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Possibilities and consequences of the Total Cumulative Exergy Loss method in improving the sustainability of power generation ☆

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ABSTRACT

It is difficult to decide which power generation system is the most sustainable when environmental, economic and social sustainability aspects are taken into account. Problems with conventional environmental sustainability assessment methods are that no consensus exists about the applied models and weighting factors and that exergy losses are not considered. Economic sustainability assessment methods do not lead to results that are independent of time because they are influenced by market developments, while social sustainability assessment methods suffer from the availability and qualitative or semi-quantitative nature of data. Existing exergy analysis methods do not take into account all exergy losses and/or are extended with factors or equations that are not commonly accepted. The new Total Cumulative Exergy Loss (TCExL) method is based on fundamental thermodynamic equations and takes into account all exergy losses caused by a technological system during its life cycle, i.e. internal exergy losses, exergy losses caused by emission abatement and exergy losses related to land use. The development of the TCExL method is presented as well as the application of this method and environmental, economic and social sustainability assessment methods to two case studies: power generation in combination with LNG evaporation and Fossil versus renewable energy sources for power generation. According to the results of the assessments, large differences exist between the environmental sustainability assessment and TCExL methods in the sense that different parts of the systems contribute most to their overall scores. It is concluded from the case studies that involving the TCExL method in choices between power generation systems with the same energy sources has no consequences, i.e. it does not result in a different ranking of the systems, but can lead to the choice of a system that has a lower economic sustainability if the assessed systems use different energy sources. However, it must be noted that the economic sustainability changes over time, while the results of the TCExL method do not.

1. Introduction

Different power generation systems exist and it is difficult to decide which of these is the most sustainable when the environmental, economic and social aspects of sustainability are taken into account. A problem with conventional environmental sustainability assessment methods is that there is no consensus about the applied models and weighting factors, as discussed in Section 3.2, and that they do not consider exergy losses. Furthermore, the economic sustainability assessment methods do not include all indirect costs and do not lead to results that are independent of time because they are influenced by market developments, while the social sustainability assessment methods suffer from the availability and qualitative or semi-quantitative nature of data. A problem with existing exergy analysis methods is that these methods do not take into account all exergy losses and/or are extended with factors or equations that are not commonly accepted. In 2012, the Total Cumulative Exergy Loss (TCExL) method was introduced (under its previous name CExL method) as an alternative to existing exergy analysis methods [1]. This paper presents the development of the TCExL method including recent improvements of the method. The possibilities and consequences of the TCExL method are investigated by applying the TCExL method and regular sustainability assessment methods to two case studies. The first case study consists of three systems for power generation in combination with Liquefied Natural Gas (LNG) evaporation and the second

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Nomenclature

H-gas	natural gas with a specific calorific value
LNG	Liquefied Natural Gas
CEENE	Cumulative Exergy Extraction from the Natural Environment
CExC	Cumulative Exergy Consumption
CExD	Cumulative Exergy Demand
CExL	Cumulative Exergy Loss
CExCA	Cumulative Exergy Consumption for Construction and Abatement
ELCA	Exergetic Life Cycle Analysis
IHDI	Inequality-adjusted Human Development Index
NPP	Net Primary Production
NPV	Net Present Value
ORC	Organic Rankine Cycle
PWR	Present Worth Ratio
ReCiPe	method for life cycle impact assessment
TCExL	Total Cumulative Exergy Loss
UNDP	United Nations Development Programme

case study compares power generation from Fossil and renewable energy sources. It is also investigated what the differences between the assessment methods are with regard to the parts of the assessed systems that contribute most to the overall scores of the methods. The case studies presented here are improvements and modifications of the previously presented LNG [2] and Fossil versus renewable [1] case studies. The comparison of the results of the adapted case studies in this paper enables a more profound insight into the possibilities and consequences of the use of the TCExL method. More detailed information about the applied methods and the modelling of the systems of the case studies is provided by Stougie [3].

2. Development of the Total Cumulative Exergy Loss method

2.1. Requirements

A problem with sustainability assessment is that a commonly accepted operationalization of the term 'sustainability' could not be found in literature. The well-known definition by the Brundtland commission, i.e. 'sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs' [4, p.43] needs operationalization as well. According to literature, sustainability is usually considered as having environmental, economic and social components, and a life cycle point of view is recommended to prevent problem shifting between different life cycle phases and/or sustainability aspects [5]. To deal with the lack of a commonly accepted operationalization of sustainability, a list of requirements to sustainability assessment methods has been drawn up on the basis of previous research in this field [6,7] and additional knowledge gathered from studying literature. Requirements that are commonly met by sustainability assessment methods are taking into account the operational phase of installations and equipment, and the amounts of inputs and outputs. It is less common to include the construction and decommissioning of the installations and equipment, and the following components: depletion and/or scarcity of the inputs, distinction between renewable and non-renewable inputs, disposal and/or abatement of emissions and waste flows, land use, exergy losses and the economic and social aspects of sustainability. Additional requirements not related to sustainability are that sustainability assessment methods should be objective and that sufficient data should be available for their calculations. A method is not considered as objective when e.g. different views exist about how its indicators should be calculated, when it makes use of weighting factors and/or when its results vary over time because of market influences and the like. In fact, the latter is the result of variations in one or more of the input variables used by that method instead of a consequence of the method itself, but for reasons of simplicity both aspects have been grouped into 'objectivity'.

An exergy analysis method is as objective as possible when it calculates exergy losses based on standard thermodynamic equations. Components of the list of requirements that cannot directly be considered by calculating exergy losses are the depletion and scarcity of resources and the economic and social aspects of sustainability. The depletion and scarcity of resources can indirectly be expressed in terms of exergy loss via the (total cumulative) exergy loss caused by the extraction of resources, i.e. the scarcer a resource becomes, the more exergy will be lost during its extraction. If the assessed technological system includes technological installations for the transformation of the outputs to the required inputs, i.e. the closing of material cycles, the depletion and/or scarcity of the inputs is no longer an issue. An alternative to taking into account these technological installations is the substitution of the exergy value of minerals with the exergy replacement costs of the minerals [8]. The exergy replacement costs are calculated from the amount of exergy that would be needed to obtain these minerals when the mines are empty and the minerals have been dispersed throughout the earth's crust. The economic and social aspects of sustainability are related to exergy losses via the inputs and outputs of the systems. Extending the TCExL method with factors or equations to directly incorporate the economic and social aspects of sustainability would lead to a loss of objectivity of the method as different views exist about how to do that and because these factors and equations do not originate from thermodynamic equations. Furthermore, exergy losses themselves do have economic and social aspects because exergy is needed for all processes and activities.

2.2. Definition of the Total Cumulative Exergy Loss

The exergy analysis method that has been developed on the basis of the aforementioned requirements is the Total Cumulative Exergy Loss (TCExL) method [1,2]. The initial name of this method was the CExL method, but when later on appeared that this name had already been used by professor Szargut (e.g. [9]) to define the Cumulative Exergy Consumption (CExC, [10]) of a product minus the specific exergy of the product itself, it was decided to rename the method into the TCExL method to avoid confusion between the two different methods. The TCExL is the summation of the internal exergy losses caused by the system itself (Section 2.3), the exergy loss caused by processes for the abatement of the waste flows and emissions (Section 2.4), and the exergy loss accompanied with the land used by that system (Section 2.5). The TCExL method can be regarded as a combination of, or extension to, the existing exergy analysis methods called Cumulative Exergy Consumption for Construction and Abatement (CExCA, [11]), Cumulative Exergy

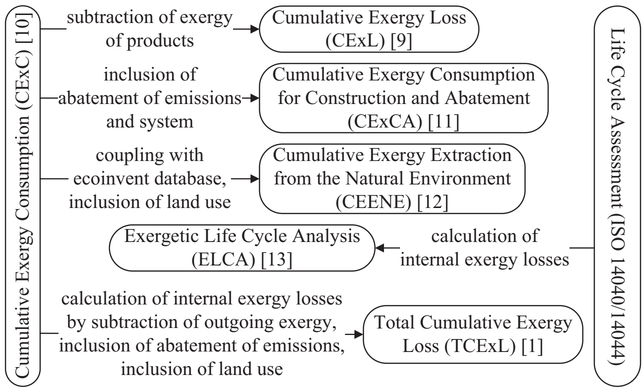

Fig. 1. The relationship between the TCExL method and other exergy analysis methods.

Extraction from the Natural Environment (CEENE, [12]) and Exergetic Life Cycle Analysis (ELCA, [13]), as depicted in Fig. 1.

2.3. Calculation of the internal exergy loss

The internal exergy loss is calculated from the amounts of exergy represented by the inputs to and outputs from the installations and equipment during the phases of construction, operation and decommissioning. This internal exergy loss is equal to the total input of exergy minus the total output of exergy. The SimaPro software tool [14] in combination with the ecoinvent database version 2.2 [15] is used to calculate the Cumulative Exergy Demand (CExD, [16]) of the system, i.e. the total input of exergy. Subtracting the total output of exergy, i.e. the amount of exergy represented by the products, emissions and waste flows, from the CExD results in the internal exergy loss caused by the system.

2.4. Calculation of abatement exergy loss

The abatement exergy loss is equal to the exergy loss caused by processes that abate the waste flows and emissions of a technological system to an acceptable level. Until now, only the abatement exergy values of carbon dioxide, sulphur dioxide, nitrogen oxides and phosphates have been found in literature, which equal 5.9, 57, 16 and 18 MJ/kg, respectively [11,17,18]. The carbon dioxide, sulphur dioxide and nitrogen oxides emissions are flue gas emissions and the phosphates are emitted to water. The amounts of waste flows and emissions needed for calculating the abatement exergy loss are reported by SimaPro/ecoinvent. In the future, abatement exergy values of other components will be included as well.

2.5. Calculation of the exergy loss caused by land use

The exergy loss caused by land use is the amount of exergy that cannot be captured from sunlight by the ecosystem because of the land occupied by the installations, equipment, etc. of the system, e.g. by coal power plants, solar PV installations, roads, mines and other man-made components of the system. This exergy loss is calculated from the natural potential Net Primary Production (NPP), i.e. the net amount of carbon that is assimilated by vegetation during a certain period, when this land is not occupied [19] and an average biomass exergy conversion factor of 42.9 MJ exergy per kg of carbon [20]. The NPP takes into account local natural conditions like water availability, soil quality and temperature. The world average exergy loss of 215 GJ per hectare per year used in this research has been calculated by Alvarenga et al. [20] from a world map with NPP values. Dividing the world average exergy loss by the average solar irradiation in Western Europe (2.78 kWh/m^2 per day [1]) and the amount of exergy per amount of sunlight (0.9327 [10]) would result in 0.63% efficiency of capturing solar energy via photosynthesis, which is consistent with the less than 1% efficiency according to literature [3]. The ecoinvent database distinguishes between several types of land use. An improvement of the current TCExL method compared to the method presented previously [1,2] is that the types of land that are used by a technological system for the growing of trees or another type of biomass are not taken into account in the calculation of the exergy loss caused by land use to prevent double-counting. These land types are 'Dump site, benthos', 'Forest, intensive', 'Forest, intensive, normal', 'Forest, intensive, short-cycle', 'Industrial area, benthos', 'Pasture and meadow, extensive', 'Permanent crop, fruit, intensive' and 'Shrub land, sclerophyllous'. Whenever biomass like trees or grass is used as an input to a technological system, this is accounted for via the CExD calculated of that system.

2.6. Reflection on the TCExL method

The TCExL method can be used for the assessment of all kinds of technological systems, e.g. energy conversion processes, chemicals manufacturing, waste processing and recycling of materials. The results of the method could be improved by including more abatement exergy values of emissions, which is the subject of future research. The advantage of the TCExL method compared to the aforementioned exergy analysis methods is that it is based on the calculation of exergy losses only and that all exergy losses caused by a technological system during its life cycle are included.

3. Comparison of the TCExL method with other sustainability assessment methods

3.1. Method of comparison

The possibilities and consequences of the TCExL method in improving the sustainability of power generation are investigated by conducting case studies that each consist of three different systems for power generation, followed by confronting the separate results of the environmental, economic, social and exergetic assessments of the systems with each other and ranking of the systems per assessment method. It can then be concluded which of the systems of a case study is preferred from an exergetic point of view and what it means for the environmental, economic and social sustainability if the system is chosen that is preferred from an exergetic point of view. The differences between the assessment methods are considered in more detail by investigating which processes of the systems contribute most to the overall scores of the sustainability assessment methods. The next sections describe the sustainability assessment methods the TCExL method is compared with.

3.2. Environmental sustainability

The environmental sustainability of the systems is assessed by applying an environmental life cycle assessment method that calculates ReCiPe endpoint indicators. The ReCiPe method has been chosen because it is a recent development in this field, i.e. published in 2009 [21], resulting from a thorough cooperation between experts in the field of LCA during which they combined the CML 2002 midpoint and Eco-indicator 99 endpoint methods into the ReCiPe method. The resulting ReCiPe method offers the possibility to calculate 18 midpoint indicators of environmental impact, e.g. stratospheric ozone concentration, as well as 3 endpoint indicators, i.e. damage to human health, ecosystem diversity and resource availability, which can subsequently be combined into one overall endpoint indicator. A difficulty with calculating indicators of environmental impact in general is that no consensus exists about the models and weighting factors applied to calculate these indicators, e.g. regarding the environmental impact of emissions, but an environmental sustainability assessment method is needed to compare the TCExL method with. This difficulty is more pronounced in case of calculating endpoint indicators than with midpoint indicators. The reason for choosing endpoint instead of midpoint indicators is the need for a single environmental sustainability indicator per assessed system. The SimaPro software tool version 7.3 [14] in combination with the ecoinvent database version 2.2 [15] is used to calculate the ReCiPe indicators. The lower the ReCiPe score, the higher the environmental sustainability.

3.3. Economic sustainability

A well-known economic indicator to calculate the economic performance of a technological system is the Net Present Value (NPV). However, because of the importance of the investment costs of installations, it has been decided to calculate the Present Worth Ratio (PWR) as the indicator of the economic sustainability. The PWR is defined as the Net Present Value (NPV) of the revenues and costs during the lifetime of the installation divided by the NPV of the investment costs of the installation. The higher the PWR, the more likely the investment is. In this research, the lifetime of the installations after construction is assumed to be 20 years and the discount rate applied in the calculations is 8 per cent. The prices used for coal and electricity equal €2.65/GJ and €60/MWh, respectively, which are realistic numbers in the Netherlands. The price of carbon dioxide emissions was assumed to be €20/ton, which is consistent with the price before the financial crisis. Section 4.2 presents the results of varying the price of carbon dioxide emissions. The yearly revenues mentioned in the brief descriptions of the technological systems are the revenues used for calculating the PWR, i.e. without considering the capital costs. It was assumed that the revenues and costs remain constant during the lifetime.

3.4. Social sustainability

A standard method for determining the social sustainability is still under development [22,23]. Therefore and because it would be too time-consuming and costly to gather site-specific social data, a method based on the Inequality-adjusted Human Development Index (IHDI) of countries reported by the UNDP [24] is applied. The reason for using IHDI indicators is that these are available of a large number of countries and that they take into account the inequality between the people living in a country as well. The social sustainability method was introduced in 2011 [25] and calculates the overall IHDI of a system ($IHDI_{overall}$) from the number of man-hours spent in the different stages of the production chains, the country of origin of the employees, the resulting percentage of man-hours per country relative to the total number of man-hours ($perc.man.hrs_i$) and the IHDIs of the countries ($IHDI_i$) the employees originate from as follows (1).

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

4. Case study Power generation in combination with LNG evaporation

The case study presented here is a variant of the case study presented earlier [2] in the sense that it does no longer include the Liquefied Natural Gas (LNG) and nitrogen supply chains and the mixing of the resulting natural gas with nitrogen to obtain the H-gas (natural gas with a specific calorific value, e.g. consisting of approximately 91 mass% methane and 9 mass% nitrogen) used by large-scale gas consumers in the Netherlands. The resulting systems comprise the generation of power and the evaporation of LNG to natural gas. The reason for presenting the systems 'excluding the H-gas supply chain' in this paper is the better comparability with the systems of the other case study.

4.1. Description of the systems

The assessment includes the extraction, processing and transport of coal and the treatment of the wastes and emissions according to the ecoinvent database in SimaPro. The construction, operation and decommissioning of the installations are considered as well.

The product of all systems, i.e. the functional unit, is the production of 1 PJ of electricity and the evaporation of 0.40 Mton of LNG.

4.1.1. Use of waste heat from a coal-fired power plant for LNG evaporation

The Waste heat system consists of a coal-fired power plant of which the residual heat is used by an LNG import terminal. This ultra-supercritical power plant has a capacity of 1070 MWe and its electrical efficiency is about 47 per cent [26]. The resulting CO_2 is captured via monoethanolamine absorption with an efficiency of approximately 80 per cent. The compression and storage of CO_2 are not considered in this case study for reasons of comparability with the other systems. The coal consumption for the production of 1 PJ of electricity is 0.11 Mton and 0.20 Mton of CO_2 is captured. The emissions to air equal 37 ton of CO_2, 52 kg of NO_x, 0.41 ton of SO_x, 0.96 Mton of N_2, 93 kton of O_2 and 52 kton of H_2O. The amounts of waste heat to a river and slags/ashes amount to 0.81 PJ and 13 kton, respectively.

The investment costs and yearly revenues of the system allocated to the production of 1 PJ of electricity are €96 million and €9.0 million per year, respectively.

The man-hours needed for exploration/processing, deep sea transport (transport over long maritime distances, e.g. transatlantic) of coal and operation of the power plant have been calculated at 2×10^5, 7×10^4 and 2×10^4 man-hours per Mton of coal, respectively. The same numbers of man-hours apply to the other two systems of this case study.

4.1.2. Integration of an oxyfuel power plant with air separation and LNG evaporation

The coal-fired oxyfuel power plant of the Oxyfuel system is integrated with an air separation unit and an LNG import terminal [26,27]. The power plant has a capacity of 1000 MWe and an electrical efficiency of about 45 per cent. The resulting CO_2 is captured like in the Waste heat system. The production of nitrogen as a by-product of the air separation unit is considered via allocation on the basis of the exergy values of product and by-product. The nitrogen by-product can be used for all kinds of industrial applications. The coal consumption for the production of 1 PJ of electricity is 0.10 Mton. The captured amount of CO_2 is equal to 0.21 Mton. The CO_2, O_2 and H_2O emissions are 11, 27 and 36 kton, respectively. The amounts of waste heat to a river and slags/ashes equal 0.78 PJ and 11 kton, respectively.

The investment costs and yearly revenues of the system allocated to the production of 1 PJ of electricity are €74 million and €12 million per year, respectively. The lower investment costs and higher revenues compared to the other two systems are caused by the production of nitrogen as a by-product and the subsequent allocation of a part of the investment costs and operational costs to the nitrogen by-product.

4.1.3. Separate power plant plus an LNG terminal combined with an Organic Rankine Cycle

The power plant of this system, named the ORC system, is equal to the power plant of the Waste heat system, but its waste heat is not used for LNG evaporation. Instead, the LNG cold (the work potential this LNG has because of its very low temperature of −162 °C) is used for electricity production through an Organic Rankine Cycle (ORC). Sea water of 10 °C acts as the 'high' temperature source and ethane is used as the working fluid of the ORC. The coal consumption for the production of 1 PJ of electricity is 0.10 Mton and 0.21 Mton of CO_2 is captured. The emissions to air are equal to 34 kton of CO_2, 48 ton of NO_x, 0.37 ton of SO_x, 0.89 Mton of N_2, 85 kton of O_2 and 48 kton of H_2O. The amounts of waste heat to a river and slags/ashes amount to 1.1 PJ and 12 kton, respectively.

The investment costs and yearly revenues of the system allocated to the production of 1 PJ of electricity are €94 million and €9.4 million per year, respectively.

4.2. Results of the assessments

Table 1 presents the results of the assessments of the three systems of the LNG case study. According to this table, the Oxyfuel system is the system that is preferred from the exergetic as well as the environmental, economic and social sustainability points of view, while the other systems are not profitable. This implies that it has no consequences when the TCExL method is used to choose between the three systems. The negative PWR scores of the Waste heat and ORC systems indicate that it is not profitable to invest in these systems, which is caused by too high investment costs compared to the revenues (and costs) during the lifetime of the systems. The results in Table 1 are the numbers based on a carbon dioxide emission price of €20/ton, which is consistent with the price before the financial crisis. Lowering the price to €5/ton results in PWR scores for the Waste heat, Oxyfuel and ORC systems of −0.47, 0.09 and −0.43, respectively. Increasing the price to €50/ton results in three positive PWR scores, i.e. 0.35, 1.04 and 0.42, respectively. Around €30/ton, the PWR scores of the Waste heat and ORC systems become positive numbers. Varying the carbon dioxide emission price does not change the ranking of the three systems. The negligible difference between the IHDI scores is caused by the fact that the three systems are located in the same place and use coal and LNG that originate from the same countries, but each use a different amount of coal.

From investigating the results of the LNG systems including the H-gas supply chain [3], it is learned that large differences exist between the four assessment methods when looking in more detail at the results. E.g., the ecoinvent process called production of natural gas is responsible for 70 per cent of the ReCiPe score of the Oxyfuel system, but causes only 0.23 per cent of its TCExL score.

5. Case study Fossil versus renewable energy sources for power generation

The case study presented here is an improved version of the case study presented earlier [1] in the sense that some adaptations have been made to the assessed systems, another economic indicator is used, the $IHDI_i$ of the countries have been updated and that the calculation of the internal exergy loss makes use of the CExD reported by SimaPro/ecoinvent instead of calculating it by hand based on limited models of the systems.

Table 1
Assessment results of the systems of the LNG case study.

	Waste heat	Oxyfuel	ORC
ReCiPe (MPt)	13	9.0	12
PWR (−)	−0.20	0.41	−0.15
$IHDI_{overall}$ (−)	0.633	0.636	0.634
TCExL (PJ)	4.9	3.6	4.6

5.1. Description of the systems

The assessment includes the extraction and/or growing, processing and transport of all inputs of the systems and the treatment of the wastes and emissions according to the processes modelled in SimaPro/ecoinvent. The construction, operation and decommissioning of the installations are considered as well.

The product of all systems, i.e. the functional unit, is the production of 1 PJ of electricity. The production of by-products, e.g. process heat (Co-firing system, Section 5.1.1) and grass fibres (Bioethanol system, Section 5.1.3), is taken into account via allocation of the inputs, emissions, etc. to the product and by-products on an exergy basis.

5.1.1. Co-firing of coal and wood pellets

The Co-firing system is modelled on the basis of the Amercentrale power plant in Geertruidenberg, Netherlands [28]. Allocated to the production of 1 PJ of electricity, this power plant co-fires 87 kton of coal and 37 kton of trees. The trees are processed into wood pellets in the Georgia Biomass plant [29] and then transported to the Netherlands. The resulting emissions to air of the power plant equal 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. 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 other case study. The man-hours needed for the processing of trees to wood pellets and subsequent deep sea transport have been calculated at 2×10^5 and 3×10^5 man-hours per Mton of wood pellets, respectively.

5.1.2. Wind farm

The Wind farm system is modelled on the basis of the wind farm that is under construction in the Noordoostpolder area in the Netherlands [30]. The wind farm has a capacity of about 5 PJ of electricity per year. The wind farm needs 2.4 PJ of wind energy to produce the 1 PJ of electricity of the functional unit. The investment costs and yearly revenues excluding subsidy of the system allocated to the production of 1 PJ of electricity are €198 million and €8.7 million per year, respectively. The subsidy to be received during the first 15 years of operation is calculated at €12 million per year. The man-hours needed for the construction, operation and decommissioning of the Wind farm system have not been calculated, as it is assumed that all employees originate from the Netherlands, resulting in an $IHDI_{overall}$ equal to the IHDI of the Netherlands.

5.1.3. Combustion of bioethanol from verge grass

The Bioethanol system is based on the research conducted by de Vries [31] and has a capacity of about 30 MW of electricity. Assuming that the system operates 8000 h per year, this results in a yearly capacity of 0.9 PJ and therefore the system has been scaled up to the 1 PJ of electricity per year of the functional unit, which is a more common number to be used in comparing systems. The Bioethanol system comprises the growing, mowing and transport of verge grass, its subsequent fermentation to

Table 2
Assessment results of the systems of the Fossil versus renewable case study.

	Co-firing	Wind farm	Bioethanol
ReCiPe (MPt)	19	0.54	8.0
PWR (−)	0.42	−0.12	1.2
$IHDI_{overall}$ (−)	0.64	0.86	0.86
TCExL (PJ)	8.7	2.1	9.5

bioethanol and combustion of the bioethanol in a combined-cycle power plant. The grass fibres and protein by-products resulting from the fermentation process are considered via allocation on an exergy basis, as explained in the introduction of Section 5.1. The investment costs of this system allocated to 1 PJ of electricity are €86 million and the yearly revenues amount to €21 million, assuming that €15 per ton of verge grass (40% dry matter) is received for its processing in the Bioethanol system. The man-hours needed for the construction, operation and decommissioning of the Bioethanol system have not been calculated as it is assumed that all employees originate from the Netherlands, like in the Wind farm system.

5.2. Results of the assessments

Table 2 presents the results of the assessments of the three systems of the Fossil versus renewable energy sources case study. The Wind farm system is the preferred system from the environmental and exergetic points of view, one of the preferred systems from a social point of view, but the least preferred system from the economic sustainability point of view. This implies that involving the TCExL method in choices between systems that use different sources of energy can have a negative influence on the economic sustainability of the subject of the case study. The negative PWR score of the Wind farm system indicates that it is not profitable to invest in this system, like it was the case with the Waste heat and ORC systems of the other case study. The results in Table 2 are the numbers based on a discount rate of 8 per cent. Lowering the discount rate to 6 per cent results in a slightly positive PWR score for the Wind farm, i.e. 0.029, and PWR scores of 0.72 and 1.6 for the Co-firing and Bioethanol systems, respectively. The $IHDI_{overall}$ scores of the Wind farm and Bioethanol systems are equal to the IHDI of the Netherlands as it was assumed that all employees originate from the Netherlands. The lower $IHDI_{overall}$ score of the Co-firing system is mainly the result of the coal supply chain. Like in the LNG case study, large differences exist when looking into more detail at the results of the assessments [3]. E.g., the processes that cause about 80 per cent of the ReCiPe scores of the systems are responsible for only 40, 7.5 and 43 per cent of the TCExL scores of the Co-firing, Wind farm and Bioethanol systems, respectively.

6. Discussion and conclusions

The systems of the case studies are intended to carefully represent the systems that are under construction and/or feasible in the Netherlands. However, the costs of back-up installations to deal with the discontinuity in the send-out of the LNG terminal (e.g. caused by varying consumer demand depending on the weather) and the discontinuity in electricity production by the Wind farm system caused by too low or too high wind speeds have not been taken into account.

The TCExL method is considered as an improvement compared to other exergy analysis methods found in literature because it includes all exergy losses caused by a technological system during its life cycle, i.e. internal exergy losses, abatement exergy losses and the exergy loss caused by land use, and is based on the calculation of exergy losses only. Requirements of the presented list of requirements to sustainability assessment methods that can only indirectly be met by the TCExL method are the depletion and scarcity of resources and the economic and social aspects of sustainability. The TCExL method could be improved by including more abatement exergy values of emissions. Advantages of the TCExL method compared to regular, i.e. non-exergetic, sustainability assessment methods are that the TCExL method does not make use of weighting factors, its results are independent of time and that it is based on quantitative data only. The TCExL method can be used for the assessment of all kinds of technological systems and can contribute to making these systems, e.g. power generation systems, more sustainable.

The applied non-exergetic assessment methods have been selected on the basis of a thorough literature research into sustainability assessment of technological systems. The results of these methods have not been compared with the results of alternative methods in their specific fields because the methods have been selected for their common use and/or usability in this research. Furthermore, the main research goal was to compare the results of the TCExL method with the results of the regular methods for assessing the environmental, economic and social sustainability of technological systems.

According to the results of the assessments, large differences exist between e.g. the environmental sustainability assessment and TCExL methods with regard to the parts of the systems that contribute most to the overall scores of the systems.

On the basis of the results of the LNG case study, it can be concluded that involving the TCExL method in choices between power generation systems that use the same energy source has no consequences, because the same system is preferred according to the results of the TCExL, environmental, economic and social sustainability assessment methods. In case different energy sources are used, like in the Fossil versus renewable case study, involving the TCExL method can lead to the choice of a system with a lower economic sustainability. However, it must be noted that the economic sustainability does not include all indirect costs and changes over time, while the TCExL method is based on fundamental thermodynamic equations.

References

[1] Stougie L, van der Kooi HJ, Stikkelman RM. 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. Perugia, Italy: Firenze University Press; 2012 June 26–29. p. 391–05.
[2] Stougie L, van der Kooi HJ. Sustainability assessment of power generation in combination with LNG evaporation: a comparison of lca methods and exergy analysis. In: Koroneos C, Rovas D, Dompros A, editors. ELCAS 2013: proceedings of the 3rd international exergy, life cycle assessment & sustainability workshop & symposium, Nisyros Island, Greece; 2013 July 7–9. p. 623–34.
[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] WCED, Our common future, report of the world commission on environment and development. New York: Oxford University Press; 1987.
[5] Finnveden G, Hauschild M, Ekvall T, Guinée J, Heijungs R, Hellweg S, et al. Recent developments in life cycle assessment. J Environ Manage 2009;91 (1):1–21.
[6] Stougie L, van der Kooi HJ. Exergy and sustainability. Int J Exergy 2012;11 (4):508–17.
[7] Stougie L, Dijkema GPJ, van der Kooi HJ, de Swaan Arons J. Entropy or exergy – a measure in environmental policy making? (in Dutch). Delft, Netherlands: Delft University of Technology, Interduct; 1994 [Technical report].
[8] 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, Turku, Finland; 2014, June 15–19, p. 307–18.
[9] Szargut J, Morris DR. Cumulative exergy losses associated with the production of lead metal. Int J Energy Res 1990;14:605–16.

[10] Szargut J, Morris DR, Steward FR. Exergy analysis of thermal, chemical and metallurgical processes. New York: Hemisphere Publ. Corp; 1988.
[11] Dewulf J, Van Langenhove H, Dirckx J. Exergy analysis in the assessment of the sustainability of waste gas treatment systems. Sci Total Environ 2001;273(1–3):41–52.
[12] Dewulf J, Bösch M, De Meester B, Van der Vorst G, Van Langenhove H, Hellweg S, et al. Cumulative exergy extraction from the natural environment (CEENE): a comprehensive life cycle impact assessment method for resource accounting. Environ Sci Technol 2007;41(24):8477–83.
[13] Cornelissen RL. Thermodynamics and sustainable development; the use of exergy analysis and the reduction of irreversibility [dissertation]. Enschede, Netherlands: Twente University; 1997.
[14] Pré Consultants, Amersfoort, Netherlands. SimaPro LCA software – Available at: <http://pre.nl/content/simapro-lca-software> [accessed 26.1.2011].
[15] Ecoinvent Centre (Swiss Centre for Life-Cycle Inventories) St-Gallen, Switzerland. Ecoinvent database – Available at: <http://www.ecoinvent.org> [accessed 26.1.2011].
[16] Bösch ME, Hellweg S, Huijbregts MAJ, Frischknecht R. Applying cumulative exergy demand (CExD) indicators to the ecoinvent database. Int J Life Cycle Assess 2007;12(3):181–90.
[17] Dewulf J, Van Langenhove H, Mulder J, van den Berg MMD, van der Kooi HJ, de Swaan Arons J. Illustrations towards quantifying the sustainability of technology. Green Chem 2000;2:108–14.
[18] Van der Vorst G, Dewulf J, Van Langenhove H. Developing sustainable technology: metrics from thermodynamics. In: Bakshi BR, Gutowski T, Sekulic D, editors. Thermodynamics and the destruction of resources. Cambridge: Cambridge University Press; 2011. p. 249–64.
[19] Haberl H, Erb KH, Krausmann F, Gaube V, Bondeau A, Plutzar C, et al. Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. Proc Natl Acad Sci 2007;104(31):12942–7.
[20] Alvarenga RA, Dewulf J, Van Langenhove H, Huijbregts MA. Exergy-based accounting for land as a natural resource in life cycle assessment. Int J Life Cycle Assess 2013;18(5):939–47.
[21] 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.
[22] Benoît C, Mazijn B. Guidelines for social life cycle assessment of products. Paris: UNEP/SETAC Life Cycle Initiative; 2009.
[23] Benoît C, Norris GA, Valdivia S, Ciroth A, Moberg A, Bos U, et al. The guidelines for social life cycle assessment of products: just in time! Int J Life Cycle Assess 2010;15:156–63.
[24] 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].
[25] 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, Novi Sad, Serbia. University of Niš; 2011 July 4–7. p. 3157–70.
[26] de Buck A, Croezen H, Rensma K. The 'oxy-fuel' route (in Dutch). Technical Report No.: 08.3509.09. Delft, Netherlands: CE Delft; 2008.
[27] Anonymous, The LNG/oxyfuel route for new coal plants – environmental benefits plus cost savings? Technical Report No.: 2MJAF0801. Utrecht, Netherlands: SenterNovem; 2008.
[28] Essent, Amercentrale (in Dutch). Leaflet No.: 10/05/5014. 's-Hertogenbosch, Netherlands: Essent; 2010.
[29] Georgia biomass, LLC. Website – Available at: <http://www.gabiomass.com> [accessed 21.9.2011].
[30] Koepel Windenergie Noordoostpolder. Website – Available at: <http://www.windkoepelnop.nl> [accessed 14.9.2011].
[31] de Vries SS. Thermodynamic and economic principles and the assessment of bioenergy [dissertation]. Delft, Netherlands: Delft University of Technology; 1999.