

THE RELATION BETWEEN EXERGY AND SUSTAINABILITY ACCORDING TO LITERATURE

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Abstract

A thorough investigation of literature about the relation between exergy and sustainability was conducted in September 2010. An overview of opinions and methods in the field of exergy analysis and sustainability is briefly presented. Exergy analysis has several advantages compared to energy analysis, but a careful underpinning of the relation between exergy and sustainability has not yet been found. Sustainability consists of environmental, economic and social sustainability. Especially the social aspect of sustainability is not, or just minimally, taken into account in the methods found in literature. During future research, the consequences of involving exergy analysis in decisions regarding future energy supply will be investigated with respect to the three aforementioned aspects of sustainability.

Introduction

Many publications have been written about exergy analysis, sustainability and combinations thereof. As already stated in [1,2], there is a need for a careful underpinning of the relation between exergy and sustainability. Sustainability is usually described as consisting of three pillars: environmental, economic and social sustainability, see e.g. [3]. In 1994 it was concluded that exergy loss is at least a qualitative measure that can be used in environmental policy making regarding technological processes [4]. Exergy analysis makes visible where quality of energy is lost. This loss of energy quality cannot be made visible in energy analysis, while it is this energy quality that we need to carry out the things we want to do. By identifying the places where quality of energy is lost, exergy analysis clearly pinpoints where improvements should be made. Exergy analysis can also be used to determine the thermodynamic optimum of e.g. a process or a plant. Another advantage of exergy analysis is that in exergy analysis both mass and energy flows can be taken into account by means of their exergy values, thus without the need of classification factors. This publication is the result of a thorough investigation of what has been published about the relation between exergy and sustainability. It provides, in brief, an

overview of opinions and methods that the authors regard as the most relevant when looking for an underpinning of the relation between exergy and sustainability.

Research method

The search for scientific literature in the field of exergy and sustainability started with looking for publications with the word 'exerg*' as well as 'sustainab*' in the title, in which the asterisk sign '*' acts as a wildcard. Hereto the catalogue of Scopus [5] was explored with the query 'TITLE(exerg*) AND TITLE(sustainab*)'. In addition, in Scopus also the query 'TITLE(thermodynamic*) AND TITLE(sustainab*) AND TITLE-ABS-KEY(exerg*)' was carried out. Because Scopus does not cover all publication years of the two journals dedicated to exergy analysis, i.e. 'Exergy, an International Journal' which was published in 2001 and 2002, and its successor 'International Journal of Exergy' which has been published from 2004 onwards, also literature searches were conducted with the use of the search engines of Sciencedirect [6] and Inderscience [7] respectively. The queries carried out in the database of Sciencedirect were 'TITLE(exerg*) and TITLE(sustainab*)' as well as 'TITLE(thermodynamic*) and TITLE(sustainab*)'. The database of Inderscience was queried with 'article TITLE(exerg*) and article TITLE(sustainab*)' and with 'article TITLE(thermodynamic*) AND article TITLE(sustainab*) AND full record(exerg*)'.

In addition the database of Google Scholar [8] was searched for references with the following words in the title: 'exergy and sustainable', 'thermodynamics and sustainable', 'exergy and sustainability' or 'thermodynamics and sustainability'. Unfortunately it was not possible to use wildcards like '*' when searching the database of Google Scholar.

The literature search was carried out in September 2010 and resulted in 116 publications. The abstracts of these publications have been studied as far as they were freely accessible via the website of the library of the Delft University of Technology and/or the regular worldwide-web. Based upon the abstracts, a number of publications was selected for further reading, again as far as freely accessible. The knowledge gathered from studying these publications and related publications forms the basis of this publication.

Exergy efficiency should be improved

According to [9 p.49] "Exergy can be considered the confluence of energy, environment and sustainable development". The authors discuss the relationships between exergy and three forms of environmental impact: order destruction and chaos creation, resource degradation, and waste exergy emissions. They describe that all three forms of environmental impact decrease with increasing 'process exergy efficiency'. When the authors state that "Exergy methods can be used to improve sustainability" [9 p.49], they refer to the work of [10]. According to [10], exergy analysis is one of the keystones for obtaining sustainable development. The scope of this work is limited to sustainable development associated with production and it is stated that "for sustainable development the destruction of the exergy reservoirs of natural resources has to be minimized to a level at which there is no damage to the

environment and at which the supply of exergy to further generations is secured” [10 p.64]. In [10] sustainable development is limited to taking into account the depletion of natural resources and emissions to the environment and it is stated that there is no depletion of resources and no emission to the environment in a reversible process. At this point, it is disregarded that conserving exergy does not mean no depletion of resources, because in a reversible process a resource could be transformed into a product without exergy loss. A careful underpinning of the relation between exergy and sustainability is missed in [9,10]. Furthermore, the research mentioned above only takes into account the environmental aspect of sustainability.

Exergy analysis contributes to sustainability, but...

Thermodynamics, exergy analysis, can contribute to “the design of efficient and self-sustaining technological-ecological networks that operate within ecological constraints”, but it is concluded that “No single metric (regardless how well aggregated) or derivative criterion is able to offer a completely satisfactory solution for all situations” [11 p.6]. It has also been written that exergy analysis should be used in addition to other tools, like energy analysis and tools from economics and environmental sciences (e.g. cost-benefit analysis and environmental life cycle assessment respectively) [12]. According to [12 p.676] “The link between the efficiency of resource utilisation, pollutant emissions, and ‘exergy consumption’ is real, but not direct.” This is illustrated with the fact that there is no explicit difference between exergy originating from a fossil energy source and exergy originating from a renewable energy source. It is also being said that exergy evaluations are important but that “exergy evaluations are not enough to judge if a system is sustainable in all respects or not” because objections may be raised like “farmland is used for production of fuel instead of food in a world of poverty and starvation, which makes this into a moral issue” [13 p.228]. Based upon these opinions, it would be interesting to investigate in more detail what exergy analysis could contribute when striving for sustainability.

The role of ecosystem goods and services

In [14] it is pointed out that the ecosystem goods and services (in short: ecosystem services) form the basis of planetary activities and human well-being, and should be taken into account when is aimed at sustainable development. The ecosystem services can be divided into four categories [14]: provisioning services (“products directly obtained from ecosystems, such as food and genetic resources”), regulating services (“benefits obtained from the regulation of ecosystem processes, including control of climate and pollination”), supporting services (“those that are necessary for the production of all other ecosystem services, such as nutrient and water cycles”) and cultural services (“spiritual and recreational benefits people obtain from ecosystems, such as knowledge systems, social relations, and aesthetic values”). According to [14] provisional and regulating services are more or less accounted for by LCA, exergy and emergy analysis. The supporting and cultural services are ignored, except for LCA in which cultural services “may be considered via social LCA” [14 p.2234]. *Emergy analysis* “characterizes all products and services in equivalents of solar energy, that is, how much energy would be needed to do a particular task if solar

radiation were the only input” [15 p.216]. The method has encountered a lot of criticism which according to [15 p.218] mainly “seems to stem from the difficulty in obtaining details about the underlying computations, and a lack of formal links with related concepts in other disciplines”. Other methods that have been developed to take into account (some of the) ecosystem goods and services are the *Ecologically Based LCA method (Eco-LCA)* [16], *Ecological Cumulative Exergy Consumption (ECEC)* [17] and *Eco-exergy* [18]. The role of ecosystem goods and services is acknowledged, but an undisputed and commonly accepted method of analysis is preferred. Maybe this could be tackled by accounting for the surface of earth made unavailable to the biosphere.

Exergy analysis and Life Cycle Assessment

Supposing that exergy efficiency or the loss of exergy is a measure of sustainability, it should be realized that the (exergetic) efficiency usually varies along the production chain, i.e. a highly efficient final step in a production process can be preceded by highly inefficient intermediate process steps, and vice versa. It is therefore relevant to take into account the whole production chain [19], and, if applicable, also the use and disposal/recycling of the product.

According to [10 p.61], the method of calculating the *Cumulative Exergy Consumption* (CExC) as introduced by [19] is “the first step of analysing the life cycle on the basis of exergy”. The CExC expresses “the sum of the exergy of natural resources consumed in all the steps of a production process” [19 p.171]. In calculating the CExC index, the network of production processes is divided into four levels [19,20]. The first level to be analysed is the process under consideration, the so-called final process. At this level the immediate consumption of fuels, non-energetic raw materials, intermediate products as well as exergy consumption for transportation is taken into account. The same holds for the second level in which the intermediate products are produced and where also the extraction, transportation and storage of the fuels and non-energetic materials consumed in level one are taken into account. The third level produces the machines and installations needed in level one and takes into account the extraction, transportation and storage of fuels and non-energetic raw materials consumed in level two. Finally, in level four the production of machines and installations for level two and for extraction and transportation of fuels and raw materials is considered. It is stated that it is usually unnecessary to proceed beyond the second level because the first and second levels account for about ninety to ninety-five per cent of the CExC [19]. The CExC is equivalent to *Valero’s ‘exergy cost’ method* [21,22]. The concept of Exergetic Cost or Exergetic Expense of a physical flow of a system is defined as “the amount of exergy per unit time to produce this flow” [22 p.2].

The method called ‘*Cumulative Exergy Extraction from the Natural Environment*’ (CEENE) can be considered as an extension to calculating the CExC [23]. The CEENE method “quantifies the exergy ‘taken away’ from natural ecosystems” [23 p.8477] and covers the withdrawal of natural resources including land use. Land use has been taken into account to correct for the inconsistency between the assessment of direct and indirect exergy use, e.g. directly via solar cells and indirectly via biomass or fossil fuels. Another, but related, reason for taking into account land use was: land

used for industrial or other human activities is not available anymore for natural processes like growing trees or flowers. The CEENE method is compatible with existing databases for life cycle analysis, e.g. CEENE factors for the 184 reference flows of the Ecoinvent database [24] have been calculated [23].

The method of *Exergetic Life Cycle Analysis* (ELCA) can be considered as an extension to the regular Life Cycle Analyses [10]. During the impact assessment of an ELCA, the exergy values of the mass and energy flows and subsequently the exergy destruction is determined of the several process units. The irreversibility of the product is equal to the total exergy destruction in the life cycle [10]. Basically, only the internal exergy losses, i.e. the exergy losses caused by irreversibilities, are taken into account. But sometimes also the external exergy losses are considered, e.g. when it is sure that an emission or waste stream is useless and its exergy is lost outside the system boundaries [25]. An extension to the method of ELCA is called *Zero-exergy emission ELCA* (Zero-ELCA) which takes into account “all environmental problems associated with emissions by accounting for the abatement exergy of emissions” [10 p.68]. Originally, in ELCA no distinction was made between renewable and non-renewable resources. The ELCA method has been extended by diminishing the life cycle irreversibility with the exergy content of the renewable resources [26]. In this publication the exergy input of the sun is regarded as ‘free’ and this exergy or the irreversibilities caused by transforming solar exergy into renewable fuels is not taken into account.

The method of *Life Cycle Exergy Analysis* (LCEA) compares the so-called indirect exergy used for construction, maintenance and clean-up of the plant with the amount of exergy delivered during operation of the plant [27]. According to [13 p.226] “Sustainable engineering could be defined as systems which make use of renewable resources in such a way that the input of non-renewable resources will be paid back during its life time”. This is illustrated by stating that it is not obvious that the exergy being spent in the production of a solar panel will be paid back during its use [13].

The LCA methods described in this paragraph mainly focus on the use of feedstocks and resources. The impact caused by emissions plays a minor role, except for the Zero-ELCA method. Furthermore, the phases of use and disposal/recycling of a product should be taken into account when relevant, and attention should be paid to the economic and social aspects of sustainability.

Sustainability is broader than just the environmental aspect

Extended Exergy Accounting (EEA) integrates cumulative exergy consumption (CExC) and thermo-economic methods into an approach in which also labour and environmental impact are taken into account [28]. The extended exergy consists of the thermodynamic exergy and the equivalent exergy of capital, labour and environmental remediation activities [21]. Another application of exergy analysis is its use in allocating economic and/or environmental costs, e.g. by means of exergoeconomic and exergoenvironmental analyses. *Exergoeconomic analysis* can be used in making visible the origin of costs (capital costs and the costs of exergy losses) and in comparing these costs [29]. *Exergoenvironmental analysis* [30] is a modification of the concept of exergoeconomic analysis and is used to allocate the environmental

impact of a system, determined with the LCA methodology in combination with the Eco-indicator 99 method, to the system components (process units). Apart from the environmental impact determined with the LCA methodology, also the exergy destruction caused by the components is taken into account.

The method called *Environomics* [31,32] originates from classical thermoeconomics and is used to simultaneously take into account thermodynamic, economic and environmental aspects in the analysis and optimisation of energy systems. The environomic model consists of an objective function plus “a set of decision variables and equality and inequality constraints which describe the synthesis, design and operation of the system being modelled” [32 p.723]. According to [32 p.723] “Such a model, coupled with an optimization scheme, permits one to mathematically search for the optimal solution within the space of all possible solutions and responds in part to the concept of sustainability during the development of a new or the operation of an existing system”.

A multi-criteria approach in which four groups of sustainability indicators are designated, i.e. technical, environmental, economic and social indicators, is presented in [33]. Unfortunately, due to lack of sufficient social data, e.g. data regarding job creation, general welfare etc., the social indicators have not been included in the analysis. The group indicators are the result of normalization and subsequently averaging of the indicators within each group. The overall sustainability indicator is defined as the average of the group indicators. Also an iterative multi-criteria approach has been proposed that takes into account energetic, economic and environmental aspects in optimizing a plant or in choosing “the most sustainable energetic strategy in a given local context” [34 p.166], see also [35].

As described in this paragraph, several methods have been developed to take into account the environmental as well as the economic aspect of sustainability. The social aspect of sustainability is not, or just minimally, taken into account.

Sustainability indicators based on exergy

Several researchers have developed sustainability indicators in an attempt to quantify the sustainability of technological processes. E.g. in [36] three sustainability indicators are presented that have been developed based on exergy: a renewability parameter which is defined as “the fraction of renewable exergy consumption with respect to the total exergy consumption” [36 p.109], an environmental parameter related to the condition that “no harmful products are to be emitted by the technosphere” [36 p.110] and a production efficiency parameter to take into account the efficiency of the production process itself. Also other sustainability indicators have been developed, either elaborating on the work of others or newly developed, see for example [37-42]. The general problem with these sustainability indicators is that their definitions are not commonly accepted and that they don't take into account all three aspects of sustainability.

Discussion and conclusions

According to this literature investigation many researchers are active in the field of exergy and sustainability. Several methods and indicators to measure sustainability based upon exergy have been developed, but a careful underpinning of the relation between exergy and sustainability has not yet been found in literature. Also, the social aspect of sustainability is not, or just minimally, taken into account in these methods and indicators. From this literature investigation it was learnt that it is important to consider the whole life cycle of a process or product, and that the role of ecosystem goods and services should not be neglected. During future research, the consequences of involving exergy analysis in decisions regarding future energy supply will be investigated with respect to the environmental, economic and social aspects of sustainability.

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