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

Lydia Stougie[a] and Hedzer van der Kooi[b]

[a] Delft University of Technology, Delft, Netherlands, l.stougie@tudelft.nl (CA),
[b] Delft University of Technology, Delft, Netherlands, jvdkooi@casema.nl

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 timeless results 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, but can lead to the choice of a system that has a lower economic sustainability if the 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.

Keywords:
Total Cumulative Exergy Loss, Environmental, Economic and Social Sustainability, Power Generation.

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 and that they do not consider exergy losses. Furthermore, the economic sustainability assessment methods do not include all indirect costs and lead to timeless results 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

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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 LNG evaporation and the second 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.

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. 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 [3]. 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 [4,5] and additional knowledge gathered from studying literature. Requirements that are commonly met by 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.

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 exergy loss caused by the extraction of resources, i.e., the scarcer a resource becomes, the more exergy will be lost during its extraction. 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. 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. [6]) to define the CExC 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, the exergy loss caused by processes for the abatement of the waste flows and emissions and the exergy loss accompanied with the land used by that system. The TCExL method can be regarded as a combination of, or extension to, the existing exergy analysis methods called Cumulative Exergy Consumption and Abatement (CExCA, [7]), Cumulative Exergy Extraction from the Natural Environment (CEENE, [8]) and Exergetic Life Cycle Assessment (ELCA, [9]).

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 [10] in combination with the ecoinvent database version 2.2 [11] is used to calculate the Cumulative Exergy Demand (CExD, [12]) of the system, i.e. the total input of exergy. Subtracting 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 [9,13,14]. The amounts of waste flows and emissions needed for calculating the abatement exergy loss are reported by SimaPro/ecoinvent.

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. This exergy loss is calculated in analogy with the method that is part of the CEENE method [8], i.e. from the average solar irradiation in Western Europe multiplied with the exergy/energy factor of sunlight of 0.9327 [15], the efficiency of photosynthesis and the amount of land used. According to [8], the efficiency of photosynthesis equals 2%, but on the basis of literature [16-18], an efficiency of 0.75% is used in this research instead. This results in an exergy loss of 256 GJ per hectare per year. 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 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. However, at the moment only abatement exergy values of a few emissions are taken into account because of the limited availability of abatement exergy values of emissions. Another point of attention is the use of an assumed, though realistic, efficiency of photosynthesis in calculating the exergy loss related to land use, but the influence of this efficiency on the TCExL score is relatively small.

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 the result of a thorough cooperation between experts in the field of LCA and a recent development in this field. The ReCiPe combines the CML 2002 and Eco-indicator 99 methods [19]. 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 in combination with the ecoinvent database version 2.2 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 was 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, electricity and carbon dioxide emissions equal 2.65 euro/GJ, 60 euro/MWh and 20 euro/ton, respectively. 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.

3.4. Social sustainability

A standard method for determining the social sustainability is still under development [20,21]. 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 [22] 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 [23] 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 these 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 (1).

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

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 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 [24]. The resulting CO_2 is captured via monoethanolamine absorption. The storage of CO_2 is not considered in this case study. 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 CO_2, NO_x, SO_x, N_2, O_2 and H_20 emissions to air equal 37 ton, 52 kg, 0.41 ton, 0.96 Mton, 93 kton and 52 kton, respectively. 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 euro and 9.0 million euro per year, respectively.

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 [24,25]. 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 has been considered via allocation on the basis of the exergy values of product and by-product. 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_20 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 euro and 12 million euro 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 '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 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 CO_2, NO_x, SO_x, N_2, O_2 and H_2O emissions are equal to 34 kton, 48 ton, 0.37 ton, 0.89 Mton, 85 kton and 48 kton, respectively. 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 euro and 9.4 million euro 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.

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

From investigating the results of the LNG systems including the H-gas supply chain, 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.

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 and grass fibres, 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, the Netherlands [26]. 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 [27] 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 euro and 8.0 million euro 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 $2*10^5$, $7*10^4$ and $2*10^4$ man-hours per Mton of coal, respectively. 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 [28,29]. 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 euro and 8.7 million euro per year, respectively. The subsidy to be received during the first 15 years of operation is calculated at 12 million euro 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 [30] and has a capacity of about 30 MW of electricity. The Bioethanol system comprises the growing, mowing and transport of verge grass, its subsequent fermentation to 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. The investment costs of this system allocated to 1 PJ of electricity are 86 million euro and the yearly revenues amount to 21 million euro, assuming that 15 euro 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, analogous to 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. Like in the LNG case study, large differences exist when looking into more detail at the results of the assessments. 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.

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	1.17
$IHDI_{overall}$ [-]	0.64	0.86	0.86
TCExL [PJ]	8.7	2.1	9.5

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 and the discontinuity in electricity production by the Wind farm system caused by too low or too high wind speeds have not been considered.

The TCExL method is considered as an improvement compared to other exergy analysis methods found in literature because it is based on the calculation of exergy losses only and because it includes all exergy losses caused by a technological system during its life cycle. 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 and by conducting more research into the exergy loss related to land use. 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 timeless and that it is based on quantitative data only. The TCExL method can be used for the assessment of all kinds 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 part of the systems that contribute most to the overall scores of the systems. 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.

On the basis of the results of both case studies, 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.

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