems: The case of nickel processing. Energy 2013;62:37-45.

[7] Valdivia S., Ugaya C.M.L., Hildenbrand J., Traverso M., Mazijn B., Sonnemann, G., A UNEP/SETAC approach towards a life cycle sustainability assessment - our contribution to Rio+ 20. The International Journal of Life Cycle Assessment 2013;18: 1673-1685.

[8] Meyer L., Tsatsaronis G., Buchgeister J. and Schebek L., Exergoenvironmental analysis for evaluation of the environmental impact of energy conversion systems. Energy 2009;34(1):75-89.

[9] Goedkoop M., Heijungs R., Huijbregts M., De Schryver A., Struijs J., Van Zelm R., ReCiPe 2008, A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level, Report I: Characterisation. The Hague, Netherlands: Ministry of Housing, Spatial Planning and Environment; 2009.

[10] European Commission-Joint Research Centre - Institute for Environment and Sustainability, International Reference Life Cycle Data System (ILCD) Handbook - Recommendations for Life Cycle Impact Assessment in the European context. First edition November 2011. EUR 24571 EN. Luxemburg: Publications Office of the European Union; 2011.

[11] Pré Consultants, Amersfoort, Netherlands. SimaPro LCA software – Available at: <http://pre.nl/content/simapro-lca-software> [accessed 26.1.2011].

[12] Ecoinvent Centre (Swiss Centre for Life-Cycle Inventories) St-Gallen, Switzerland. Ecoinvent database – Available at: <http://www.ecoinvent.org> [accessed 26.1.2011].

[13] Stougie L., Van der Kooi H., The sustainability of LNG evaporation. In: Bojić M., Lior N., Petrović J., Stefanović G., Stevanović V., editors. ECOS 2011: Proceedings of the 24th International Conference on Efficiency, Cost, Optimization, Simulation, and Environmental Impact of Energy Systems; 2011 Jul 4-7; Novi Sad, Serbia. University of Niš:3157-70.

[14] Benoît C., Mazijn B., Guidelines for social life cycle assessment of products. UNEP/SETAC Life Cycle Initiative; Paris, 2009.

[15] Benoît C., Norris G.A., Valdivia S., Ciroth A., Moberg A., Bos U., Prakash S., Ugaya C., Beck T., The guidelines for social life cycle assessment of products: just in time! The International Journal of Life Cycle Assessment 2010;15:156-63.

[16] Malik K., Human Development Report 2013 - The Rise of the South: Human Progress in a Diverse World. New York, USA: United Nations Development Programme; 2013. Technical report.

[17] Stougie L., Van der Kooi H.J., Stikkelman R.M., Electricity production from renewable and non-renewable energy sources: a comparison of environmental, economic and social sustainability indicators with exergy losses throughout the supply chain. In: Desideri U., Manfrida G., Sciubba E., editors. ECOS 2012: Proceedings of the 25th International Conference on Efficiency, Cost, Optimization, Simulation, and Environmental Impact of Energy Systems; 2012 Jun 26–29; Perugia, Italy. Firenze University Press:391-405.

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

[19] Dewulf J., Van Langenhove H., Dirckx J., Exergy analysis in the assessment of the sustainability of waste gas treatment systems. Science of the Total Environment 2001;273(1-3):41-52.

[20] Dewulf J., Bösch M., De Meester B., Van der Vorst G., Van Langenhove H., Hellweg S., Huijbregts M., Cumulative exergy extraction from the natural environment (CEENE): a comprehensive life cycle impact assessment method for resource accounting. Environmental Science & Technology 2007;41(24):8477-83.

[21] Cornelissen R.L., Thermodynamics and sustainable development; the use of exergy analysis and the reduction of irreversibility [dissertation]. Enschede, Netherlands: Twente University; 1997.

[22] Valero A., Lozano M.A., Muñoz M., A general theory of exergy saving. I. On the exergetic cost. Computer-Aided Engineering and Energy Systems: Second Law Analysis and Modelling 1986;3:1-8.

[23] Bösch M.E., Hellweg S., Huijbregts M.A.J., Frischknecht R., Applying cumulative exergy demand (CExD) indicators to the ecoinvent database. The International Journal of Life Cycle Assessment 2007;12(3):181-90.

[24] Szargut J. Appendix 1. Standard chemical exergy, Egzergia. Poradnik obliczania I stosowania, Gliwice: Widawnictwo Politechniki Shlaskej; 2007.

[25] Dewulf J., Van Langenhove H., Mulder J., Van den Berg M.M.D., Van der Kooi H.J., De Swaan Arons J., Illustrations towards quantifying the sustainability of technology, Green Chemistry 2000;2:108-14.

[26] Van der Vorst G., Dewulf J., Van Langenhove H., Developing Sustainable Technology: Metrics From Thermodynamics. In: Bakshi B.R., Gutowski T., Sekulic, D, editors. Thermodynamics and the Destruction of Resources. Cambridge: Cambridge University Press. 2011. p. 249-64.

[27] Haberl H., Erb K.H., Krausmann F., Gaube V., Bondeau A., Plutzar C., Gingrich S., Lucht W., Fischer-Kowalski M., Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. Proceedings of the National Academy of Sciences 2007;104(31):12942-7.

[28] Alvarenga R.A., Dewulf J., Van Langenhove H., Huijbregts M.A., Exergy-based accounting for land as a natural resource in life cycle assessment, The International Journal of Life Cycle Assessment 2013;18(5):939-47.

[29] Valero A., Agudelo A., Valero A., The crepuscular planet. A model for exhausted atmosphere and hydrosphere. Energy 2011;36:3745-53.

[30] De Buck A., Croezen H., Rensma K., The ‘oxy-fuel’ route (in Dutch), Delft, Netherlands: CE Delft; 2008. Technical Report No.: 08.3509.09.

[31] Essent N.V., Amercentrale – Available at: <http://www.essent.nl/content/Images/26746_Amercentrale_26-32384.pdf> [accessed 20.12.2011].

[32] Georgia Biomass, LLC. Website – Available at: <http://www.gabiomass.com> [accessed 21.9.2011].

[33] Koepel Windenergie Noordoostpolder. Website – Available at: <http://www.windkoepel-nop.nl> [accessed 8.9.2011].

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