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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