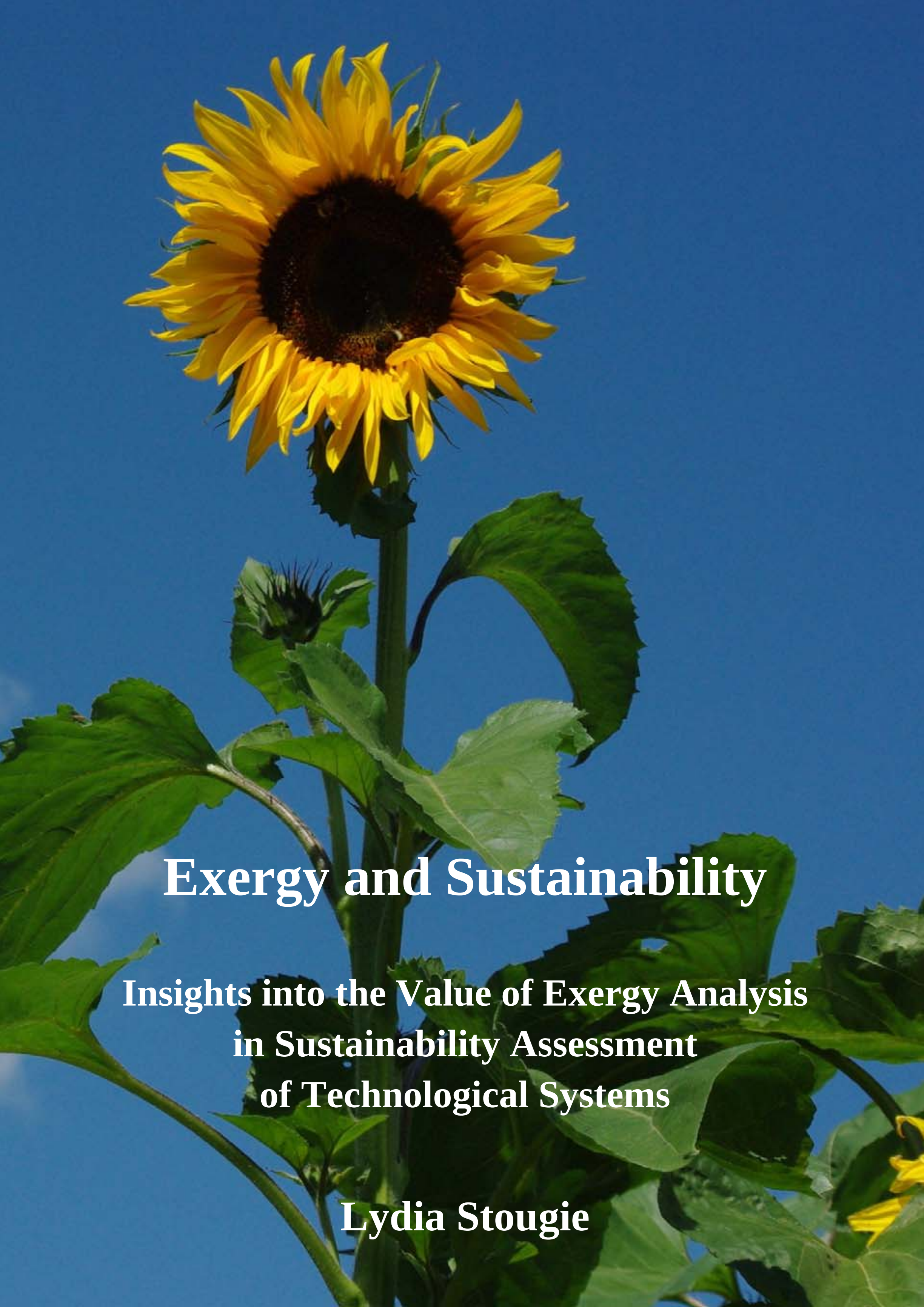

Exergy and Sustainability

Insights into the Value of Exergy Analysis in Sustainability Assessment of Technological Systems

Lydia Stougie

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PROEFSCHRIFT

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Lydia Stougie - September 2014

Summary

Exergy and sustainability - insights into the value of exergy analysis in sustainability assessment of technological systems

A major challenge in striving for a more sustainable society is the selection of technological systems. Given the capital intensity of industrial production plants, power generation systems and infrastructure, investment decisions create path dependencies for decades to come. It is difficult to know which technological system is preferable when considering the multiple objective of environmental, economic and social sustainability. E.g., a system that is preferred from the environmental point of view is not necessarily the system that is preferred from the economic and/or social point of view. Furthermore, the results of the assessments change over time because of new insights into environmental, economic and social sustainability and because they are prone to changing needs, economic conditions and societal preferences. Because of these uncertainties, it is hard to decide which technological system or systems should be chosen, e.g. to meet national and international targets with regard to climate change.

Another way of assessing technological systems is the use of exergy analysis, a thermodynamic assessment method. Exergy analysis makes visible where work potential is lost. This work potential is needed for all the things we would like to do, i.e. nothing happens without the consumption of some work potential. Work potential that is lost, is lost forever. The only way to replenish the amount of work potential available on earth is by capturing new work potential from solar and/or tidal energy. Researchers active in the field of exergy and sustainability claim that the loss of work potential, also known as exergy loss, and sustainability are related. However, the loss of work potential is no part of the regular sustainability assessment methods.

The objective of this research is to provide insight into the value of exergy analysis in sustainability assessment of technological systems. A literature research into the relationship between exergy and sustainability resulted in a theoretically founded relationship between exergy losses and the environmental impact of technological systems. A problem with investigating the relationship between exergy and sustainability is that there is no single measure of sustainability. Combining the results of the environmental, economic and social sustainability assessments into one sustainability indicator leads to a loss of information and necessitates the use of weighting factors. Another difficulty is that a commonly accepted operationalization of the term ‘sustainability’ does not exist. Accordingly, a list of requirements to methods for sustainability assessment of technological systems has been drawn up. All assessment methods cover the operational phase of installations, equipment and infrastructure including the amounts of inputs and outputs. Not all methods take into account the phases of construction and decommissioning of the installations, equipment and infrastructure and the following components of sustainability: the depletion and/or scarcity of the inputs, the distinction between renewable and nonrenewable inputs, the disposal and/or abatement of emissions and waste flows, land use, exergy losses, economic aspects and social aspects. In addition, methods for the calculation of sustainability indicators should be objective and sufficient data should be available to calculate these indicators.

The sustainability assessment methods found in the literature appear to be incomplete with respect to the list of requirements. The environmental life cycle assessment methods are not fully objective because they make use of weighting factors and because no consensus exists about all models used for quantifying environmental impact. The economic methods do not include all indirect costs and their indicators change over time because of market developments. The social methods suffer from the limited availability and qualitative or semi-quantitative nature of many data. The exergy analysis methods found in literature do not consider all components of sustainability and/or make use of indicators, equations and weighting factors that are not commonly accepted. It was therefore decided to develop a new exergy analysis method on the basis of fundamental scientific equations.

The newly developed exergy analysis method has been named the Total Cumulative Exergy Loss (TCExL) method and takes into account as many of the designated components of sustainability as possible. The TCExL is the summation of the exergy loss caused within the technological system including its supply chains, the exergy loss caused by abatement of the resulting emissions and the exergy loss related to the land occupied by the technological system including its supply chains. The latter is relevant because land use prevents capturing new exergy from sunlight by the ecosystem. Components of the list of requirements that can only indirectly be considered when calculating the exergy loss caused by a technological system are the depletion and scarcity of resources as well as the economic and social aspects of sustainability. The TCExL method is an improvement compared to existing exergy analysis methods in the sense that it is solely based on the calculation of exergy losses and that it takes into account all exergy losses caused by a technological system during its life cycle. However, until now the abatement exergy loss of only a few emissions is included because of the lack of data regarding other emissions.

The value of exergy analysis in sustainability assessment of technological systems has been investigated by conducting two case studies that comprise several power generation systems and subsequently comparing the results of the assessment methods with and without exergy of the systems of each case study. Power generation was chosen as the subject of the case studies because of the major role of electricity in our society. The choice of the systems of the case studies is not meant to indicate that these systems are preferable and/or desirable compared to other central or decentral power generation systems, nor that it is not important to look at the transport, distribution, use and/or storage of electricity.

The first case study consists of the following systems for coal-fired power generation in combination with LNG evaporation: a power plant of which the waste heat is used for LNG evaporation, an oxyfuel power plant that is combined with air separation and LNG evaporation, and a stand-alone power plant plus the combination of LNG evaporation with an Organic Rankine Cycle (ORC). The other case study concerns power generation from fossil and renewable sources and compares the co-firing of coal and wood pellets with a wind farm and with power generation from the combustion of bioethanol that originates from the fermentation of verge grass. The method applied for determining the environmental sustainability is the ISO-certified environmental Life Cycle Assessment (LCA) method with ReCiPe endpoint indicators as the result. The present worth ratio (PWR) has been calculated to determine the economic sustainability. A newly developed method based on man-hours and the Inequality-adjusted Human Development Index (IHDI) reported by the UNDP has been used to assess the social sustainability, because a standard method for social LCA is still under development and because it would be too time-consuming and costly to gather site-specific social data.

From the case studies, it is concluded that the sustainability of our society can be improved by applying exergy analysis in the assessment of technological systems, but that in the case of comparing technological systems with different inputs, a technological system that is preferred from an exergetic point of view is not always preferred from the economic and social points of view. If according to the results of the TCExL method a system is preferred that has a lower economic sustainability, it must be realised that economic indicators do not include all indirect costs and change over time. In the case of comparing technological systems with different inputs or with inputs from different locations, the calculation of a social sustainability indicator like the $\mathrm{IHDI}_{\mathrm{overall}}$ indicator introduced in this research can have an added value compared to calculating only the TCExL. From a sustainability point of view, it is important to use exergy wisely. The higher the amount of exergy that is available on earth, the better people will be able to meet their needs. Therefore, the TCExL can be used as a fundamental indicator in the operationalization of the definition of sustainable development by the Brundtland commission. It is also concluded that exergy analysis leads to more fundamental insights into which process or part of a system has the largest potential for improvement than the standard sustainability assessment methods.

It is recommended that exergy losses be taken into account when striving for a more sustainable society and that the TCExL method be used in decisions between technological systems. Furthermore, it is recommended that a working group be set up to investigate the possibilities for increasing the use of exergy analysis and that the TCExL method be implemented in software tools.

Samenvatting

Exergie en duurzaamheid - inzichten in de waarde van exergieanalyse bij de beoordeling van de duurzaamheid van technologische systemen

Een grote uitdaging bij het streven naar een duurzamere samenleving is de keuze van technologische systemen. Gegeven de kapitaalintensiviteit van industriële installaties, elektriciteitscentrales en infrastructuren, resulteren investeringsbeslissingen in padafhankelijkheden die tientallen jaren voortduren. Het is moeilijk te zeggen welk technologisch systeem de voorkeur heeft wanneer zowel naar het milieuaspect als naar de economische en sociale aspecten van duurzaamheid wordt gekeken. Een systeem dat bijvoorbeeld de voorkeur heeft vanuit milieuoogpunt, heeft niet noodzakelijkerwijs de voorkeur vanuit economisch en/of sociaal oogpunt. Ook veranderen de resultaten van duurzaamheidsbeoordelingen in de tijd vanwege nieuwe inzichten m.b.t. milieukundige, economische en sociale duurzaamheid en doordat ze gevoelig zijn voor veranderende behoeftes, economische omstandigheden en sociale voorkeuren. Door deze onzekerheden is het lastig om te beslissen welk technologisch systeem of systemen gekozen zou(den) moeten worden, bijvoorbeeld om te voldoen aan nationale en internationale klimaatdoelstellingen.

Exergieanalyse, een thermodynamische beoordelingsmethode, is een andere manier om technologische systemen te beoordelen. Exergieanalyse maakt zichtbaar waar arbeidspotentieel verloren gaat. Dit arbeidspotentieel is nodig voor alles wat we willen doen, met andere woorden: er gebeurt niets zonder dat er wat van dit arbeidspotentieel verbruikt wordt. Arbeidspotentieel dat verloren gaat, is voor altijd weg. De enige manier om de beschikbare hoeveelheid arbeidspotentieel op aarde aan te vullen, is het vastleggen van arbeidspotentieel afkomstig van zonne- en/of getijdenenergie. Onderzoekers actief op het gebied van exergie en duurzaamheid stellen dat het verlies aan arbeidspotentieel, ook wel bekend als exergieverlies, en duurzaamheid met elkaar verband houden. Echter, het bepalen van het verlies aan arbeidspotentieel is geen onderdeel van de reguliere methodes voor de beoordeling van duurzaamheid.

De doelstelling van dit onderzoek is inzicht geven in de waarde van exergieanalyse bij de beoordeling van de duurzaamheid van technologische systemen. Literatuuronderzoek naar het verband tussen exergie en duurzaamheid resulteerde in een

theoretisch onderbouwd verband tussen exergieverliezen en de milieu-impact van technologische systemen. Een probleem bij het onderzoeken van het verband tussen exergie en duurzaamheid is dat er geen enkelvoudige maat voor duurzaamheid bestaat. Het combineren van de resultaten van milieukundige, economische en sociale duurzaamheidsbeoordelingen in één duurzaamheidsindicator leidt tot informatieverlies en maakt het gebruik van weegfactoren noodzakelijk. Een andere moeilijkheid is dat een algemeen geaccepteerde operationalisering van de term ‘duurzaamheid’ niet bestaat. Er is daarom een lijst met eisen aan methodes voor duurzaamheidsbeoordeling opgesteld. Alle beoordelingsmethodes houden rekening met de operatiefase van installaties, apparatuur en infrastructuur, inclusief de hoeveelheden toegevoerde en afgevoerde stoffen (hierna genoemd inputs en outputs). Niet alle methodes houden rekening met de constructie en ontmanteling van de installaties, apparatuur en infrastructuur en met de volgende componenten van duurzaamheid: uitputting en schaarste van de inputs, het onderscheid tussen hernieuwbare en niet-hernieuwbare inputs, het verwijderen en/of onschadelijk maken van emissies en afvalstromen, landgebruik, exergieverliezen, economische en sociale aspecten. Daarnaast zouden methodes voor de berekening van duurzaamheidsindicatoren objectief moeten zijn en moeten voldoende gegevens beschikbaar zijn om deze indicatoren te berekenen.

De methodes voor duurzaamheidsbeoordeling die in de literatuur gevonden werden, blijken niet aan alle hiervoor genoemde eisen te voldoen. De milieukundige levenscyclusmethodes zijn niet volledig objectief doordat ze gebruik maken van weegfactoren en doordat er geen consensus bestaat over alle modellen die gebruikt worden voor het kwantificeren van milieu-impact. De economische methodes omvatten niet alle indirecte kosten en hun indicatoren veranderen in de tijd door marktontwikkelingen. De sociale methodes hebben te lijden onder de beperkte beschikbaarheid en de kwalitatieve of semi-kwantitatieve aard van veel gegevens. De in de literatuur gevonden methodes voor exergieanalyse houden geen rekening met alle duurzaamheidscomponenten en/of maken gebruik van indicatoren, vergelijkingen en weegfactoren die niet algemeen geaccepteerd zijn. Daarom werd besloten een nieuwe methode voor exergieanalyse te ontwikkelen op basis van fundamentele wetenschappelijke vergelijkingen.

Deze nieuw ontwikkelde exergieanalysemethode werd de Total Cumulative Exergy Loss (TCExL, ‘Totale Cumulatieve Exergieverlies-’) methode genoemd. De methode houdt rekening met zoveel mogelijk van de hiervoor genoemde duurzaamheidscomponenten. De TCExL-indicator is de sommatie van het exergieverlies veroorzaakt binnenin het technologische systeem inclusief toevoerketens, het exergieverlies veroorzaakt door het onschadelijk maken van de resulterende emissies en het exergieverlies gerelateerd aan het landgebruik door het technologische systeem inclusief toevoerketens. Het laatste is relevant aangezien dit landgebruik verhindert dat het ecosysteem nieuwe exergie vastlegt uit zonlicht. Uitputting en schaarste van inputs en de economische en sociale aspecten van duurzaamheid zijn componenten van de lijst die alleen indirect meegenomen kunnen worden bij het berekenen van het exergieverlies veroorzaakt door een technologisch systeem. De TCExL-methode is een verbetering ten opzichte van bestaande exergieanalysemethodes in de zin dat de methode alleen gebaseerd is op de berekening van exergieverliezen en rekening houdt met alle exergieverliezen die gedurende de levenscyclus van een technologisch systeem veroorzaakt worden. Echter, door het ontbreken van gegevens zijn tot nu toe alleen van een aantal emissies de exergieverliezen meegenomen die gepaard gaan met het onschadelijk maken van deze emissies.

De waarde van exergieanalyse bij de duurzaamheidsbeoordeling van technologische systemen is onderzocht aan de hand van twee casussen bestaande uit verschillende elektriciteitsproductiesystemen waarbij de resultaten van de beoordelingsmethodes met en zonder exergie met elkaar vergeleken zijn. Elektriciteitsproductie werd als onderwerp van de casussen gekozen vanwege de belangrijke rol van elektriciteit in onze maatschappij. De keuze voor de onderzochte systemen wil niet zeggen dat deze systemen de voorkeur hebben en/of wenselijk zijn vergeleken met ander (de)centrale systemen voor elektriciteitsproductie. Evenmin dat het niet belangrijk is om naar het transport, de distributie, het gebruik en/of de opslag van elektriciteit te kijken.

De eerste casus bestaat uit een drietal systemen voor kolengestookte elektriciteitsproductie in combinatie met de verdamping van LNG: een elektriciteitscentrale waarvan de restwarmte wordt gebruikt voor verdamping van LNG, een oxyfuel elektriciteitscentrale geïntegreerd met luchtscheiding en LNG-verdamping, en een aparte elektriciteitscentrale met daarnaast LNG-verdamping gecombineerd met een Organic Rankine Cycle (ORC). De andere casus betreft elektriciteitsproductie uit fossiele en hernieuwbare bronnen en vergelijkt het gecombineerd verbranden van steenkool en houtpellets met een windmolenpark en met elektriciteitsproductie op basis van bioethanol afkomstig van de fermentatie van bermgras. De methode gebruikt voor het bepalen van de milieukundige duurzaamheid is de ISO-gecertificeerde milieukundige levenscyclusanalyse- (LCA-)methode met ReCiPe eindpuntindicatoren als resultaat. De Present Worth Ratio (PWR, ‘contante waardeverhouding’) werd berekend om de economische duurzaamheid te bepalen. Een nieuw ontwikkelde methode gebaseerd op mensuren en de door de VN gepubliceerde index van menselijke ontwikkeling die rekening houdt met ongelijkheden binnen landen (Inequality-adjusted Human Development Index, IHDI) is gebruikt om de sociale duurzaamheid te bepalen aangezien de standaardmethode voor sociale LCA nog in ontwikkeling is en omdat het te tijdrovend en kostbaar zou zijn om locatiespecifieke gegevens te verzamelen.

Op basis van de casussen wordt geconcludeerd dat de duurzaamheid van onze maatschappij verbeterd kan worden door exergieanalyse toe te passen bij de beoordeling van technologische systemen, maar dat een technologisch systeem dat de voorkeur heeft vanuit exergetisch oogpunt niet altijd de voorkeur heeft vanuit de economische en sociale oogpunten wanneer de vergeleken technologische systemen verschillende inputs hebben. Wanneer volgens de resultaten van de TCExL-methode een systeem met een lagere economische duurzaamheid de voorkeur heeft, moet gerealiseerd worden dat economische indicatoren niet alle indirecte kosten meenemen en veranderen in de tijd. Bij het vergelijken van technologische systemen met verschillende inputs of met inputs vanuit verschillende locaties kan de berekening van een sociale duurzaamheidsindicator zoals de in dit onderzoek geïntroduceerde $\mathrm{IHDI}_{\mathrm{overall}}$ indicator een toegevoegde waarde hebben ten opzichte van het alleen berekenen van de TCExL-indicator. Vanuit het oogpunt van duurzaamheid is het belangrijk om exergie verstandig te gebruiken. Hoe groter de hoeveelheid exergie die op aarde beschikbaar is, hoe beter mensen in staat zullen zijn om in hun behoeften te voorzien. De TCExL-indicator kan daardoor gebruikt worden als een fundamentele indicator bij de operationalisering van de Brundtland-definitie van duurzaamheid. Er wordt eveneens geconcludeerd dat exergieanalyse leidt tot fundamentelere inzichten in welk proces of deel van een systeem het grootste verbeteringspotentieel heeft dan de standaardmethodes voor duurzaamheidsbeoordeling.

Het wordt aanbevolen om rekening te houden met exergieverliezen bij het streven naar een duurzamere samenleving en om de TCExL-methode te gebruiken bij keuzes tussen technologische systemen. Bovendien wordt aanbevolen om een werkgroep op te richten die de mogelijkheden onderzoekt om het gebruik van exergieanalyse te bevorderen en om de TCExL-methode te implementeren in softwarepakketten.

Contents

Appendices

Chapter 1

Introduction

Every process or system, whether it is a technological system for power generation, a chemical plant or another type of process or system, is accompanied with the loss of work potential. It is this work potential that we need to do the things we would like to do. Work potential is also known as ‘energy quality’ or ‘exergy’. Exergy analysis is a thermodynamic assessment method that enables us to quantify the loss of work potential in each part of the process or system.

Section 1.1 introduces the work potential of materials and energy, and explains why a focus on work potential is more effective in achieving a more sustainable society than a focus restricted to materials and energy. The objective of the research and the related research questions are described in Section 1.2. This is followed by the demarcation of the research in Section 1.3. The chapter concludes with the research approach and the outline of the thesis in the Sections 1.4 and 1.5, respectively.

1.1 Background and motivation

Many people are concerned about the future of our planet and our society. The rapid consumption of fossil fuels leads to emissions that appear to contribute to enhanced global warming and an increase in frequency of natural disasters like heavy rainfalls and times of drought. It also leads to a serious diminishing of the amounts of relatively easy to obtain fossil fuels on earth, and eventually a shortage of these fossil fuels. The same holds for the availability of metals used in e.g. consumer electronics. The increasing awareness of planetary boundaries and the limited availability of material and energy resources contribute to an increased interest in making our society more sustainable.

According to the well-known statement of the WCED (1987, p.43), sustainable development is development that ‘meets the needs of the present without compromising the ability of future generations to meet their own needs’. But, how to do that? How can we make our society more sustainable? Which choices should be made? Which developments or technologies should be stimulated or discouraged? A system that seems to be very advantageous now may later on appear to cause unforeseen negative side-effects somewhere else in the supply chain, in connected supply chains, on another time-scale, or a combination of these.

Furthermore, sustainability is broader than just the environmental aspect. The economic feasibility and the economic aspect of sustainability cannot be neglected. The same holds for its social component. The environmental, the economic and the societal aspects of sustainability are known as the three 'pillars' of sustainability (Teles dos Santos and Park, 2009).

Energy saving is considered one of the measures that could, and should, be taken in achieving a more sustainable society. Of course, energy saving means a lower demand for energy sources, like fossil fuels, and a lower demand for alternative technologies like solar cells, wind turbines and so on. But it is not only the amount of energy that counts. What really counts is the work potential of the energy or, in other words, the potential this energy has to do the things we would like to do.

What is meant by the work potential of energy can be illustrated as follows and is explained in more detail in Section 2.1. Thousand joules of electricity can be used for driving an electric motor, a mobile phone, a personal computer, an electric heater and many more. The same amount, thousand joules, of warm water at a temperature of 50 ℃ has far less applications and could be used for e.g. heating a room or for taking a bath. Appendix A explains that 1,000 joules of warm water at 50 ℃ equal the work potential of 77 joules of electricity, assuming that the temperature of the environment is 25 ℃.

Not only energy sources and energy carriers have a work potential, but also material flows and goods like raw materials, chemical products and furniture. We can use this work potential efficiently or we can waste it. Every human process or activity is accompanied with this loss of work potential. The loss of work potential due to our activities can be calculated, for example the loss of work potential caused by generating power, transport of fuels, the manufacturing of solar cells, cooking meals and watching television. Work potential that has been lost is lost forever. The only way to replenish the amount of work potential available on earth is by capturing new work potential from solar and/or tidal energy. A loss of work potential cannot be made visible by conducting an energy analysis.

Knowing that it is the work potential that we need to carry out the things we would like to do and knowing that every activity causes a loss of work potential, it seems at least reasonable to take into account this work potential when striving for a more sustainable society. Possibly, this can help in making the right choices regarding future energy supply systems, in policy making and in meeting the international agreements regarding emission targets, energy saving and the share of sustainable energy.

Other names of work potential are 'quality of energy' and 'exergy'. According to the literature, exergy and sustainability are related, but literature research has not resulted in a quantitative underpinning of this relationship. Neither has an exergy analysis method been found in literature that fully takes into account all three pillars of sustainability. Besides the societal relevance of investigating the relationship between exergy and sustainability, it is therefore also scientifically relevant to investigate whether and how taking into account exergy can contribute to making our society more sustainable when the environmental, economic and social aspects of sustainability are considered. The research described in this thesis belongs to the research areas of sustainability assessment as well as exergy analysis.

Exergy is defined as the maximum amount of work that can be obtained when a substance, mass flow or other amount of energy is brought into total equilibrium with the reference environment. Section 2.1 explains exergy and exergy analysis in more detail.

1.2 Objective and research questions

On the basis of the aforementioned, the objective of this research is formulated as follows:

To provide insight into the value of exergy analysis in sustainability assessment of technological systems.

The research objective will be pursued by a combination of literature research and case study research, which leads to the following main research questions:

1. What is known about the relationship between exergy and sustainability?
2. What requirements do methods for the assessment of the sustainability of technological systems have to meet?
3. Which methods, with and without exergy, are suitable for the assessment of the sustainability of technological systems?
4. Which method can be used to compare the results obtained from applying the selected methods, with and without exergy, in case studies?
5. What is learned from the case studies about the value of exergy analysis in sustainability assessment of technological systems?

1.3 Demarcation

The value of exergy analysis in sustainability assessment of technological systems is investigated by a combination of literature research and conducting case studies. Power generation is chosen as the subject of the case studies because of the major role of electricity in our society, i.e. the number of electrical appliances and services that depend on electricity is growing and a failure somewhere in the electricity grid can cause a disruption of our modern society. It was decided to focus on central, i.e. large-scale, power generation systems because of their long life-time, high investment costs and large impact. The choice of central power generation systems as subject of the case studies is not meant to indicate that central power generation systems are preferable and/or desirable compared to decentral ways of power generation.

The technological systems are considered from a life cycle point of view and therefore the construction, operation and decommissioning of the installations, its supply chains etc. are taken into account. The transport, distribution, use and storage of the produced electricity are not considered because these would be the same for all case study systems (as the power generation takes place in the Netherlands). As a result, it is not possible to draw conclusions about the sustainability of power generation in relation to the sustainability of the transport, distribution, use and storage of electricity.

Furthermore, the research is limited to the sustainability of the technological systems as such and therefore does not include sustainability management. In view of the wish to advise Dutch policy makers, it was decided to limit the case studies to power generation systems that could be applied in the Netherlands, i.e. no large-scale hydropower installations or the like.

1.4 Research approach

The research consists of three phases, as depicted in Figure 1.1. During the first phase, called *Exploration*, literature research is combined with knowledge gathered from research in the field of exergy analysis and environmental sustainability to answer the first research question ‘What is known about the relationship between exergy and sustainability?’. The exploration is also used to get an overview of exergy analysis methods related to sustainability assessment and to get insight into which regular, i.e. non-exergetic, methods are applied and/or recommended for sustainability assessment. Furthermore, the exploration is used for drawing up a list of requirements that sustainability assessment methods have to meet in order to answer the second research question ‘What requirements do methods for the assessment of the sustainability of technological systems have to meet?’.

The second phase, called *Methods selection*, considers the choice of the methods that will be used to assess the sustainability of the technological systems of this research, which is the answer to the third research question ‘Which methods, with and without exergy, are suitable for the assessment of the sustainability of technological systems?’. This third research question is answered by assessing the exergy analysis and non-exergetic sustainability assessment methods in view of the list of requirements resulting from the answer to the second research question and by using knowledge gathered from research in the field of exergy analysis and environmental sustainability. The information obtained during the exploration phase is used to answer the fourth research question as well, namely ‘Which method can be used to compare the results obtained from applying the selected methods, with and without exergy, in case studies?’. This method is called the method of comparison.

Case study research is the subject of the third phase of the research. The technological systems of the case studies are chosen on the basis of information about power generation systems in the Netherlands in combination with the requirements posed by the method of comparison. After that, the technological systems of the case studies are assessed by applying the selected exergy analysis and regular sustainability assessment methods. Finally, the assessment results and the method of comparison are used to answer the fifth research question ‘What is learned from the case studies about the value of exergy analysis in sustainability assessment of technological systems?’ and to draw conclusions.

1.5 Thesis outline

The exploration phase of this research is described in Chapters 2 to 4. Chapter 2 introduces the concept of exergy and elaborates on its use. Chapter 3 provides an overview of exergy analysis methods in the field of sustainability and the answer to the first research question *‘What is known about the relationship between exergy and sustainability’*. The fourth chapter goes into detail about the operationalization of sustainability and standard sustainability assessment methods. This chapter answers the second research question *‘What requirements do methods for the assessment of the sustainability of technological systems have to meet?’* and concludes with an investigation of the suitability of the standard sustainability assessment methods and the exergy analysis methods of the previous chapter.

Methods selection is the subject of Chapter 5. The third research question *‘Which methods, with and without exergy, are suitable for the assessment of the sustainability of technological systems?’* is answered and the newly developed exergy analysis method as well as the environmental, economic and social sustainability assessment methods that are applied in this research are presented. The chapter concludes with the answer to the fourth research question *‘Which method can be used to compare the results obtained from applying the selected methods, with and without exergy, in case studies?’*.

Chapters 6 to 8 deal with the research phase called case study research. They subsequently introduce and describe the case studies ‘Power generation in combination with LNG evaporation’ and ‘Fossil versus renewable energy sources for power generation’.

Chapter 9 provides an overview of the answers to research questions one to four and answers the fifth research question *‘What is learned from the case studies about the value of exergy analysis in sustainability assessment of technological systems?’*. This is followed by discussion and conclusions in Chapter 10 and recommendations in Chapter 11.

Detailed information about the calculation of exergy values of mass and energy flows can be found in Appendix A. Appendix B describes the literature research into exergy and sustainability and Appendix C provides brief descriptions of the exergy analysis methods found during the literature research. Appendices D and E give detailed information about the case studies ‘Power generation in combination with LNG evaporation’ and ‘Fossil versus renewable energy sources for power generation’, respectively.

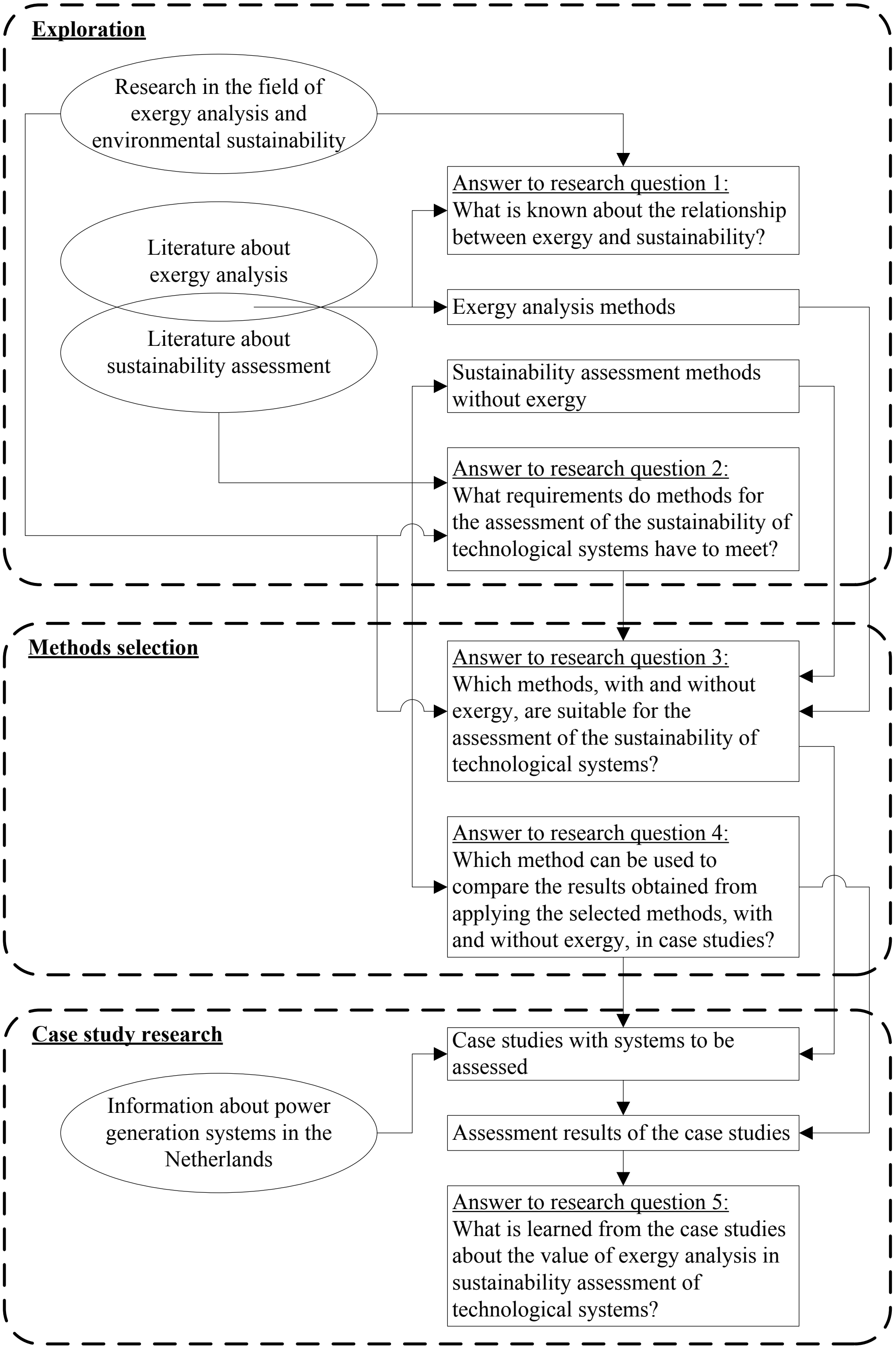

Figure 1.1: Research approach.

Chapter 2

The use of exergy analysis

My first introduction to the concept of exergy was around 1990 when professor De Swaan Arons of the Delft University of Technology showed us, Chemical Engineering students, the citation 'All joules are equal but some joules are more equal than others.' by Sussmann (1985) and explained the concept of exergy. A few years later this resulted in my graduation thesis 'Exergy analysis for the comparison of processes - Case study Methanol' (Stougie, 1992). It was followed by several other projects in the field of exergy and the research project called 'Entropy or exergy - a measure in environmental policy making?' (Stougie et al., 1994) which is considered as the seed of this research.

This chapter starts with a brief introduction to exergy analysis for those who are new to or not very familiar with the concept of exergy (Section 2.1). To illustrate the differences between energy and exergy analysis, both methods are used to compare two methanol production processes in Section 2.2. Which is followed by an overview of applications of exergy analysis in Section 2.3 and a more detailed discussion about exergy analysis and policy making in Section 2.4. The chapter ends with concluding remarks about the use of exergy analysis in Section 2.5.

2.1 What is exergy analysis?

This section explains the differences between energy and exergy, the numerical and graphical presentation of exergy analysis results and gives an overview of application fields of exergy analysis. More detailed information about exergy analysis and the calculation of exergy values of various flows can be found in Appendix A.

2.1.1 Energy and eXergy

Energy analysis does not distinguish between types of energy. One joule of electricity has the same value as one joule of heat, and one joule of heat at 1000 ℃ has the same value as one joule of heat at 10 ℃. In accordance with the first law of thermodynamics (energy can never be destroyed or created, it only changes forms), the total amount of ingoing energy of a steady-state open system always equals the total amount of outgoing energy of that system. Energy analysis cannot visualise the loss of energy quality caused by any process or system, while it is this energy quality that we need to carry out the things we would like to do. The loss of energy quality can be visualised by conducting an exergy analysis. Exergy analysis has several advantages compared to energy analysis, as described by Lems et al. (2004); Dincer (2002b); Dincer and Rosen (2005); Dewulf et al. (2008); Kanoglu et al. (2009); Kaygusuz and Bilgen (2009) and many others. One of the advantages 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 or weighting factors. By identifying the locations where quality of energy is lost, exergy analysis clearly pinpoints where the largest potential for improvement is. Exergy analysis can also be used to determine the thermodynamic optimum of for example a process or a plant, as explained in Section 2.2.

The loss of energy quality, exergy loss, can be divided into two components: internal exergy loss and external exergy loss. The summation of the internal and external exergy losses is called the total exergy loss.

Internal exergy loss
The internal exergy loss, also called exergy destruction (Tsatsaronis, 2008), is caused by irreversibilities of the process under consideration. All processes in the real world are irreversible and are thus accompanied with internal exergy losses. A process is reversible 'when its direction can be reversed at any point by an infinitesimal change in external conditions' (Smith and Van Ness, 1987, p.39). Reversible processes, also called 'ideal' processes, do not exist in real life; they can only be imagined. In real life, the total amount of exergy of the outgoing flows is always lower than the total amount of exergy of the ingoing flows of a process (or system). The difference between these amounts is called the internal exergy loss and is visualised in Figure 2.1. This internal loss of exergy cannot be observed with an energy analysis because of the first law of thermodynamics.

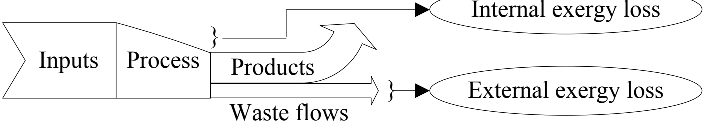

Figure 2.1: Visualisation of internal and external exergy losses.

As explained before, internal exergy loss is exergy that is lost due to the irreversibility of processes in real life. These processes are irreversible because of a driving force that gets the process going in a finite time. For example, the process of heat transfer is caused by a difference in temperature as the driving force, a chemical reaction takes place because of the chemical potentials and amounts of the reactants and products, etc. The larger the driving force, the larger the irreversibility and the larger the amount of exergy that is lost. The exergy loss is proportional to the total increase of entropy caused by that process or system (Equation 2.1).

$$Ex_{\text{loss}} = T_0 \Delta S_{\text{total}} \tag{2.1}$$

with:
Ex_{loss} = loss of energy quality
T_0 = temperature of the reference environment
ΔS_{total} = total entropy change

In contrast with technological processes, biological processes are known for their high efficiency as a result of many small and coupled transformations. E.g., in his thesis named ‘Thermodynamic explorations into sustainable energy conversion: Learning from living systems’, Lems (2009) shows that the exergy efficiency of the production of hydrogen from carbon fuels via industrial steam reforming equals 60 to 65 per cent and that living cells achieve an exergy efficiency of 89 to 92 per cent.

External exergy loss
The external exergy loss is equal to the amounts of exergy represented by waste flows, i.e. flows that are considered to be useless and that are ‘thrown away’ into the environment (Figure 2.1). These waste flows are the same as the flows that are considered to be useless when performing an energy analysis. The only difference is that exergy analysis considers the exergy amounts of these flows where energy analysis considers the energy amounts of these flows. The calculation of the exergy values of various flows is explained in Appendix A.

Decreasing exergy losses
The exergy losses caused by a process or activity are influenced by the choice of its inputs (which feedstocks, energy carriers) and the type of process (which technology) itself. E.g., the use of natural gas (about 100% energy quality) for the production of heat at a temperature of 60 ℃ (low energy quality) by central heaters applied in dwellings causes large exergy losses. An example of the influence of the type of process is the generation of power from fuels like hard coal and natural gas via the intermediate production of heat. These fuels as well as the produced electricity have an energy quality of about 100%, but the intermediate heat has a considerably lower energy quality. The formation of an intermediate product with a lower energy quality than the final product implies that a larger amount of input and/or another input of exergy is needed to produce the desired amount of product. Figure 2.2 shows the change in energy quality of the inputs, intermediates and products during some processes for power generation and heat production. The larger the decrease in energy quality between input and output or between input and intermediate, the larger the exergy loss. The use of renewable energy sources like the sun for the production of a product with a low energy quality, like hot tap water, is not by definition sustainable, especially if the construction of the installations needed for capturing sunlight is taken into account.

According to Szargut (2005), exergy losses can be decreased by e.g. minimizing the mixing of streams that differ in temperature, pressure or chemical composition, not using excessively large or small driving forces, applying counter-current instead of co-current processes, locating compressors in a cool place and applying co-generation processes like the production of electricity and steam or the simultaneous production of chemicals and electricity.

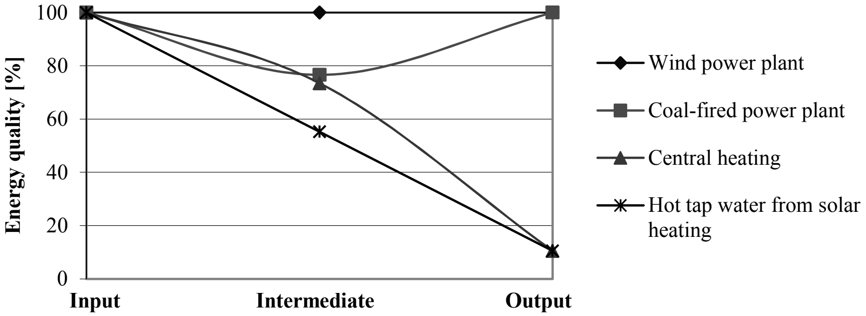

Figure 2.2: Decrease of energy quality from inputs to intermediates and outputs during power generation and heat production.

The results of exergy analyses can be presented in several ways, which is the subject of Section 2.1.2.

2.1.2 Presentation of results

The results of exergy analyses can be visualised in diagrams or presented as numbers.

Graphical presentation
Examples of the graphical presentation of the results are the visualization of the ingoing and outgoing exergy flows of a process in a Grassmann diagram and the visualisation of exergy losses in a value diagram. The Grassmann diagram (Figure 2.3), is the exergetic variant of the Sankey diagram known from energy analyses.

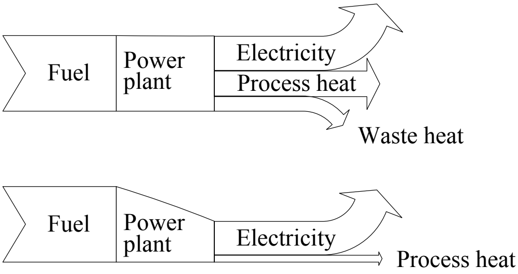

Figure 2.3: Sankey (top) and Grassmann (bottom) diagrams of an imaginary combined heat and power plant.

Value diagrams are developed for the thermodynamic evaluation of heat transfer processes, but can be used for the evaluation of thermal power plants as well (Woudstra, 2002, 2012). They show the (1-T_0/T) value of the heated and cooled flows versus the amount of heat that is transferred. The value diagram of three heat exchangers (named evaporator, superheater and economiser) is shown in Figure 2.4. The total area below the upper curve equals the exergy content of the heat that is transferred to the heat exchangers. The non-shaded areas represent, from left to right, the exergy content of the heat that is absorbed by the evaporator, superheater and economiser, respectively. The shaded areas are equal to the exergy losses caused by the heat transfer in the evaporator, superheater and economiser, respectively.

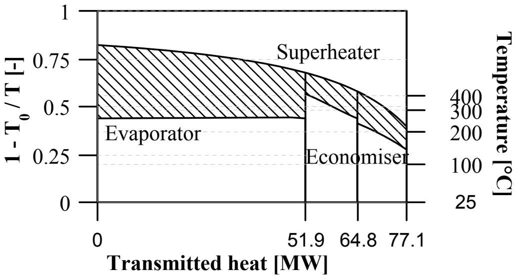

Figure 2.4: Value diagram of three heat exchangers.

Numerical presentation

Examples of the numerical presentation of the results are the universal exergy efficiency, the functional exergy efficiency and the amount of exergy loss per amount of product. The universal exergy efficiency (Equation 2.2) is relatively easy to calculate but has the disadvantage that it strongly depends on the total amounts of exergy input and output of the process under consideration. e.g. when one unit out of hundred units of input is lost, the efficiency is 99 per cent, while the same loss results in an efficiency of 80 per cent when one unit out of five units is lost.

$$\eta_{\mathrm{Ex,univ}} = \frac{\sum Ex_{\mathrm{out}}}{\sum Ex_{\mathrm{in}}} \tag{2.2}$$

The problem of the sensitivity of efficiencies to the absolute value of the inputs and outputs has to a large extent been solved by the introduction of efficiencies that are called functional efficiencies (Woudstra, 1995; Hepbasli, 2008). The functional exergy efficiency does not necessarily consider all inputs and outputs but looks at the inputs and outputs that are relevant to the considered process or apparatus. The functional efficiency is defined as the total amount of exergy of the products divided by the total amount of exergy of the sources, i.e. the input flows that are essential to producing the product, as depicted in Equation 2.3.

$$\eta_{\mathrm{Ex,func}} = \frac{\sum Ex_{\mathrm{product}}}{\sum Ex_{\mathrm{source}}} \tag{2.3}$$

The disadvantage of applying a functional exergy efficiency is that its definition depends on the process or apparatus under consideration. This means that it has always to be determined which output flows are product flows and which input flows are essential to produce the product. Woudstra (1995, 2012) provides definitions of functional exergy efficiencies of a number of processes and apparatuses.

An alternative to determining exergy efficiencies is the calculation of exergy losses. The determination of the amount of exergy loss per amount of product, e.g. per unit of mass, has the advantage that it is unambiguous and that not always the amounts of exergy entering and leaving the process or system need to be calculated, as explained in Appendix A. Nevertheless, exergy losses are usually calculated from the amounts of exergy entering and leaving the process or system.

The differences between energy and exergy analysis are illustrated by analysing two methanol production processes in Section 2.2.

2.2 Illustration of the differences between energy and exergy by comparing two methanol production processes

To illustrate the differences between energy and exergy analysis, this section deals with the comparison of two methanol production processes and the comparison of these processes with a thermodynamically optimal methanol production process. The two methanol production processes that are compared are the ICI low pressure methanol process and the newer Leading Concept Methanol process, which has been developed by ICI as well. The research presented in this section originates from Stougie (1992).

2.2.1 Brief description of the processes

The ICI low pressure methanol (ICI LP) process was developed by ICI in 1966 to replace the older high pressure methanol process (Stougie, 1992). The ICI LP process consists of the following five parts: production of synthesis gas, compression, methanol synthesis, expansion and purification. The synthesis gas, a mixture of CO, CO_2 and H_2, is produced at 20 bar and 880 ℃ by steam reforming of natural gas in tubes filled with a Ni/Al_2O_3 catalyst. This steam reforming is an endothermic process of which the required heat is supplied by the burning of extra natural gas in a furnace that contains the aforementioned tubes. After removing the produced water by condensation, the synthesis gas is compressed and fed to the methanol synthesis loop. The steam reforming of natural gas results in a make-gas with an excess of hydrogen for the production of methanol, which can be solved by adding externally supplied carbon dioxide before it enters the methanol synthesis loop. The reactions take place at 50 to 100 bar and 200 to 300 ℃ with $Cu/ZnO/Al_2O_3$ as the catalyst. The crude methanol is separated from the unconverted synthesis gas by condensation and then expanded and sent to the purification section.

The make-gas of the Leading Concept Methanol (LCM) process is produced from methane feed mixed with a purge from the methanol synthesis loop. This is done by primary steam reforming followed by partial oxidation with pure oxygen and secondary reforming. The endothermic primary steam reforming reactions take place in a Gas Heated Reformer (GHR) that is heated by the hot secondary reformed synthesis gases. The overall reforming process is autothermal. Another advantage of the GHR is that the pressure in this reactor can be as high as the pressure in the methanol synthesis reactor, which makes the make-gas compressor applied in the ICI LP process superfluous. The methanol synthesis loop and purification section of the LCM process are equal to those of the ICI LP process.

The data used to model the ICI LP and LCM methanol production processes mainly originate from Van Bergen and Moscou (1985); Avontuur and Goossens (1991), respectively. These data have been completed with data from Wesselingh et al. (1987); Anonymous (1992) and calculations with the help of the software tool Chemcad (Stougie, 1992).

As stated before, exergy analysis can be used to calculate the potential for improvement of a process. For example by assuming that methanol production is tied to the occurring reactions at their specific conditions and that these reactions take place irreversibly, but that the remaining part of the process could be operated reversibly (Denbigh, 1956). This is an example of an 'ideal' methanol production process. However, the direct reaction of methane with oxygen to methanol, i.e. without synthesis gas as an intermediate, would even be better. The next section presents the results of the analyses of the ICI LP and LCM processes as well as a comparison with the results of both 'ideal' processes.

2.2.2 Results of the comparison

Figure 2.5 presents the results of the energy and exergy analyses of the ICI LP process. This figure shows that according to the results of the energy analysis, the purification section has the largest room for improvement, followed by the reformer and reactor loop sections. However, according to the results of the exergy analysis, the reformer section has the largest improvement potential, i.e. about three quarters of the exergy is lost in this section. Thus, the results of energy and exergy analyses can lead to totally different conclusions with regard to which part of a technological system has the largest improvement potential.

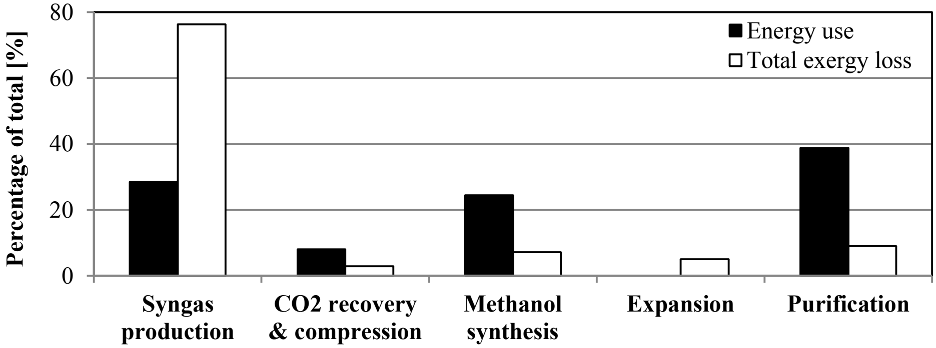

Figure 2.5: Distribution of the energy use and total exergy loss between the sections of the ICI LP methanol process.

Table 2.1 presents an overview of the analysis results of both methanol production processes. According to this table, the LCM process is preferred to the ICI LP process except for the emission of waste heat. It is understandable that the LCM process performs better because the ICI LP requires the combustion of methane in a furnace to provide the heat needed for its reforming reactions.

Table 2.1: Comparison of both methanol production processes.

[per kg methanol]	ICI LP process	LCM process
Energy in waste flows [MJ]	9.75	8.00
Internal exergy loss [MJ]	8.49	5.76
Total exergy loss [MJ]	9.76	6.65
Carbon efficiency [mole CH_4/mole CH_3OH]	1.26	1.11
Waste heat [MJ]	6.49	7.65
Electricity use [MJ]	0.95	0.02

Table 2.2 compares the results of the regular methanol production processes with ideal methanol production processes. Both processes are compared with their equivalent that operates ideally except for its reactions and with a process that applies the direct reaction of methane with oxygen to methanol. According to Table 2.2, the reactions of the ICI LP and LCM methanol production processes account for about 40 per cent of the exergy loss caused by these processes. The direct reaction accounts for only 18 and 27 per cent of the internal exergy losses of the ICI LP and LCM processes, respectively.

Table 2.2: Comparison of the internal exergy losses of the regular and ideal methanol production processes.

[MJ/kg methanol]	Regular process	Ideal process with real reactions
ICI LP process	8.49	3.55
LCM process	5.76	2.32
Direct conversion[1]		1.55

[1] Direct reaction of methane with oxygen to methanol.

2.2.3 Recent developments

Nowadays, methanol is still mainly produced from methane via synthesis gas (Fiedler et al., 2011). The exploration of shale gas has resulted in lower prices of natural gas and a subsequent re-start of old methanol plants and the construction of new conventional methanol plants. Another topical development is the production of synthesis gas from carbon dioxide originating from flue gases and hydrogen produced by electrolysis of water (Olah et al., 2009). When the electricity needed for electrolysis originates from wind energy, the production of methanol can be used as a means to absorb peak supplies of wind power.

Apart from the aforementioned developments, research is conducted into e.g. liquid-phase methanol synthesis from synthesis gas, which leads to a higher synthesis gas conversion per pass than conventional methanol synthesis (DOE, 2004). Although not analysed in detail, the lower pressure during the production of synthesis gas and the higher conversion per pass of this liquid-phase methanol process are indications of a lower exergy loss. The photoelectrochemical reduction of carbon dioxide to methanol (Rajeshwar et al., 2013) has the advantages that neither methane nor natural gas is used as a feedstock and that the required energy (exergy) for the process originates from the sun. The direct catalytic conversion of methane to methanol, e.g. Alayon et al. (2012), is an improvement from an exergetic point of view because the production of synthesis gas is avoided, which is an endothermic reaction. This illustration of the differences between energy and exergy analysis is followed by a description of the many application areas of exergy analysis in Section 2.3.

2.3 Applications of exergy analysis

The applications of exergy analysis vary from engineering and environmental applications to thermo-economics, the area of sustainable development and more. An overview of the development and applications of the concept of exergy up to 2004 is presented by Sciubba and Wall (2007). Dewulf et al. (2008) provide a critical review of the potential and limitations of exergy in environmental science and technology. Below, a brief overview of applications of exergy analysis is presented.

Engineering applications
Engineering applications mentioned by Sciubba and Wall (2007) are the following: power cycles and components (steam power cycles, gas turbine cycles, renewable energy cycles and other energy conversion cycles), heat exchangers and heat networking, cryogenics, chemical processes, distillation and desalination, and industrial and agricultural systems analysis. In general, it can be said that exergy analysis can be used to analyse all kinds of technological processes and systems, and in optimizing them, for example the analysis and optimisation of methanol production processes (Section 2.2). Another example is the research by Eftekhari (2013) titled ‘Low Emission Conversion of Fossil Fuels with Simultaneous or Consecutive Storage of Carbon Dioxide’. He concludes that the exergy-intensive carbon dioxide capturing methods are the main weak point of the use of zero-emission underground coal gasification processes and that theory indicates that less exergy-intensive processes can be developed.

Societal systems
Apart from analysing technological processes and systems, exergy analysis can be used to analyse the exergetic performance of a country or region as a whole. Examples of countries and regions that have been analysed are Brazil, Ghana, Italy, Netherlands, Norway, United States, Sweden and Turkey (Sciubba and Wall, 2007; Ptasinski et al., 2008; Dewulf et al., 2008). Different researchers apply different exergy analysis methods. E.g., Ptasinski et al. (2008) calculated conversion efficiencies of sectors of the Dutch society on the basis of the year 2000 energy balance published by Statistics Netherlands. They defined the conversion efficiencies as the ratio between the output to a sector including fluxes of primary and natural resources, products and trash to other sectors, and the corresponding input. The resulting

exergy conversion efficiencies of the extraction, conversion, agriculture, industry, transport, tertiary and domestic sectors equal 96, 71, 27, 85, 58, 30 and 6 per cent, respectively (Ptasinski et al., 2008).

Environmental applications
Examples of environmental applications mentioned by Sciubba and Wall (2007); Dewulf et al. (2008) are the accounting for the environmental impact of emissions, the depletion of natural resources, recycling and life cycle assessment. Furthermore, Lems (2009) uses exergy analysis for the analysis of biological processes.

As the exergetic value of an emission is not a measure of its environmental impact, other ways have to be found to take into account the environmental impact of emissions. The same holds for the depletion of natural resources like raw materials and energy carriers. Depletion is a fact, not a process of which an exergy analysis can be carried out. Section 3.1 elaborates on both aspects.

Exergy analysis combined with economic methods
In thermo-economics or exergo-economics, exergy analysis is combined with engineering economics. This combination is used to price the specific exergy content of a mass or energy flow instead of pricing the mass flow as is common practice in engineering economics. Examples of thermo-economic methods are Extended Exergy Accounting and Exergoeconomic analysis (section 3.4).

Sustainable development
As described in more detail in Section 3.3, exergy analysis is regarded as useful when striving for a more sustainable society, but a quantitative underpinning of the relationship between exergy analysis and sustainability has not been found in literature.

Summarising, exergy analysis visualises where quality of energy is lost and has several advantages compared to energy analysis. The results of an exergy analysis can be visualised in diagrams or presented as numbers (efficiencies, exergy losses). Exergy analysis has a wide range of application areas. Section 2.4 elaborates on the use of exergy analysis in policy making.

2.4 Exergy analysis and policy making

Several researchers have proposed the use of exergy loss and/or exergy efficiency in policy making, e.g. Hirs (1993); Dincer (2002b); Hirs (2003); Rosen et al. (2008). Besides, Wall (2002) proposes the taxing of the use of non-renewable resources via their amount of exergy and Liao et al. (2013) suggest a tax based on the exergy embodied in products.

The Dutch professor Hirs (1993) proposed the use of exergy loss as a basis for energy taxing. The main advantage according to Hirs (1993, p.1241) is ‘the strong incentive for investors to conserve energy in combination with the absence of interference with free market operations.’ He advocates to consider the partial or complete replacement of the common Value Added Tax with the Entropy Added Tax (EAT).

This call has not resulted in Dutch policy that takes into account exergy, neither has the research project ‘Entropy or exergy - a measure in environmental policy making?’ (Section 3.1) carried out in 1994 and commissioned by the Dutch Ministry of Housing, Spatial Planning and the Environment. In January 2014, the term exergy, in Dutch ‘exergie’, was mentioned only three times in documents on the website of the Dutch government (www.rijksoverheid.nl), which provides public information on legislation and rules issued by the Government of the Netherlands. I.e., it is mentioned by an interviewee in a brochure about innovative projects which was initiated in 2008 by the Dutch transition network, in a report about energy innovation in the Dutch built environment issued by the interdepartmental programme on the Dutch energy transition in 2009 and in an annex to a report about the progress of the Dutch energy innovation agenda in 2010 by the same interdepartmental programme.

Besides, it is mentioned one time on another website by the Dutch government (www.overheid.nl), i.e. in a subsidy programme about energy and innovation, more specific: in a paragraph about innovative systems and components in the built environment. Examples of research projects that were financed within the energy and innovation programme, i.e. within its no longer existing part named the EOS-LT programme, are the LowEx project about the reduction of the use of high quality energy resources in the built environment (www.lowex.net) and the SREX project about Synergy between Regional planning and EXergy (www.exergieplanning.nl).

The only publication found in literature about the successful introduction of the concept of exergy in policy has been written by Favrat et al. (2008). They describe the introduction of an exergy indicator in a local law on energy in Switzerland, i.e. in the Canton of Geneva. This legal framework prescribes the inclusion of an exergy approach in the documents for large building projects required from city developers. It was learned from personal correspondence with the authors in February 2014 that this law is still in force, that the major interest is that each actor is aware of his responsibility with regard to causing exergy losses and to make sure that the decisions that are taken do not prevent the choice of a more exergy efficient solution in the future.

Although exergy analysis seems not to be used in policy making, except for one of the Cantons of Switzerland, sustainability and (the prevention of) climate change have the attention of governments and policy makers. E.g., in the form of the Kyoto Protocol, the Sustainable Development Strategy (SDS) of the European Union and the informal cooperation between energy, climate and environment Ministers from thirteen member countries of the European Union, among which the Dutch Minister for the Environment, named ‘The Green Growth Group’.

The Dutch government aims at making the Dutch economy more sustainable by combining ‘green’ and ‘growth’ in its policy called ‘Green Growth’. This Green Growth is based on the following four pillars: ‘smart use of market incentives’, ‘an encouraging framework with legislation that promotes dynamics’, ‘innovation’ and ‘the government as a network partner’. The government has identified important challenges and opportunities within eight domains of its Green Growth policy. Examples of domains are ‘Energy: a sustainable, affordable and reliable energy’ and ‘Climate: towards an ambitious national/international climate policy’. In September 2013 the Dutch government reached the ‘Energy Agreement for Sustainable Growth’ with more than forty Dutch organizations. This agreement includes energy saving, the realization and/or stimulation of technological systems like wind farms and the closure of three coal-fired power plants.

Possible explanations for the only very limited use of exergy analysis in policy making are the unfamiliarity with the concept of exergy analysis and its possibilities, the concept being regarded as difficult and/or the lack of easy-to-use software tools for the assessment of sustainability in combination with exergy losses. Dincer and Rosen (2013) emphasise the importance of education and awareness of exergy by the public, including the government, engineers and scientists. They state that ‘Government, being another type of reflection of the public, will be far less prone to use exergy methods, even when they can be beneficial, if it feels that the public does not understand exergy even in the simplest way and therefore will not appreciate government efforts.’ (Dincer and Rosen, 2013, p.502). The research presented in this thesis intends to contribute to the knowledge about exergy analysis.

2.5 Concluding remarks

Exergy analysis is a more fundamental way of looking at technological systems than energy analysis. Exergy analysis makes visible where work potential is lost and has a wide variety of application areas. The exergy losses caused by a process or activity are influenced by the choice of its inputs and the type of process itself.

The analysis of two methanol production processes showed that large differences exist between the results of energy and exergy analyses and that there is a large improvement potential of these processes when they are compared with a thermodynamically optimal methanol production process. This illustrates the added value of exergy analysis when analysing, comparing and improving chemical production processes compared to energy analysis.

Despite several publications and calls about the use of the exergy concept in policy making, it seems that only Switzerland’s Canton of Geneva has introduced exergy in one of its laws. Possibly, the awareness of the concept of exergy and its possibilities is too little, exergy analysis is regarded as difficult and/or there is a need for easy-to-use software tools. This research aims to contribute to the knowledge about exergy analysis.

Chapter 3 goes into more detail about the use of exergy in the field of sustainability.

Chapter 3

Knowledge about exergy and sustainability

This chapter gives insight into what is already known about the use of exergy analysis in the field of sustainability. The environmental aspect of sustainability is dealt with in Section 3.1, which presents the results of a study into the potential benefits of exergy analysis in environmental policy making, i.e. the research project 'Entropy or exergy - a measure in environmental policy making?'. This is followed by a discussion of the relationship between exergy and the economic and social aspects of sustainability in Section 3.2. Section 3.3 presents the results of a literature research into the relationship between exergy and sustainability. The exergy analysis methods found during the literature research are described in Section 3.4. Concluding remarks about exergy and sustainability are presented in Section 3.5.

3.1 Exergy as a measure of environmental impact

The question whether exergy could be used as a measure in environmental policy making was posed in 1993 by the Dutch Ministry of Housing, Spatial Planning and the Environment (Stougie et al., 1994). The ministry wanted to know whether exergy is a measure of the environmental impact caused by the use of raw materials, energy and by emissions. To answer this question, Stougie et al. (1994) have conducted a qualitative investigation of the relation between exergy and the many aspects of environmental policy making (Section 3.1.1), followed by an analysis of the production of aluminium and polystyrene as examples (Sections 3.1.2 and 3.1.3). Section 3.1.4 presents the findings of the research project, which is considered as the seed of the research presented in this thesis. Parts of this section have already been published by Stougie and Van der Kooi (2009, 2012).

3.1.1 Qualitative investigation

The qualitative investigation has been carried out by combining two points of view. These are the environmental policy making and the concept of exergy itself.

The viewpoint of environmental policy making has been handled by interviewing environmental experts of the Dutch ministry and by studying technical reports (Adriaanse and Van Soest, 1990; Maas, 1991, 1993) relevant to the Dutch environmental policy. The resulting list of aspects relevant to environmental policy making has been considered carefully by investigating whether and how each aspect of the list could be related to the concept of exergy. On the other hand, the concept of exergy has been examined very carefully in order to find aspects of environmental impact that could be tackled with exergy. For that purpose, brainstorming sessions between the researchers have been conducted. The resulting questions and themes have been investigated qualitatively. In this way, numerous questions related to environmental policy making and the concept of exergy have been considered.

During the qualitative investigation, the following aspects of environmental impact were identified: climate change (global warming, ozone depletion), acidification, eutrophication, dispersion of hazardous compounds, disposal of waste, disturbance, drying up and wasting of materials and energy carriers. These aspects of environmental impact can all be traced back to the use of raw materials and energy, and the emission and dispersion of pollutants. The following paragraphs describe the relationships between exergy losses and the use of raw materials, energy and emissions in more detail.

Use of raw materials
Aspects that are important with respect to the use of non-renewable raw materials (material resources) are the extraction, scarcity and depletion of these raw materials. The extraction of a raw material from our natural environment is a technological process that is accompanied with exergy losses. This exergy loss is part of the exergy losses that occur along a supply chain. The scarcer a raw material becomes, the more effort is needed to extract it, i.e. the use of energy carriers and other supplies to extract the raw material will be higher, and the higher the accompanying exergy loss is expected to be.

The extraction of raw materials from the natural environment leads to a decrease or even depletion of these raw materials. The fact that the amount of raw material in the natural environment has decreased because of the extraction is not a technological process; it is a fact. Facts are not accompanied with exergy losses, therefore this decrease of raw materials cannot be accounted for when analysing a supply chain. Figure 3.1 depicts the difference between extraction and the decrease of the amount of raw materials.

The extracted raw materials represent an amount of exergy. This amount of exergy cannot be added to the exergy losses along the supply chain, because not all of the exergy contained in the raw materials will be lost, i.e. part of it will end up in useful products. An alternative way of quantifying the decrease of the amount of raw materials in the natural environment is to regard the natural environment as a system that represents a certain reservoir of exergy that decreases as a result of the

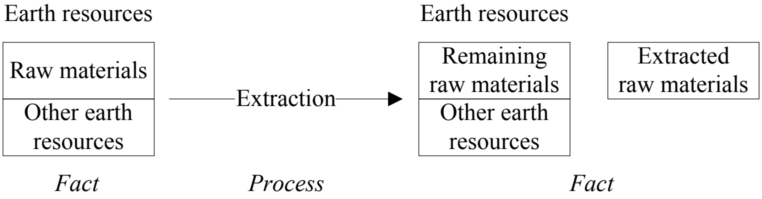

Figure 3.1: Difference between the technological process of extraction and the fact that the amount of raw materials in the natural environment (one of the earth resources) decreases because of extraction.

extraction of raw materials. Again, the decrease of this exergy reservoir cannot be added to the exergy loss caused by the extraction of raw materials, but should be considered as a separate indicator. Nevertheless, depletion is indirectly related to the exergy loss caused by a technological system, i.e. in the same way as scarcity is.

Besides that the use of raw materials results in exergy losses during their extraction, a relation is expected between the amount of raw material used as input to a technological process or chain of processes and the exergy losses occurring in that process or chain of processes. I.e., it is expected that the higher the exergy input (the use of raw materials) per unit of product, the larger the amount of exergy that will be lost. It is also expected that the higher the exergy input per unit of product, the higher the probability of the formation of emissions and the accompanying external exergy loss.

Energy use
In accordance with the first law of thermodynamics, energy is never consumed nor created but only changes forms. What does change is the quality of energy. The loss of energy quality along a supply chain is calculated when performing an exergy analysis. The energy used as input of a technological process, e.g. electricity and natural gas, can be considered by accounting for the exergy that is lost during exploration and production of these energy carriers. This can be done in the same way as is done in the case of raw materials. When a technological process produces an energy carrier like electricity as a by-product, the exergy loss caused by the conventional production of this amount of electricity can be subtracted from the exergy losses of the technological process, which is in accordance with the guidelines of environmental Life Cycle Assessment.

Emissions
The exergy loss caused by emissions could be considered in three ways. First, the exergy value of the emissions could be calculated. The total amount of exergy represented by emissions and other waste flows, e.g. waste heat, is called the external exergy loss. This external exergy loss is the exergy equivalent of the ‘losses’ of energy considered when performing an energy analysis (Section 2.1.1). Usually, this external exergy loss is small compared to the internal exergy loss of a technological process. However, the external exergy loss is not a measure of the environmental impact, e.g. toxicity, of these emissions and waste flows.

A second way of considering emissions is to value these emissions at the exergy losses caused by producing these emissions from raw materials available on earth. The problem with this method is that it is not likely that processes exist for the dedicated production of all emissions and that it is not logical to assess the emissions and waste flows in this way.

The third way of considering emissions is taking into account the exergy losses that would be caused by processes that abate these emissions to an acceptable level, like end-of-pipe techniques. This third way is preferred because it is the only way to make sure that the environmental impact of emissions is accounted for, i.e. no harmful emissions are emitted to the environment anymore. In this way, the environmental impact of emissions and the exergy loss caused by abatement are indirectly connected because the more harmful an emission, the lower the emission standard will be and presumably the higher the exergy loss to abate this emission. This higher exergy loss is caused by a higher demand of raw materials, energy and auxiliaries to comply with the standards.

Another aspect of emissions is the dispersion of emissions in the environment. Dispersion of emissions results in an increase of disorder, which is equivalent to an increase of entropy (chaos) and a loss of exergy. This dispersion could be accounted for by enlarging the process under consideration with dispersion processes, but this is unnecessary when the process has already been extended with end-of-pipe techniques that abate the emissions to an acceptable level.

Representativeness of exergy loss as a measure of environmental impact Exergy loss is a representative measure if it can unambiguously be related to environmental impact. The representativeness can be investigated by comparing the exergy losses and environmental impacts of processes, supply chains or parts thereof.

An important aspect when comparing processes is that these processes comply with the emission standards, because it does not make sense to compare the exergy losses of two processes that produce the same product if one process does not comply with the standards. Probably the process that does not comply with the standards has a higher environmental impact, while the other process has higher exergy losses because of end-of-pipe emission treatment processes. It is expected that exergy loss is a representative measure of environmental impact if the compared processes comply with the applicable standards at their locations because the other aspects of environmental impact, i.e. the use of raw materials and energy, are related to exergy loss. Furthermore, a careful consideration of system boundaries is important because in many cases it will be necessary to take into account additional processes or units to ensure the comparability of the alternative processes or materials.

The problem with determining whether exergy loss is a representative measure of environmental impact is that no fully objective method exists to quantify environmental impact. The methods that have been developed make use of estimates and factors to weigh environmental aspects. An alternative is to compare the exergy losses with the constituent parts of environmental impact, like the use of raw materials and energy. The lower the use of raw materials and/or energy, the lower the exergy loss will be. The higher the potential environmental impact of an emission, the stricter the emission standard is likely to be. The lower the amount of raw materials and energy needed to comply with these standards, the lower the environmental impact and the lower the exergy loss will be. This is discussed in more detail in Sections 3.1.2 and 3.1.3. The other way around, it can be qualitatively underpinned that exergy loss implies environmental impact, i.e. exergy loss is caused by technological processes and these processes have environmental impact in terms of raw materials and energy use and/or emissions.

It was concluded from the qualitative investigation that almost all environmental effects are related to the inefficient use of raw materials and energy caused by technological activities, like processes, and the emission and dispersion of pollutants.

Every (technological) process is accompanied with exergy losses, as is common knowledge between thermodynamicists. The depletion of natural resources like raw materials and energy carriers is the result of processes like extraction. Depletion itself is a fact, not a process, therefore depletion cannot be expressed in terms of exergy loss. However, depletion is related to scarcity and the scarcity of a resource can indirectly be expressed in terms of exergy because the scarcer the resource, the more difficult the extraction of that resource and the higher the exergy loss caused by that extraction is expected to be. The harmfulness, e.g. toxicity, of emissions is not a (technological) process either and therefore cannot be expressed in terms of exergy loss. This can be solved by assuming that the more harmful the waste emission, the more stringent the standards for this emission (should be), and by not taking into account emissions that meet their standards.

To underpin the results of the qualitative investigation, two production processes have been analysed, i.e. the production of aluminium and polystyrene, as described in Sections 3.1.2 and 3.1.3, respectively.

3.1.2 Production of aluminium

The analysis of the production of aluminium has been carried out by composing mass and energy balances of the production chains, followed by calculating the exergy losses of all process units. The data used to describe the production chain of aluminium mainly originate from Habersatter (1991) completed with data from SAC (1991); SPIN (1992). The exergy losses have been calculated by applying the standard exergy values tabulated by Kotas (1985). The internal and external exergy losses of each process unit as well as the chain effects have been calculated. The chain effects are the exergy losses caused by the production of feedstocks and utilities needed in the process units. The data presented in this section originate from Stougie et al. (1994).

The production of aluminium from bauxite ore is called primary production of aluminium and is depicted in Figure 3.2. The remaining part of bauxite after alumina (Al_2O_3) separation consists of sand and metal (ferro) compounds and is called 'red mud' because of its red colour. Aluminium can also be produced from aluminium waste, which is called secondary production.

The environmental impact caused by the primary production of aluminium is presented in Tables 3.1 to 3.3. Emissions larger than 10 kg per ton of end product are presented. The exergy losses due to the primary production of aluminium are presented in Table 3.4.

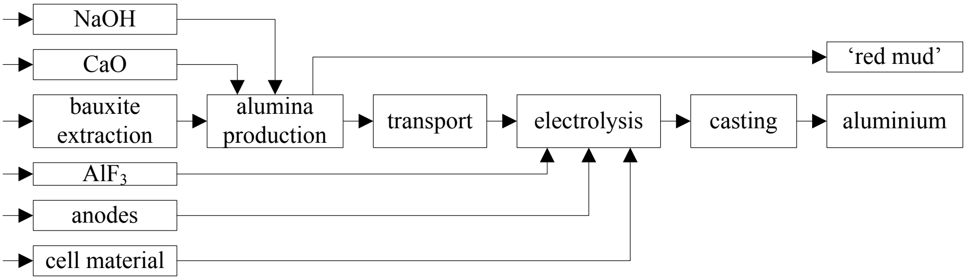

Figure 3.2: Primary production of aluminium.

Table 3.1: Inputs into the process units of primary aluminium production.

[ton/ton aluminium]	Bauxite extraction	Alumina production	Transport	Electrolysis	Casting
Bauxite ore	19				
Bauxite		4.8			
CaO		0.087			
NaOH		0.43			
Alumina				1.9	
AlF_3				0.018	
Anodes				0.43	
Cell material				0.0085	
Aluminium					1.0
Total	19	5.3	0	2.4	1.0

The amount of input used decreases along the production chain of aluminium (Table 3.1), but this does not apply to the exergy loss. The exergy loss of a process unit depends on the kind of conversion taking place, i.e. physical or chemical. A reason why the amounts of input and exergy loss are not comparable, could be the relatively low exergy value of the inputs (feedstocks).

Table 3.2: Energy use in the process units of primary aluminium production.

[GJ/ton aluminium]	Bauxite extraction	Alumina production	Transport	Electrolysis	Casting
Electricity	0.03	1.6		54	2.1
Heavy fuel oil	2.5	16	10		2.9
Extra light fuel oil				3.8	
Natural gas					1.3
Total	2.6	18	10	58	6.3
% of total	2.7	19	11	61	6.6

When the exergy losses excluding chain effects from Table 3.4 are compared with the energy use of Table 3.2, it appears that the distribution of exergy losses across the various process units is comparable to the energy used in the process units. This could, again, be explained by the low energy value, and thus low exergy value, of the feedstocks.

Table 3.3: Emissions due to the process units of primary aluminium production.

[ton/ton aluminium]	Bauxite extraction	Alumina production	Transport	Electrolysis	Casting
CO_2	0.20	1.6	0.82	11	0.68
Waste water	0.60	10			15
Soil	14				
SO_2		0.013	0.020	0.024	
COD		0.019			
‘Red mud’		2.9			
Solid waste		0.58		1.2	0.047
CO				0.45	
Hydrocarbons				0.094	
NO_x				0.023	

Table 3.4: Exergy losses due to the process units of primary aluminium production.

[GJ/ton aluminium]	Bauxite extraction	Alumina production	Transport	Electrolysis	Casting
Internal	2.4	19	0.42	43	6.2
External	0.10	1.9	0.06	0.45	2.6
Subtotal[1]	2.5	21	0.48	43	8.9
% of total	3.2	28	0.63	57	12
Chain effects	0.31	7.4	0.54	180	7.0
Total	2.8	28	1.0	223	16
% of total	1.0	11	0.38	82	5.9

[1] Excluding chain effects.

According to Table 3.3, the production of alumina causes a large amount of ‘red mud’. The high CO_2 emission due to electrolysis is notable as well. It is unknown whether these emissions meet the standards. Assuming that the emission of soil and waste water is less important, electrolysis and alumina production cause the highest emissions as well as the highest exergy losses (Table 3.4), which implies that the calculated exergy losses point in the right direction regarding the environmental impact caused by emissions. However, as explained before, the harmfulness of waste emissions cannot directly be expressed in terms of exergy loss.

From an environmental point of view, recycling is preferred to landfilling. It has been investigated whether this is also the case from an exergetic point of view by comparing the primary production of aluminium, i.e. landfilling, with the secondary production of aluminium, i.e. recycling. It appeared that the exergy loss caused by secondary aluminium production amounts to about ten per cent of the exergy loss caused by primary aluminium production and thus that the results of exergy analysis are in accordance with the preference from an environmental point of view.

The production of aluminium is one of the two technological processes that have been investigated to underpin to results of the qualitative investigation described in Section 3.1.1. The other process, i.e. the production of polystyrene, is described in Section 3.1.3 and is followed by some concluding remarks regarding the study as a whole in Section 3.1.4.

3.1.3 Production of polystyrene

The data used to describe the production chain of polystyrene mainly originate from Habersatter (1991), completed with data from Chauvel and Lefebvre (1989); Franck and Stadelhofer (1988). The data presented in this section originate from Stougie et al. (1994). The analysis of the production of polystyrene has been carried out in the same way as the analysis of the production of aluminium described in the previous section.

Polystyrene is produced from crude oil as depicted in Figure 3.3. During alkylation/dehydrogenation, benzene is alkylated with ethylene to ethylbenzene, followed by dehydrogenation of ethylbenzene to styrene.

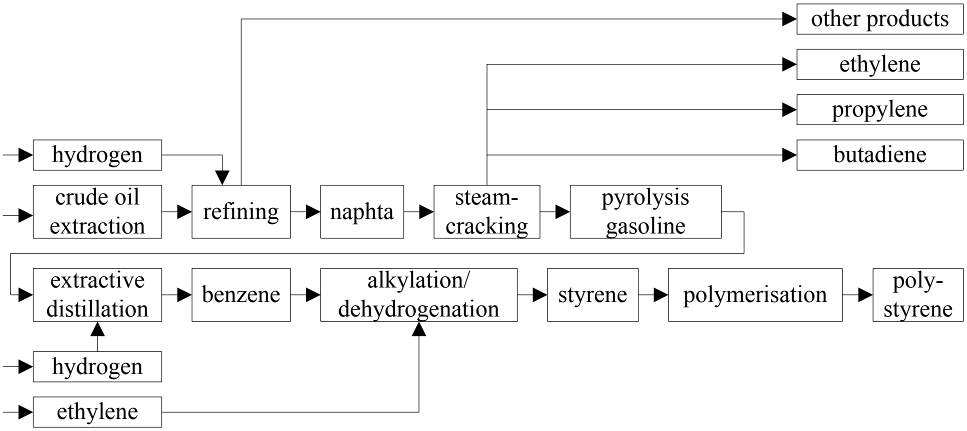

Figure 3.3: Production of polystyrene.

The environmental impact caused by the production of polystyrene is presented in Tables 3.5 to 3.7. The exergy losses due to the primary production of polystyrene are presented in Table 3.8.

Looking at the environmental impact of the process units (Tables 3.5 to 3.7), the high energy use and large amount of CO_2 emitted in the alkylation/dehydrogenation are notable. According to Table 3.8 most of the total exergy loss is caused by the alkylation/dehydrogenation as well. Steam cracking is considered to be the process unit with the second most environmental impact because of its relatively high energy use and the amount of solid waste. Steam cracking is the process unit with the second

Table 3.5: Inputs into the process units of polystyrene production.

[ton/ton PS]	Crude oil extract.	Refining	Steam crack.	Extractive distill.	Alkylation/ dehydrog.	Polymerisation
Crude oil	1.6	1.5				
Naphta			1.4			
Pyrolysis gasoline				0.79		
Hydrogen				0.0037		
Benzene					0.80	
Ethylene					0.29	
Styrene						0.98
Other					0.0071	0.031
Total	1.6	1.5	1.4	0.80	1.1	1.0

Table 3.6: Energy use in the process units of polystyrene production.

[GJ/ton PS]	Crude oil extract.	Refining	Steam crack.	Extractive distill.	Alkylation/ dehydrog.	Polymerisation
Electricity	0.12	0.06	0.13	0.01	0.33	0.9
Natural gas	0.23		7.2			
Heavy fuel oil	0.01	3.7			6.5	
Steam				1.5	7.8	1.1
Total	0.36	3.8	7.4	1.5	15	2.0

Table 3.7: Emissions due to the process units of polystyrene production.

[kg/ton PS]	Crude oil extract.	Refining	Steam crack.	Extractive distill.	Alkylation/ dehydrog.	Polymerisation
CO_2	35	302	23		1,047	232
Dissolved solids	19					
Solid waste			75			20

most total exergy loss as well. From this it may be concluded that exergy analysis points out the process units with the highest environmental impact.

3.1.4 Findings

On the basis of the qualitative investigation described in Section 3.1.1, it is concluded that almost all environmental effects can be related to the inefficient use of raw materials and energy caused by technological activities, like processes, and the emission and dispersion of pollutants. The depletion of natural resources and the harmfulness of emissions cannot directly be expressed in terms of exergy loss. However, it is expected that the scarcer the resource, the more exergy is lost dur-

Table 3.8: Exergy losses due to the process units of polystyrene production.

[GJ/ton PS]	Crude oil extract.	Refining	Steam crack.	Extractive distill.	Alkylation/ dehydrog.	Polyme-risation
Internal	1.5	0.13	1.9	0.07	1.7	0.51
External	0.04	0.06	8.6	0.00	0.05	0.01
Subtotal[1]	1.5	0.19	11	0.07	1.7	0.5
% of total	11	1.3	72	0.15	12	3.6
Chain effects						
Feedstocks & utilities[2]	0.41	0.51	1.0	2.2	12	4.4
Credits by-products[3]	0	-0.25	-2.9	-2.3	-0.27	-0.01
Total	1.9	0.46	8.6	0.02	14	5.0
% of total	6.5	1.5	29	0.07	46	17

[1] Excluding chain effects.

[2] Production of feedstocks and utilities.

[3] The production of valuable by-products avoids exergy losses caused by the regular production of these by-products.

ing extraction of that resource, and that the more harmful an emission, the more stringent the standards for this emission, and the higher the exergy loss accompanied with meeting these standards is. Moreover, the harmfulness is no longer important if the technological systems is extended with measures to make sure that the standards are met. According to the results of the exergy analyses of primary and secondary aluminium production, the secondary production of aluminium is preferred, which is in accordance with the preference from an environmental point of view.

It appeared difficult to underpin the results of the qualitative investigation by analysing the production chains of aluminium and polystyrene (Sections 3.1.2 and 3.1.3) because of the lack of an objective measure of the environmental impact caused by raw material use, energy use and emissions. In a qualitative way it could be made plausible that exergy loss is accompanied with environmental impact. The other way round, i.e. that a higher environmental impact implies a higher exergy loss, can be understood intuitively but could not be convincingly underpinned on the basis of the examples.

It is concluded that exergy loss is at least a qualitative measure that can be used in environmental policy making regarding technological processes. It is expected that the environmental sustainability increases with a decrease in exergy loss. The economic and social aspects of sustainability have not been considered in this project and are the subject of the next section.

3.2 Exergy and the economic and social aspects of sustainability

The relationship between economic sustainability and exergy losses is more complicated than the relationship between environmental sustainability and exergy losses. As explained in Chapter 2, every process and activity is accompanied with the loss of exergy, which is caused by driving forces. The larger the driving force applied in a process or activity, the faster it will take place and the less volume (and/or space) is needed. E.g., the larger the difference in temperature between the two flows in a heat exchanger, the faster the exchange of heat between these flows will take place and the smaller the heat exchanging area, and thus the heat exchanger, can be. When considering only the equipment/installation itself, a small size and thus large exergy losses are preferred from an economic point of view. However, the larger the exergy loss, the more exergy is needed as an input to that process and thus the larger the consumption of materials and energy carriers will be during the operational phase. It depends on the costs of the construction and decommissioning of the equipment/installation on the one hand and the costs during the operational phase on the other hand whether a lower exergy loss is accompanied with a higher economic sustainability.

Without knowing what exactly is meant with social sustainability and how it can and/or will be operationalised in this research, it is not possible to predict the relationship between social sustainability and exergy losses. Nevertheless, social sustainability will somehow be related to the extraction and processing of materials and energy carriers needed for processes and activities via the working conditions during extraction and processing.

Exergy analysis is a fundamental way of assessing processes and activities. Exergy losses are related to physical, i.e. real, transformations. Economic and social aspects are related to these transformations as well. It is therefore relevant to investigate the value of exergy analysis in sustainability assessment of technological systems. Section 3.3 describes the results of a literature research into the relationship between exergy and sustainability.

3.3 Literature about exergy in relation to sustainability

In 2010 a literature research was carried out in the field of exergy and sustainability. Hereto the databases of Scopus (www.scopus.com), Sciencedirect (www.sciencedirect.com), Inderscience (www.inderscience.com) and Google Scholar (scholar.google.com) have been queried as described in Appendix B. The literature research resulted in the 116 publications listed in this appendix. The literature research was repeated in May 2014 to search for more recent literature in this field. The knowledge gathered from studying the publications of Appendix B and related publications as well as a few more recent publications forms the basis of this section and Section 3.4. Parts of both sections have already been published (Stougie and Van der Kooi, 2011a).

Dincer and Rosen (2005) qualitatively illustrate that an increase in the exergy efficiency of a process is accompanied with a decreasing environmental impact and an increasing sustainability of the process. They write that 'The authors and others feel that exergy methods can be used to evaluate and improve efficiency and thus to improve sustainability' and recommend further research to 'ascertain a better understanding of the potential role of exergy in such a comprehensive perspective' (Dincer and Rosen, 2005, p.185). According to them sustainable development involves four key factors: environmental, economic, social and resource/energy sustainability.

In a later publication they state 'Exergy can be considered the confluence of energy, environment and sustainable development' (Dincer and Rosen (2007, p.49); Dincer and Rosen (2013, p.64)). 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'. According to the authors 'Exergy methods can be used to improve sustainability' (Dincer and Rosen (2007, p.49); Dincer and Rosen (2013, p.64)). At this point they refer to the work of Cornelissen (1997).

Cornelissen (1997) is of the opinion that exergy analysis is one of the keystones for obtaining sustainable development. The scope of his work is limited to sustainable development associated with production, i.e. manufacturing processes. He states that 'for sustainable development the destruction of the exergy reservoirs of natural resources has to be minimised to a level at which there is no damage to the environment and at which the supply of exergy to further generations is secured' Cornelissen (1997, p.64). In his work he limits sustainable development to the depletion of natural resources and emissions to the environment. According to him there is no emission to the environment and no depletion of resources in a reversible process. At this point he disregards 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.

Arrow et al. (2004, p.150) operationalised the well-known definition of sustainable development (development that 'meets the needs of the present without compromising the ability of future generations to meet their own needs' WCED (1987, p.43)) into the 'intertemporal social welfare [...] must not decrease over time.', i.e. 'the stock of all society's capital assets at *t*, inclusive of manufactured capital assets, human capital and natural capital' must be constant or increase over time (Arrow et al., 2004, p.151). As Gutowski et al. (2009) put it, the problem with this operationalization is that, though a distinction is made between the different kinds of capital asset, it only takes into account the overall stock of capital assets. This means that e.g. a decrease in natural capital could be compensated for by an increase in manufactured capital, for example: real butterflies could be replaced with butterflies made of plastic...

Gutowski et al. (2009) elaborate on this with regard to the suitability of exergy as a sustainability indicator. According to Gutowski et al. (2009, p.6) thermodynamics, exergy analysis, can contribute to 'the design of efficient and self-sustaining technological-ecological networks that operate within ecological constraints', but they conclude that 'No single metric (regardless how well aggregated) or derivative criterion is able to offer a completely satisfactory solution for all situations'. In addition, Sciubba and Zullo (2011, p.82) state that '... the attainment of a thermodynamic sustainable situation is a necessary but not sufficient condition for a real sustainable scenario.'.

Hammond (Hammond, 2004b,a, 2007) is also of the opinion 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). According to Hammond (2007, p.676) 'The link between the efficiency of resource utilisation, pollutant emissions, and "exergy consumption" is real, but not direct'. He illustrates this 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.

Gong and Wall (2001, p.228) are of the opinion that exergy evaluations are important but state 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'.

Romero and Linares (2014, p.430) state that 'exergy appears as a powerful concept describing the sustainability issue' in the sense that it provides a link between the studied system and its environment and that all flows can be expressed in terms of exergy, but they also mention some difficulties like the definition of the reference environment needed for the calculation of chemical exergy values. According to them, useful work (exergy) is not a relevant characteristic of a mineral nor of the harmfulness of wastes of a process. The former may be true, but it is still useful to calculate the exergy input of mineral treatment and other processes in order to be able to calculate exergy losses. They also mention that non-linear causes of exergy losses, e.g. as a result of malfunctioning and/or process disturbances, limit exergy-cost evaluations, i.e. the calculation of unique values of the exergetic cost of products per unit exergy of that product. Finally, they mention an additional limitation of using exergy as a strong sustainability (natural capital cannot be substituted with produced capital) indicator, which is related to the calculation of transformities, e.g. in the case of calculating the emergy values described in Section 3.4, but the calculation of transformities and/or emergy values is no part of regular exergy analyses.

According to researchers in the field of exergy and sustainability, exergy losses should be decreased. The calculation of exergy values relative to a reference environment has advantages in the sense of providing a link between a system and its environment as well as disadvantages related to defining the composition of this reference environment. Furthermore, it is mentioned that exergy analysis should be used in combination with other assessment tools. It is therefore relevant to compare the results of exergy analysis with the results of regular sustainability assessment methods. Section 3.4 provides a brief description of the exergy analysis methods found during the literature research into the relationship between exergy and sustainability.

3.4 Exergy analysis methods in the field of sustainability

The literature research into the relationship between exergy and sustainability resulted in a list of many analysis methods based on exergy analysis. This section provides a brief description of the analysis methods that have been found during the literature research, while a more detailed description can be found in Appendix C. Parts of this section have already been published (Stougie and Van der Kooi, 2011a).

A main difference between the exergy analysis methods is the extent to which the environmental, economic and social aspects of sustainability are considered by these methods. An exergy analysis method that can be considered as the basis of many other exergy analysis methods is the Cumulative Exergy Consumption (CExC) method introduced by professor Szargut (Szargut et al., 1988). Figure 3.4 shows the exergy analysis methods that are related to this CExC method in a chronological order, including a brief comment on the difference between these methods and the CExC method. The standard environmental Life Cycle Assessment method was also a source of inspiration for the development of exergy analysis methods, as depicted in Figure 3.5. Another development is methods that explicitly consider the role of ecosystem goods and services (in short: ecosystem services). Ecosystem services can be divided into the following four categories: 1) provisioning services (products directly obtained from ecosystems, like fossil and biomass fuels, minerals, renewable energy and land), 2) regulating services (e.g. regulation of air quality and climate, water purification and pollination), 3) supporting services ('necessary for the production of all other ecosystem services', such as photosynthesis and nutrient cycling) and 4) cultural services ('spiritual and recreational benefits people obtain from ecosystems, such as knowledge systems, social relations, and aesthetic values') (Zhang et al., 2010a, p.2234-2235). According to Zhang et al. (2010a), the role of ecosystem services should be taken into account because these ecosystem services form the basis of planetary activities and human well-being. Figure 3.6 presents an overview of methods that calculate the value of ecosystems. As becomes clear from Figures 3.4 to 3.6, some overlap exists between the figures. Also methods have been found in literature that apply a multicriteria approach with exergy-related and other indicators, i.e. Environomics (Frangopoulos, 1992; Curti et al., 2000), the multicriteria approaches presented by Frangopoulos and Keramioti (2010) and by Mirandola and Stoppato (2003) and many methods that make use of sustainability indicators based on exergy, e.g. Dewulf et al. (2000); Sewalt et al. (2001); Lems et al. (2002, 2003); Bastianoni et al. (2005); Cummings and Seager (2008); Hoang and Rao (2010).

Below, the exergy analysis methods of Figures 3.4 to 3.6 are briefly described in alphabetical order. A more detailed description can be found in Appendix C.

CEENE
The method called Cumulative Exergy Extraction from the Natural Environment (CEENE) is a Life Cycle Impact Assessment method that has been developed for use in combination with the Ecoinvent (www.ecoinvent.org) database (Dewulf et al., 2007). The method can be considered as an extension to calculating the Cumulative

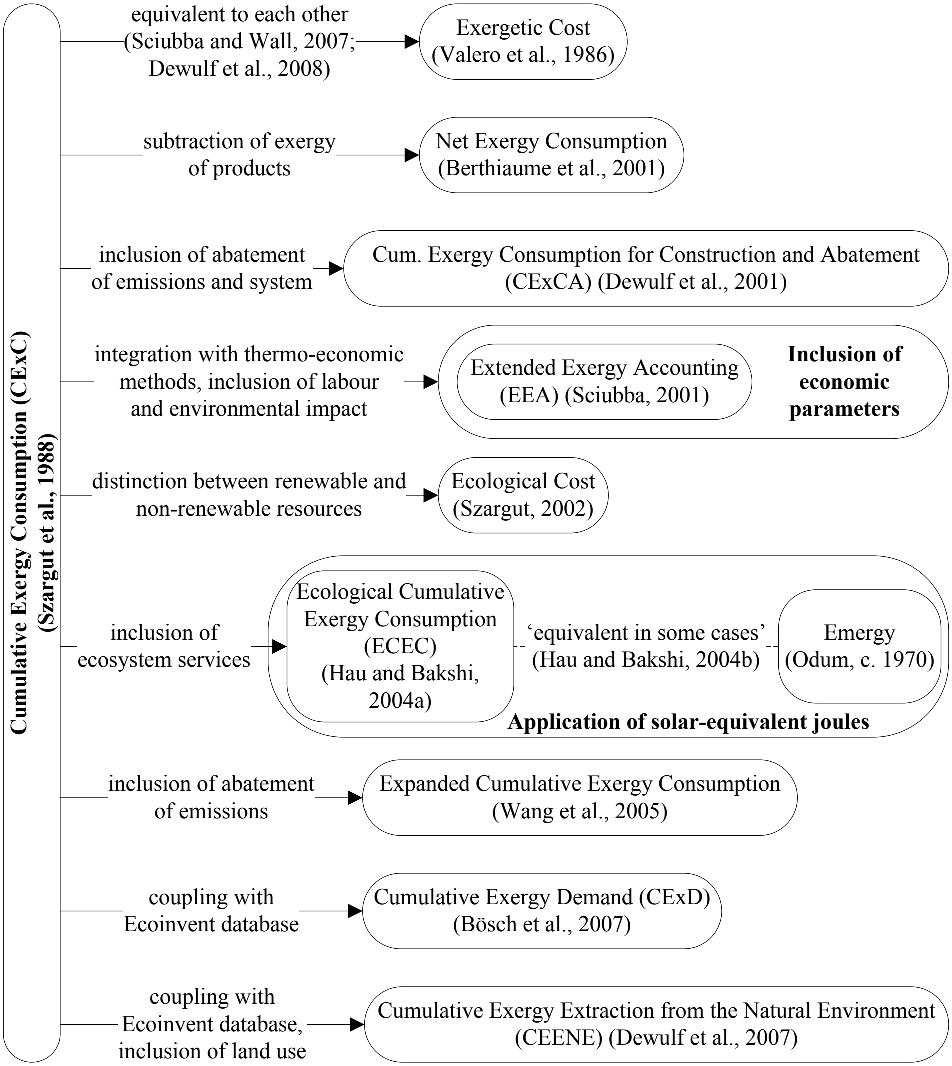

Figure 3.4: Exergy analysis methods related to the Cumulative Exergy Consumption method.

Exergy Consumption. It 'quantifies the exergy "taken away" from natural ecosystems' (Dewulf et al., 2007, p.8477) and covers the withdrawal of natural resources including land use.

Cumulative Exergy Consumption

The method of calculating the Cumulative Exergy Consumption (CExC) has been introduced by Szargut et al. (1988). It expresses 'the sum of the exergy of natural resources consumed in all the steps of a production process' (Szargut et al., 1988, p.171), or, stated differently, is equal to the 'total consumption of the exergy and natural resources connected with the fabrication of the considered product and

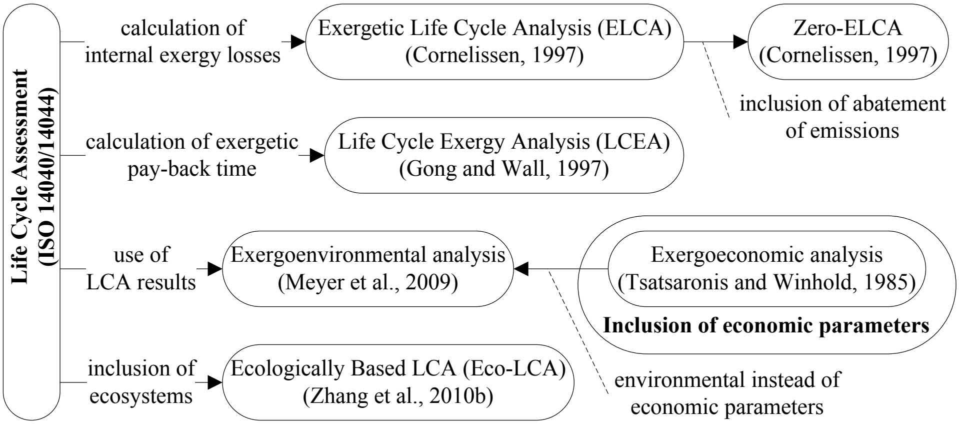

Figure 3.5: Exergy analysis methods related to the standard Life Cycle Assessment method.

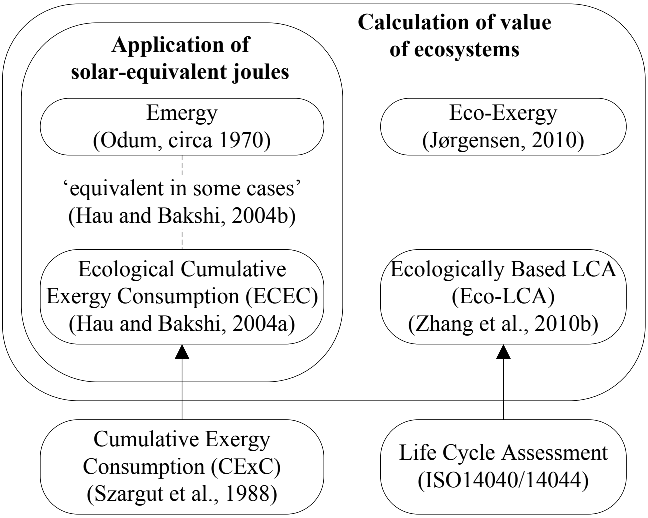

Figure 3.6: Exergy analysis methods that take into account the role of ecosystem services.

appearing in all the links of the network of production processes' (Szargut, 2005, p.57). The difference between the CExC and the specific exergy of the product is named the cumulative exergy loss (Szargut and Morris, 1990) and the CExC over the specific exergy of the product is known as the cumulative exergy efficiency or cumulative degree of perfection (CDP) (Szargut, 2005).

Cumulative Exergy Consumption for Construction and Abatement
The method of calculating the Cumulative Exergy Consumption for Construction and Abatement (CExCA) has been introduced by Dewulf et al. (2001) as the sum of the Cumulative Exergy Consumption needed for the construction and operation

of the system and the cumulative exergy consumption for abatement of emissions and the system after utilization (CExA).

Cumulative Exergy Demand
Analogous to the Cumulative Exergy Consumption, the Cumulative Exergy Demand (CExD) has been defined as 'the sum of exergy of all resources required to provide a process or product' (Bösch et al., 2007, p.182). CExD indicators are available for use in combination with the Ecoinvent (www.ecoinvent.org) database.

Eco-Exergy
The Eco-Exergy method has been introduced by Jørgensen (2010) to calculate the value of ecosystem services. The annual increase of Eco-Exergy is said to be a measure of the value of ecosystem services.

Ecological Cost
The concept of Ecological Cost is related to the concept of Cumulative Exergy Consumption and has been introduced to express 'the cumulative consumption of non-renewable primary exergy, appearing in all links of an energo-technological system as a result of the fabrication of the considered final product.' (Szargut, 2002, p.381)

Ecological Cumulative Exergy Consumption
The concept of Ecological Cumulative Exergy Consumption (ECEC) has been developed by Hau and Bakshi (2004a) as an expansion of traditional or industrial Cumulative Exergy Consumption to include the contribution of ecosystem services.

Ecologically Based LCA
The Ecologically Based LCA method (Eco-LCA) has been developed by Zhang et al. (2010b) to include the direct and indirect role of ecosystems in LCA.

Emergy analysis
Emergy analysis is a method that has been developed around 1970 by Odum to take into account ecosystem goods and services on an energetic basis. The method 'characterizes all products and services in equivalents of solar energy' Hau and Bakshi (2004b, p.216).

Environomics
The method called Environomics (Frangopoulos, 1992; Curti et al., 2000) 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.

Exergetic Cost
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' (Valero et al., 1986, p.2). The Exergetic cost is said to be equivalent to the CExC method (Sciubba and Wall, 2007; Dewulf et al., 2008).

Exergetic Life Cycle Analysis
The method of Exergetic Life Cycle Analysis (ELCA) has been developed by Cornelissen (1997) and can be considered as an extension to the regular Life Cycle Analyses with the calculation of internal exergy losses. Zero-ELCA is a variant that also includes the abatement of emissions.

Exergoeconomic analysis

In 1984 Tsatsaronis introduced the method Exergoeconomic analysis for the combined exergetic and economic analysis of energy conversion processes (Tsatsaronis and Winhold, 1985). This method calculates the costs of the exergy losses in the components of a plant. The later developed Advanced exergoeconomic analysis method splits the internal exergy loss into endogenous and exogenous as well as avoidable and unavoidable losses.

Exergoenvironmental analysis

In Exergoenvironmental analysis (Meyer et al., 2009), the concept of Exergoeconomic analysis is used to allocate the environmental impact of a process to the individual components of the process.

Expanded Cumulative Exergy Consumption

The method called Expanded Cumulative Exergy Consumption is introduced by Wang et al. (2005). It is an extension of the Cumulative Exergy Consumption with abatement exergy, like the CExCA method of Dewulf et al. (2001).

Extended Exergy Accounting

The concept of Extended Exergy Accounting (EEA) has been introduced by Sciubba (2001). EEA integrates cumulative exergy consumption (CExC) and thermoeconomic methods into an approach in which also labour and environmental impact are taken into account.

Life Cycle Exergy Analysis

The method of Life Cycle Exergy Analysis (LCEA) has been introduced by Gong and Wall (1997). An important aspect of this method is the calculation of the exergetic payback time of a system, especially of systems in which renewable energy is used as a resource.

Net Exergy Consumption

The Net Exergy Consumption (CNEx) is defined as the Cumulative Exergy Consumption minus the exergy of the products (Berthiaume et al., 2001).

Multi-criteria approaches

The multi-criteria approach presented by Frangopoulos and Keramioti (2010) designates four groups of sustainability indicators: technical indicators, environmental indicators, economic indicators and social indicators. Two of the technical indicators are related to exergy, i.e. the exergetic electric efficiency and the exergetic total efficiency. Mirandola and Stoppato (2003, p.166) propose an iterative multi-criteria approach 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’, see also Giannantoni et al. (2005). The exergy related indicators that they take into account are the exergetic efficiency and the costs of the product per exergy unit.

Sustainability indicators based on exergy

Several researchers have developed sustainability indicators in an attempt to quantify the sustainability of technological processes, e.g. Dewulf et al. (2000); Sewalt et al. (2001); Lems et al. (2002, 2003); Bastianoni et al. (2005); Cummings and Seager (2008); Hoang and Rao (2010). They introduced for example exergy-based indicators to distinguish between renewable and non-renewable resources, indicators related to the abatement of emissions and indicators that measure the efficiency of the process itself.

3.5 Concluding remarks

The use of raw materials and energy and the emission and dispersion of pollutants influence the environmental, economic and social sustainability of our society. They cause exergy losses as well, like every process and activity in real life is accompanied with the loss of exergy. No single metric will be completely satisfactory when assessing sustainability, but several researchers have recognised exergy analysis as being useful when striving for a more sustainable society.

Figure 3.7 shows the expected relationships between exergy losses and the environmental and economic dimensions of sustainability. The relationship between social sustainability and exergy loss is not known beforehand. Like described in Section 3.1, the environmental sustainability is expected to decrease when the exergy loss increases, which is represented by the area in the figure. In accordance with Section 3.2, the economic sustainability is expected to be lower at smaller and larger exergy losses because of the costs of the equipment/installation and the costs of a larger amount of inputs, respectively.

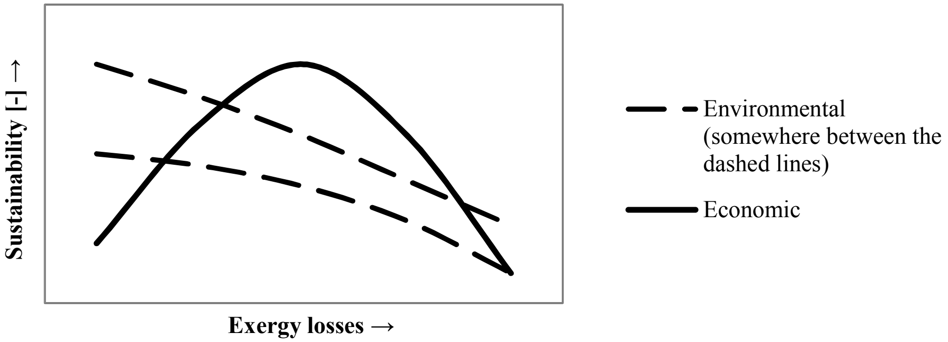

Figure 3.7: Expected relationships between the environmental and economic dimensions of sustainability and exergy losses.

The larger the amount of exergy that is available, the better people will be able to meet their needs. Exergy is needed for every process and activity, but the amount of exergy on earth is not endless. Exergy that is lost, is lost forever and the only source of new exergy to replenish the amount of exergy on earth is solar and/or tidal energy. From a sustainability point of view, it is therefore important to use exergy wisely. E.g., by preferably not using an input with a high energy quality for the production of an output with a low energy quality.

Chapter 4 deals with the assessment of the sustainability of a technological system and investigates the suitability of the exergy analysis methods that have been found during the literature research into exergy and sustainability.

Chapter 4

Assessment of the sustainability of a technological system

The sustainability of a technological system cannot be assessed without knowing what is meant with the term sustainability, which is the subject of Section 4.1. This is followed by a description of existing and recommended methods for the assessment of the sustainability of technological systems in Section 4.2. Section 4.3 discusses the requirements that sustainability assessment methods have to meet. The suitability for use in this research of the sustainability assessment methods of Section 4.2 and the exergy analysis methods of Section 3.4 is investigated in Section 4.4.

4.1 Operationalization of sustainability

The terms 'sustainability' and 'sustainable development' are used interchangedly, but as Maude (2012, p.50) clearly pin-points these are different concepts: 'Sustainability is the state or condition of being sustainable, while sustainable development is a process of change'. Something being sustainable means that it will be there forever, which does not imply that it is a good thing. The same holds for sustainable development which can be viewed as the process by which sustainability is reached, or as something that puts the emphasis on development and economic growth (Maude, 2012).

A well-known definition is the 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' (WCED, 1987, p.43), but it needs operationalization, as already mentioned in Chapter 1. Many publications have been written about the definition of sustainability and sustainable development in an attempt to operationalise the concept of sustainability.

A literature research conducted in the Scopus database (www.scopus.com) after publications with the words 'sustainab*' and 'definition' in its title, abstract or keywords resulted in a list of more than 3000 publications. Narrowing the search by focussing on review papers and requiring a maximum of one term between the terms 'definition' and 'sustainab*' resulted in 57 publications in November 2013, e.g. Jørgensen et al. (2013); De Carvalho (2011); Hahn and Knoke (2010); Gagnon et al. (2009). From studying these papers as well as the papers found during the search into the relationship between exergy and sustainability (Section 3.3) and related publications, it was learned that a commonly accepted and useful operationalization of sustainability is still missing but that sustainability is usually assumed to consist of three components: environmental, economic and social sustainability. e.g. Teles dos Santos and Park (2009, p.1923) state that 'The search for sustainable development must be based on three pillars: economic viability, social concerns and ecological issues' and according to Yi et al. (2004, p.302) 'Industrial sustainability metrics aim to quantify the ecological, economic, and social aspects of processing systems and their life cycles to facilitate sound decision making'. The UNEP/Setac Life Cycle Initiative (http://lcinitiative.unep.fr/) considers these three aspects as well (Valdivia and Sonneman, 2011). Some researchers also consider a fourth pillar of sustainability, like Frangopoulos and Keramioti (2010) who consider a technical pillar as well. This technical pillar comprises indicators like energetic and exergetic efficiency, fuel consumption, availability etc. Jørgensen et al. (2013) argue that it is not always necessary to include the economic aspect, but that it is sufficient to consider the environmental aspect and a social aspect that is expanded to cover the influence of a product (or service, technology, system) life cycle on poverty and produced capital. According to them, the economic aspect may be included if it focuses on the monetary gains or losses for the poor.

When assessing the sustainability of a technological system, it is important to consider the system from a life cycle perspective to prevent problem-shifting between different life cycle phases and/or sustainability aspects (Finnveden et al. (2009)). This implies that not only the operational phase of installations, equipment and infrastructure is considered, but also their construction and decommissioning. Furthermore, the supply chains of the required feedstocks, materials and energy carriers during construction, operation and decommissioning should be taken into account, as well as the disposal/abatement of the emissions and waste flows, and the use of land and landscape destruction.

In this research, sustainability is subdivided into the commonly designated aspects environmental, economic and social sustainability. A life cycle point of view is adopted for the assessment of the technological systems of the case studies. Section 4.2 elaborates on assessment methods in the field of sustainability assessment.

4.2 Methods for sustainability assessment

The database of Scopus (www.scopus.com) has been queried for papers published in the International Journal of Life Cycle Assessment with 'sustainability' in the title, abstract and/or keywords of the paper to get an overview of LCA methods dealing with the environmental, economic and social aspects of sustainability. It appeared that many researchers and institutions are active in the field of sustainability assessment and the development of sustainability indicators and frameworks. According to Lettieri et al. (2009, p.1), who refer to the Scientific Committee on Problems of the Environment (SCOPE) (2007), ‘there is no scientific consensus on a common set of indicators appropriate for use within or between the pillars of sustainability’.

The method that is commonly used to assess the environmental performance of technological systems is the ISO certified environmental Life Cycle Assessment (LCA) method. This is the only environmental assessment method that has been internationally standardised (Swarr et al., 2011). Also Life Cycle Assessment methods that consider the economic and social aspects of sustainability have been or are being developed, i.e. Life Cycle Costing (LCC) and social LCA (S-LCA) methods, respectively.

A Life Cycle Sustainability Assessment (LCSA) method that combines LCA, LCC and S-LCA methods is under development (Valdivia et al., 2013; Guinée et al., 2011; Valdivia and Sonneman, 2011; Klöpffer, 2008). Difficulties in developing such an overall method or framework are the qualitative nature of many social indicators (Udo de Haes, 2008) and the weighting of the three sustainability aspects. On the other hand, it is being said that ‘A weighting between the three pillars, although implicit in any practical decision, should be avoided in the scientific domain in order to maintain transparency.’ (Swarr et al., 2011, p.12). The possibility that an aspect compensates for another aspect is called ‘weak sustainability’. A suggested solution to the weighting problem is the graphical presentation of the results of the three assessments in the form of a Sustainability Triangle (LCST) or Dashboard of Sustainability (Finkbeiner et al., 2010). The Dutch sustainability monitor (Monitor Duurzaam Nederland (CBS, 2011)) is an example of the use of a sustainability dashboard.

Sections 4.2.1 to 4.2.3 subsequently deal with methods for the determination of the environmental, economic and social aspects of sustainability from a life cycle perspective.

4.2.1 Environmental sustainability

The environmental Life Cycle Assessment (LCA) is the most elaborated variant of LCA. The method has been described in detail in the ISO 14040 and 14044 standards and consists of four phases: Goal and scope definition, Inventory analysis, Impact assessment and Interpretation (Guinée et al., 2002). During the first phase ‘the goal of the study is formulated in terms of the exact question, target audience and intended application’ and ‘the scope of the study is defined in terms of temporal, geographical and technological coverage, and the level of sophistication of the study in relation to its goal.’ (Guinée et al., 2002, Part2a, p.16). Another important part of this phase is the choice of the functional unit. The functional unit ‘describes the primary function(s) fulfilled by a product system, and indicates how much of this function is to be considered in the intended LCA study’ (Guinée et al., 2002, Part2a, p.22). The Inventory analysis phase results in a table with the quantified inputs and outputs from and to the environment that are associated with the functional unit. This is followed by the Impact assessment phase, in full 'Life Cycle Impact Assessment (LCIA)', in which the results of the inventory are used to calculate their contribution to selected impact categories. During the Interpretation phase the results of the assessment are evaluated, including the assumptions and other choices made in obtaining these results, and conclusions and recommendations of the study are drawn.

Many software tools have been developed for facilitating LCAs, e.g. SimaPro (www.pre.nl) and OpenLCA (www.openlca.org), as well as databases like the Ecoinvent (ecoinvent.org) and ELCD (lca.jrc.ec.europa.eu) databases.

The Impact assessment phase results in twelve environmental impact numbers, like the contribution to global warming, acidification, eutrophication etc. when applying the CML 2002 method (Goedkoop et al., 2009). The 'Eco-indicator 99' method, and its predecessor the 'Eco-indicator 95' method, have been developed to be able to present the results of an LCA as one number (Ministry of HSPE, 2000). The calculation of the 'Eco-indicator 99' score starts with the standard LCA procedure of making an inventory of the emissions, resource extractions and land use during the life cycle of a product. This is followed by calculating the damage these emissions etc. cause to the three damage categories 'human health', 'ecosystem quality' and 'resources', and subsequently weighting these three damage categories. Later on the CML 2002 and Eco-Indicator 99 methods have been combined in the development of the 'ReCiPe 2008' method (Goedkoop et al., 2009). By applying the ReCiPe method, the user can choose to present the environmental impact as 18 'midpoint' indicators or as three 'endpoint' indicators. The 18 midpoint indicators are the following: climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, ionising radiation, agricultural land occupation, urban land occupation, natural land transformation, water depletion, mineral resource depletion and fossil fuel depletion. Like the 'Eco-indicator 99' method, the three endpoint categories of ReCiPe are 'damage to human health', 'damage to ecosystem diversity' and 'damage to resource availability'. The characterisation factors of ReCiPe can be used in combination with the aforementioned Ecoinvent database.

The uncertainties in e.g. the environmental mechanism that is involved in climate change and several quantitative linkages between the midpoint and endpoint categories have been incorporated in ReCiPe in the form of three different perspectives or scenarios which the user can choose from. These perspectives have been developed using the cultural perspectives theory of Thompson et al. (1990) and are called individualist (I), hierarchist (H) and egalitarian (E) (Goedkoop et al., 2009). According to Goedkoop et al. (2009, p.17): 'These perspectives do not claim to represent archetypes of human behaviour, but they are merely used to group similar types of assumptions and choices. For instance:

- Perspective I is based on the short-term interest, impact types that are undisputed, technological optimism as regards human adaptation.

- Perspective H is based on the most common policy principles with regard to time-frame and other issues.
- Perspective E is the most precautionary perspective, taking into account the longest time-frame, impact types that are not yet fully established but for which some indication is available, etc.'

The Hierarchist perspective is a consensus model that is often considered as the default model (www.lcia-recipe.net).

Summarising, the environmental impact of the inputs and outputs of a system as well as the occupation and transformation of land are taken into account in environmental LCA. Section 4.2.2 elaborates on the economic aspect of sustainability.

4.2.2 Economic sustainability

The recommended method for assessing the economic aspects of a technological system from a life cycle point of view is called environmental Life Cycle Costing (LCC) (Ciroth et al., 2008; Swarr et al., 2011). This environmental LCC method can be used in combination with the standard, i.e. environmental, LCA to determine two of the three components of the overall Life Cycle Sustainability Assessment (LCSA) mentioned before. The environmental LCC differs from a conventional LCC in that it takes into account the whole life cycle of a product, including the phases of use and disposal that are usually not considered in a traditional LCC. Another feature of environmental LCC is that it considers the same functional unit and system boundaries as used in the accompanying LCA. The costs comprise the costs of physical processes and associated material and energy flows as well as labour costs, costs for R&D, marketing and so on (Rebitzer et al., 2003; Swarr et al., 2011). LCC considers only the costs that relate to real money flows plus 'externalities that are expected to be internalized in the decision-relevant future' because they comprise real money flows (Ciroth et al., 2008, p.xxvii). Other externalities should not be monetised to avoid double counting the environmental impacts that are taken into account in the accompanying LCA. The results of an LCC are preferably presented in combination with the main environmental impacts, like Global Warming Potential, determined by conducting an LCA.

As LCA is a steady-state type of analysis, Huppes et al. (2004) recommend calculating the LCC based on steady-state costs. The steady-state LCC method recommended by Huppes et al. (2004) calculates the steady state costs (SSC) or average yearly costs (AYC) by applying Equation 4.1 (Huppes et al., 2004):

$$SSC = AYC = \frac{\sum_{t=1}^{t=n} C_t}{fn} \tag{4.1}$$

with:
C_{t} = costs in year t
fn = functional number of years of the system

Ciroth et al. (2008) state that discounting the final result of environmental LCC is not consistent, and is not easy to carry out, but that the usual discounting of cash flows is the norm. According to the Code of Practice for Environmental Life Cycle Costing, 'The decision as to whether a study should use discounting, and if so, with what rate, is highly dependent on the goal and scope definition.' (Swarr et al., 2011, p.70). They provide the reader some guidelines in this field, e.g. that discounting can be neglected if the duration of the product system under study is less than two years. According to Heijungs et al. (2013, p.1730) 'most mathematical treatments of LCC focus on how to introduce discounting into the scheme, calculating the net present value'.

The Net Present Value (NPV) method is well-known and has already been used in assessing the sustainability of energy systems, for example by Frangopoulos and Keramioti (2010). It calculates the net present value from the present value of all cash inflows and outflows, as depicted in Equation 4.2 (Huppes et al., 2004).

$$NPV = \sum_{t=0}^{t=n} \frac{C_t}{(1+r)^t} \tag{4.2}$$

with:
C_{t} = costs in year t
n = number of years
r = discount rate

A disadvantage of the NPV when choosing between systems is that no attention is paid to the investment costs related to those systems. This problem is solved when the Present Worth Ratio (PWR) is used as the economic indicator because the PWR considers the investment costs of the systems as well (Adekunle, 2007). The PWR is defined as the NPV of all revenues and costs during the lifetime of the system divided by the NPV of the investment costs of the system (Equation 4.3). A positive PWR indicates that it is profitable to invest in the system. The higher the PWR, the more likely the investment is.

$$PWR = \frac{NPV}{\sum\limits_{t=0}^{t=i} \frac{I_t}{(1+r)^t}} \tag{4.3}$$

with:
I_{t} = investment costs in year t
i = number of years of construction

From this section, it is learned that steady-state LCC methods exist as well as LCC methods that consider discounting and investment costs. Section 4.2.3 describes the way the social aspect of sustainability can be considered.

4.2.3 Social sustainability

The social Life Cycle Assessment (S-LCA) method is described as 'a social impact (and potential impact) assessment technique that aims to assess the social and socioeconomic aspects of products and their potential positive and negative impacts along their life cycle' (Benoît and Mazijn, 2009, p.37).

The method is still under development (Benoît Norris et al., 2013). Guidelines for the social life cycle assessment of products have been presented in 2009 (Benoît and Mazijn, 2009; Benoît et al., 2010; Lehmann et al., 2013). According to Benoît et al. (2010, p.156) these guidelines 'complement those for environmental life cycle assessment and life cycle costing, and by doing so contribute to the full assessment of goods and services within the context of sustainable development'. According to the guidelines, in S-LCA the following stakeholder categories should be assessed as a minimum: worker, consumer, local community, society and value chain actors (not including consumers) (Benoît et al., 2010). The guidelines also present several subcategories for each stakeholder category, e.g. child labour and fair salary in the category worker, health and safety and consumer privacy (consumer category), access to material resources and cultural heritage (local community), contribution to economic development and corruption (society) and finally fair competition and respect of intellectual property rights in the category value chain actors (Benoît et al., 2010). Methodological sheets for subcategories in S-LCA (Benoît Norris et al., 2013) were published in 2013 to supplement the aforementioned guidelines and to guide the application of S-LCA. Difficulties in conducting a social LCA are the type (qualitative, semi-quantitative or quantitative) and availability of data and whether and how the results can be aggregated to obtain overall S-LCA indicators (Benoît Norris et al., 2013; Valdivia et al., 2013).

The description of the method for the assessment of the social aspect of sustainability completes the descriptions of the applied and/or recommended life cycle assessment methods of all three aspects of sustainability. Section 4.3 elaborates on the requirements sustainability assessment methods have to meet.

4.3 Requirements to sustainability assessment methods

Each sustainability assessment method has its own characteristics and not every method will be suitable for use in this research. To deal with the lack of a commonly accepted and useful operationalization of the concept of sustainability, a list of requirements is drawn up that can be used to assess the methods described in the Sections 3.4 and 4.2. The methods have to fulfil requirements with regard to the components of sustainability they take into account (Section 4.3.1) as well as some general requirements that are not related to sustainability (Section 4.3.2). Combining both types of requirements leads to the overall list of requirements of Section 4.3.3.

4.3.1 Requirements related to sustainability

As explained in Section 4.1, this research considers the construction, operation and decommissioning of the installations, equipment and infrastructure to produce the product, the use of feedstocks, materials and energy carriers, the disposal and abatement of emissions and waste flows, and the use of land for installations etc. The transport, distribution, use and storage of the products are not considered in this research (Section 1.3).

Figure 4.1 presents a schematic overview of the interactions between an installation and its surroundings during the operation of an installation that are within the scope of this research. The term 'installation' used in this figure refers to the main installation as well as other installations, equipment and infrastructure somewhere in the supply chain. The interactions can be divided into mass flows, energy flows, land use and man-hours. Examples of mass flows are feedstocks, materials, products, emissions and waste flows. Whether an output is regarded as a product or as an emission or waste flow is dependent on local circumstances and should be explained in the description of the technological system under study. The processing of emissions and waste flows, i.e. disposal/abatement, is considered in this research. The energy flows are flows like fossil and renewable energy carriers and waste heat. The land use represents the land that is used by the installation itself. The land used for e.g. growing renewable feedstocks is included in the supply chain of this feedstock. Furthermore, man-hours are needed for the operation of the installation, maintenance and so on.

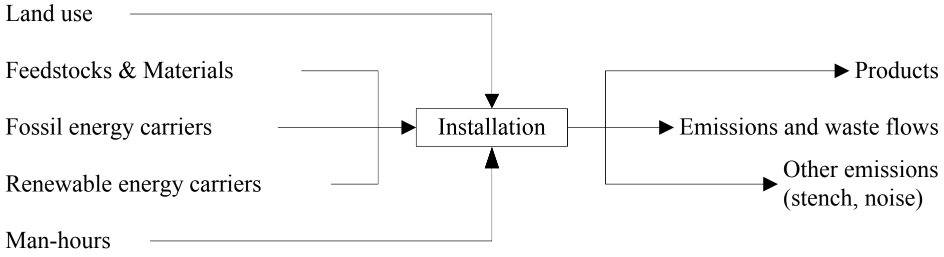

Figure 4.1: Physical interactions between an installation and its surroundings during the operational phase.

Emissions like stench and noise are not taken into account in this research because of lack of data to consider these components. The three-dimensional aspect of land use, i.e. landscape destruction caused by the height and volume of installations and infrastructure, is not considered for the same reason.

It was learned from comparing the interactions of Figure 4.1 with the components considered by the environmental LCA software tool SimaPro in combination with the Ecoinvent database that all interactions between a technological systems and its surroundings are included. According to Frischknecht et al. (2007), noise emissions are not yet included in the Ecoinvent database because no standardised reporting method for noise emissions exists. Data regarding other types of emissions like stench have not been found in the Ecoinvent database. The Ecoinvent database considers the surface area of land use, not the landscape destruction caused by the height and volume of installations.

Almost all inputs and outputs imply environmental and economic sustainability aspects and a certain amount of man-hours to produce the inputs or to process the outputs. Products represent only the economic aspect because the transport, distribution, use and storage of the products are outside the scope of this research. Man-hours represent the social aspect because of their effects on human well-being. Land use has a social dimension as well, i.e. landscape destruction, but landscape destruction is not considered in this research, as explained before.

Figure 4.1 is applicable to the operation of an installation, but when the flow named 'Products' is omitted, it is applicable to the phases of construction and decommissioning of an installation as well. This figure is used as a starting point for drawing up the list with requirements to sustainability assessment methods related to sustainability. The items of the list are introduced below and have been *italicised*.

Considering only the *amounts of inputs and outputs* is not enough to assess the environmental sustainability of these inputs and outputs. From Section 3.1 it was learned that the environmental impact of the inputs can be expressed in terms of *depletion/scarcity of the inputs*, including their precursors. The *distinction between renewables and non-renewables* (fossil resources) is related to depletion/scarcity and is of importance as well, e.g. when dealing with emissions like carbon dioxide and their origin. Making a distinction between renewable and non-renewable inputs is in line with the Life Cycle Exergy Analysis method (Section 3.4). The environmental impact of emissions and waste flows can be considered via their *disposal/abatement* and the associated use of inputs as described in Section 3.1. The economic sustainability aspect of inputs and outputs is related to their production costs and the price of the outputs, respectively.

Man-hours represent an economic component, they cost money, as well as a social component, e.g. working conditions. Man-hours are needed to produce the inputs, process the outputs and for the construction, operation and decommissioning phases of the installations, equipment and infrastructure.

Land use implies all three sustainability aspects, e.g. the influence of land use on biological processes like photosynthesis and pollination (environmental), its acquisition (economic) and landscape destruction (social), but as explained before, landscape destruction is not considered in this research.

The component of sustainability that is not visible in Figure 4.1 is the *loss of energy quality* (exergy) caused by technological processes (Chapter 2). The loss of exergy can be regarded as having environmental, economic and social components, because exergy (work potential) is needed for the things we would like to do.

As becomes clear from the description above, many sustainability components are related. E.g., most of the inputs and outputs represent environmental as well as economic aspects, and require a certain amount of man-hours to produce or process these inputs and outputs. Furthermore, man-hours represent an economic as well as a social component. The representation of multiple aspects by one input, output or other characteristic of an installation, process, product or service is no problem as long as double-counting of sustainability components is avoided when combining the results of assessment methods, e.g. when combining LCA with an environmental LCC. Neither is this a problem when carrying out separate environmental, economic and social sustainability assessments, because each assessment method has its own perspective (Section 4.4).

Based on the aforementioned, the following phases and components should be taken into account when determining the sustainability of a technological system, like a power plant, from a life cycle point of view. The overall environmental, economic and/or social dimensions of sustainability that a specific phase or component belongs to are mentioned in brackets.

- phases of construction, operation and decommissioning of the installations, equipment and infrastructure (environmental, economic)
- amounts of inputs like feedstocks, materials and energy carriers (environmental, economic)
- depletion and/or scarcity of the inputs (environmental)
- distinction between renewable and non-renewable inputs (environmental)
- amounts of outputs like products, emissions and waste flows (environmental, economic)
- disposal and/or abatement of emissions and waste flows (environmental, economic)
- man-hours (economic, social)
- land use (environmental, economic)
- loss of energy quality, i.e. exergy losses (environmental, economic, social)

4.3.2 General requirements

In addition to requirements related to sustainability itself, methods applied for the calculation of sustainability indicators should also meet more general requirements. The first general requirement is called ‘objectivity of the method’. A method is for example not regarded as objective when different views exist about how its indicators should be calculated, when it makes use of variables that are disputable, e.g. weighting factors, and/or when the results of a method change over time because of market influences or the like. Strictly speaking, the latter is not a consequence of the method itself, but the result of variations in one or more of the input variables used by that method. In this research, both aspects are grouped into ‘objectivity’ for reasons of simplicity.

The requirement that the applied methods for calculating sustainability indicators are objective is different from pursuing an objective overall sustainability assessment method that takes into account regular environmental, economic and social sustainability indicators as well as exergy losses. The importance that is attached to each of these four aspects is a subjective, and likely political, consideration.

Another requirement to assessment methods in general is that the data needed for the calculations of the methods are available and is named ‘availability of data’.

4.3.3 Overall list of requirements

The relevant components of sustainability of Section 4.3.1 and the components not related to sustainability of Section 4.3.2 can be combined into an overall list of requirements to sustainability assessment methods. The operational phase of installations, equipment and infrastructure is always taken into account by assessment methods and will therefore not be mentioned in the list of overall requirements. The same holds for the amounts of inputs and outputs to and from installations etc. The distinction between products on the one hand and emissions and waste flows on the other hand is based on the description of the technological system. The economic and social aspects of the interactions are grouped and mentioned in the list because it is not common practice to assess these aspects. The resulting overall list of requirements is presented below.

- phase of construction of the installations, equipment and infrastructure
- phase of decommissioning of the installations, equipment and infrastructure
- 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
- loss of energy quality, i.e. exergy losses
- economic aspects
- social aspects
- objectivity of the method
- availability of data

The overall list of requirements plus the operational phase and the components 'inputs', 'outputs' is suitable for use in this research because it considers all interactions between a technological system and its surroundings during its life cycle and pays attention to the general requirements named 'objectivity of the method' and 'availability of data'. The overall list of requirements is used to assess the exergy analysis methods of Section 3.4 and the non-exergetic sustainability assessment methods of Section 4.2, which is the subject of Section 4.4.

4.4 Suitability of the methods found in literature

The recommended LCA, environmental LCC and social LCA methods do not consider all aspects of sustainability, but only the aspect or aspects they are meant for. For example, the LCA method does not consider economic and social aspects of sustainability. Combination of the three assessment methods into an overall LCSA (Life Cycle Sustainability Assessment) method through weighting is subjective and leads to a loss of transparency.

The standard LCA method does not fully meet the requirement ‘objectivity of the method’, because the models used for calculating the different environmental impacts of e.g. emissions are not always commonly accepted. Several models exist if there is no consensus between the experts in that field (JRC-IES, 2011). Furthermore, weighting factors are applied for combining the environmental indicators into one overall indicator. Besides that, the environmental LCA method does not consider the loss of energy quality, i.e. exergy losses, caused by processes and activities.

The results of the environmental LCC method are influenced by choices with regard to the inclusion of externalities. Besides, the environmental LCC method does not meet the ‘objectivity’ requirement because the results are largely influenced by market developments, governmental decisions and consumer confidence.

A problem of the social LCA method is the limited availability and qualitative or semi-quantitative nature of many data. Furthermore, a standard method for conducting social LCA is still under development.

The exergy analysis methods described in Section 3.4 have shortcomings as well, which is explained below by mentioning one or more of the shortcomings of each method. First, the methods of Figure 3.4 are discussed in the same order as they appear in this figure. The **CExC** method itself calculates the overall exergy needed to produce a product, which is interesting, but this is no measure of the exergy that is lost because the CExC also includes the exergy content of the products. The related indicators named cumulative exergy loss and cumulative degree of perfection do not consider the exergy loss caused by land use. The **Exergetic Cost** method has the same shortcomings as the CExC method. The **Net Exergy Consumption** method subtracts the exergy of the products, but does not consider the disposal and/or abatement of emissions and waste flows. The **CExCA** method includes the abatement of emissions but does not account for land use. The **EEA** method includes economic parameters which makes this method less objective. The **Ecological Cost** method makes a distinction between renewable and non-renewable resources but has the same shortcomings as the CExC method. The **ECEC** and **Emergy** methods express resources and products in equivalents of solar energy, but these calculations encountered a lot of criticism. The **Expanded Cumulative Exergy Consumption** method has the same shortcomings as the CExCA method. The **CExD** and the **CEENE** methods have the aforementioned shortcomings of the CExC method. With regard to the methods of Figure 3.5, the **LCA** method itself is not satisfactory as mentioned above. The **ELCA** and **Zero-ELCA** methods do not consider land use and neither does the **LCEA** method. The **Exergoenvironmental** analysis is a method that allocates the results of an LCA to the individual components of a process or system, which is different from the goal of this research. Its predecessor, the **Exergoeconomic** analysis, does the same with economic indicators. The **Eco-LCA** method does not calculate exergy losses. The methods of Figure 3.6 have already been discussed above, except for the **Eco-Exergy** method, which does not calculate exergy losses. Finally, **Environomics** and the **multi-criteria approaches** introduced by Mirandola and Stoppato (2003) and Frangopoulos and Keramioti (2010) do not calculate exergy losses and their aggregation of different types of indicators, e.g. thermodynamic, economic and environmental indicators, leads to loss of information and makes these methods less objective. The **sustainability indicators based on exergy** found in literature do not calculate exergy losses and have the disadvantage that newly introduced indicators are usually not commonly accepted.

It is concluded that each of the aforementioned sustainability assessment methods has shortcomings. The methods do not consider all relevant components of sustainability and/or make use of indicators, equations and weighting factors that are not commonly accepted and therefore do not meet the objectivity requirement.

Because of the assumed relationship between exergy and sustainability (Chapter 2) and the shortcomings of the existing exergy methods, a new exergy analysis method is developed that is based on fundamental scientific equations and that takes into account as many of the designated components of sustainability as possible. Chapter 5 deals with the way the value of exergy analysis in sustainability assessment of technological systems can be investigated and describes the new exergy analysis method.

Chapter 5

Investigating the value of exergy analysis in sustainability assessment of technological systems

This chapter describes how the value of exergy analysis in sustainability assessment of technological systems can be investigated by a systematic comparison of the results of several sustainability assessment methods. As all of the assessment methods found in literature have shortcomings, a new exergy analysis method is developed in Section 5.1. Section 5.2 elaborates on the assessment methods the newly designed exergy analysis is compared with and is followed by a description of the way of comparison in Section 5.3.

5.1 The Total Cumulative Exergy Loss method

Section 5.1.1 explains to what extent the requirements to sustainability assessment methods can be met by exergy analysis methods in general. The new Total Cumulative Exergy Loss (TCExL) method is introduced in Section 5.1.2. This is followed by an explanation of the calculation of the components of the TCExL method, i.e. the internal exergy loss and the exergy losses caused by emission abatement and land use in the Sections 5.1.3, 5.1.4 and 5.1.5, respectively. Section 5.1.6 discusses the TCExL method.

5.1.1 Meeting the requirements

The requirement called 'objectivity of the method' is considered one of the fundamental requirements of Section 4.3.3 and is therefore the first to be discussed.

Objectivity of the method
Several of the methods described in Section 3.4 make use of newly invented factors and equations that are introduced by the researchers to include aspects of economic and social sustainability. The introduction of these factors and equations results in a less objective calculation method compared to methods based on fundamental thermodynamic equations only. An exergy analysis method is as objective as possible if it is decided to go ‘back to the basics’, i.e. when ‘just’ exergy losses are calculated by applying standard thermodynamic equations. In line with the desired objectivity of the method, the results of an objective exergy analysis method should be presented in the form of exergy losses because in this way any uncertainties related to the definition of exergy efficiencies are avoided (Section 2.1). The following paragraphs elaborate on the components of sustainability that can be taken into account by calculating exergy losses.

Construction and decommissioning of the installations, equipment and infrastructure
The phases of construction and decommissioning of the installations, equipment and infrastructure can be incorporated in an exergy analysis method by extending the system boundaries to include these phases of a life cycle.

Depletion and/or scarcity of the inputs
Each and every amount of mass and/or energy represents an amount of exergy, which means that resources (materials, energy) represent an amount of exergy as well. However, it is important to realise that the amount of exergy of resources is usually not lost completely, but partly ends up in the product (or products) of the process, as explained in Section 2.1.1. In other words, the amount of exergy represented by resources, or feedstocks, cannot be added to the internal exergy losses caused by the process or supply chain under consideration. Stated differently, the exergy losses caused by a process are no measure of the use of natural resources; they are a measure of the exergy that is lost due to the conversion of a feedstock (resource) into a product, nothing less, nothing more.

As already explained in Section 3.1.1, the depletion and scarcity of resources is a fact, not a technological process of which an exergy loss can be determined. However, it is expected that the scarcer a resource, the more exergy will be lost during the extraction of this resource. Thus, the scarcity and depletion of resources can indirectly be expressed in terms of exergy loss by taking into account the exergy losses caused by the extraction of these resources.

The depletion and/or scarcity of the inputs is no longer an issue when the assessed technological system includes technological installations for the transformation of the outputs to the required inputs, i.e. closing material cycles etc. An alternative to taking into account these technological installations is described by Valero and Valero (2014). They suggest the substitution of the exergy value of minerals with the amount of exergy that is needed to obtain these minerals when the mines are empty and the minerals have been dispersed throughout the earth’s crust.

Distinction between renewable and non-renewable inputs
With regard to the distinction between renewable and non-renewable resources, it should be realised that a unit of exergy does not contain any information about the

type of mass or energy flow that embodies this amount of exergy. Cornelissen and Hirs (2002) propose to distinguish between renewable and non-renewable resources by subtracting the exergy content of renewable resources from the internal exergy losses, but that goes against the fact that usually only a part of the exergy content of a resource is lost, as explained above. Another objection is that every exergy loss counts, whether it originates from a renewable or from a non-renewable resource. A way to distinguish between renewable and non-renewable resources is differentiating between them via the abatement of emissions, i.e. by not taking into account the abatement of CO_2 and possibly other emissions that originate from renewable resources.

Disposal and/or abatement of emissions and waste flows

Emissions and waste flows can cause environmental effects because of the work potential they represent, but as explained in Section 3.1.1, the external exergy loss caused by 'throwing away' emissions and waste flows is no measure of their environmental impact, e.g. their toxicity. Instead of considering the external exergy loss, the environmental impact of emissions and waste flows can be taken into account via the exergy losses accompanied with the abatement of the emissions and waste flows until the effects of these emissions and waste flows on the environment are negligible, which is known as abatement exergy. It is expected that the higher the possible environmental impact, the lower the acceptance level will be. Whether the exergy loss caused by the abatement of emissions with a high environmental impact is higher than that of emissions with a lower environmental impact is not relevant as long as the analysed system includes the abatement of the emissions and waste flows to an acceptable level. The abatement exergy is an internal exergy loss and can be added to the internal exergy loss caused by the main process itself.

Land use

Every technological process is accompanied with exergy loss due to the transformations that take place within that process. Besides that, technological processes limit the possibilities of the natural environment to capture new exergy from sunlight because of the surface of the earth that is needed for e.g. its installations, equipment and infrastructure. Otherwise, this area of land would be available for natural processes like photosynthesis by natural vegetation. In environmental LCA, the transformation of land is considered as well, e.g. the transformation of the land type 'pasture and meadow' into the land type 'industrial area' is denoted as 'Transformation, from pasture and meadow' and 'Transformation, to industrial area'. The transformation from different types of land can be considered in exergy analysis if a differentiation is made between land types in the calculation of the exergy loss caused by land occupation. Not only the occupied surface area plays a role, but also the height of the installations can influence natural processes like pollination, the direction of wind etc. As little data are available about the height and volume of installations and as it is difficult to quantify the influence of the height and volume of installations on the ecosystem's possibility to capture exergy, it is assumed that only the effects of occupying earth surface by technological installations and related activities have to be taken into account. The calculation of the exergy loss, or more precise: the prevention of exergy capture caused by this land use, is explained in Section 5.1.5. The exergy loss caused by land use can be added to the internal exergy losses and can be regarded as a way to take into account the role of ecosystems and services (Section 3.4).

Loss of energy quality, i.e. exergy losses
Taking into account the loss of energy quality is by definition incorporated in any exergy analysis method. As a result of the requirement that the method has to be objective, the calculation of exergy losses instead of exergy efficiencies is preferred.

Economic and social aspects
Exergy losses are related to the physical transformations taking place within the object of analysis. The economic and social dimensions of sustainability are more or less related to these physical transformations as well, e.g. the costs of inputs and the number of man-hours, but depend to a large extent on non-physical aspects like market prices and working conditions. Somehow incorporating the economic and social dimensions of sustainability in the exergy analysis method would lead to loss of objectivity of the method (Section 4.4). Nevertheless, the loss of exergy can be regarded as having economic and social components because exergy (work potential) is needed for the things we would like to do (Section 4.3.1).

Availability of data
Many publications about thermodynamics, exergy analysis and properties of substances are available for the calculation of exergy losses. If data about a specific substance are not available, these can be estimated by applying one of the many methods described in literature.

Summarising, an exergy analysis method can meet almost all requirements of Section 4.3.3, but the depletion and scarcity of resources and the economic and social dimensions of sustainability can only be taken into account indirectly. Section 5.1.2 presents the exergy analysis method that has been developed on the basis of the aforementioned.

5.1.2 Definition of the Total Cumulative Exergy Loss

As explained in Section 5.1.1, almost all requirements to sustainability assessment methods can be met by calculating the internal exergy losses caused by a system including processes for the abatement of its waste flows and emissions and the exergy loss accompanied with the land used by that system. The newly developed exergy analysis method has been named the Total Cumulative Exergy Loss (TCExL) method. The TCExL considers the aforementioned exergy losses and is subdivided into three types of exergy loss, i.e. internal exergy loss, abatement exergy loss and exergy loss caused by land use. Equation 5.1 presents the TCExL method as a formula.

$$TCExL = Ex_{\text{loss,internal}} + Ex_{\text{loss,abatement}} + Ex_{\text{loss,land use}} \tag{5.1}$$

The internal exergy loss is the exergy loss caused during the construction, operation and decommissioning of the installations and is calculated from the amount of exergy represented by the inputs and outputs to and from the installations (Equation 5.2).

The internal exergy loss includes the life cycle phases ‘Construction and decommissioning of the installations, equipment and infrastructure’ and the component ‘Depletion and/or scarcity of the inputs’ of Section 5.1.1.

$$Ex_{\text{loss,internal}} = Ex_{\text{inputs}} - Ex_{\text{products}} - Ex_{\text{emissions, waste flows}} \tag{5.2}$$

The second type of exergy loss is called abatement exergy loss and concerns the components ‘Distinction between renewable and non-renewable inputs’ and ‘Disposal and/or abatement of emissions and waste flows’. The last type of exergy loss is the exergy loss related to land use which incorporates the component ‘Land use’ of Section 5.1.1.

The TCExL method can be regarded as a combination of, or extension to, the existing exergy analysis methods called Cumulative Exergy Consumption (CExC), Cumulative Exergy Consumption and Abatement (CExCA), Cumulative Exergy Extraction from the Natural Environment (CEENE), and Exergetic Life Cycle Assessment (ELCA) described in Section 3.4.

5.1.3 Calculation of the internal exergy loss

The calculation of internal exergy losses of processes or systems is quite straightforward because the internal exergy loss is equal to the ingoing amount of exergy minus the outgoing amount of exergy of this process or system. The calculation of exergy values of electricity, heat and mass flows relative to the reference environment defined by Szargut et al. (1988) is explained in Appendix A.

5.1.4 Calculation of abatement exergy values

A quick literature research into ‘abatement exergy’ learned that researchers in this field (Dewulf et al. (2001); Wang et al. (2003, 2005); Liu et al. (2010)) use the abatement exergy values introduced by Dewulf et al. (2000) for CO_2 emissions and the values introduced by Cornelissen (1997) for SO_2, NO_x and phosphate emissions. Some authors make use of all abatement exergy values introduced by Cornelissen (1997), e.g. Rubio Rodríguez et al. (2011). Wang et al. (2005) assume that the abatement exergy of other emissions can be estimated from the abatement exergy of CO_2 by multiplying this value with the Global Warming Potential index over a 100 year period of the other emissions, but the contribution to the GWP is not expected to be a very accurate measure of the exergy loss caused by abatement of the emission. Therefore, this calculation method is not applied in this research.

Carbon dioxide
The abatement exergy value of 3 MJ/kg CO_2 introduced by Cornelissen (1997, p.120) is based on ‘separation of 90% CO_2 out of the flue gases, compression and storage in empty gas fields’. Dewulf et al. (2000) introduce another value for CO_2 abatement, namely 5.862 MJ/kg, which is based on CO_2 recovery via ethanolamine absorption and stripping, followed by compression to 80 atm. for underground storage. Van der Vorst et al. (2011) explain that the value of Cornelissen (1997) is an underestimation.

Sulphur dioxide
According to Cornelissen (1997), the abatement exergy of SO_2 is 57 MJ/kg. This value is based on a 90% removal of SO_2 in a flue gas desulphurisation unit of a coal-fired power plant by means of limestone and its subsequent conversion to gypsum.

Nitrogen oxides
The abatement exergy for NO_x is based on a 80% removal in a $DeNO_x$ unit of a coal-fired power plant and amounts 16 MJ/kg (Cornelissen, 1997). The NO_x is removed by reacting with NH_3 to N_2 and H_2O.

Phosphate
The abatement exergy of phosphate is 18 MJ/kg for 99% removal (Cornelissen, 1997).

An overview of the abatement exergy values used in this research is presented in Table 5.1. During future research, abatement exergy values based on the newest abatement technologies will be calculated as well as abatement exergy values of other emissions.

Table 5.1: Overview of the applied abatement exergy values of emissions (Cornelissen, 1997; Dewulf et al., 2000; Van der Vorst et al., 2011).

Emission	Abatement exergy [MJ/kg]
CO_2	5.86
NO_x	16
Phosphate	18
SO_2	57

5.1.5 Calculation of the exergy loss caused by land use

Another aspect of the new exergy analysis method is that the role of ecosystem goods and services is more or less taken into account by considering the amount of exergy that becomes unavailable to the ecosystem because of the land occupied by the installations, equipment etc. of the system. If this land is not occupied, the ecosystem can capture exergy from the solar energy radiated on the land via photosynthesis.

In analogy with the CEENE method introduced by Dewulf et al. (2007), the exergy loss caused by land use can be calculated by multiplying the average solar irradiation with the efficiency of capturing sunlight via photosynthesis and the amount of exergy per amount of sunlight, i.e. 0.9327 (Szargut et al., 1988), as depicted in Equation 5.3.

$$Ex_{\text{loss, land use}} = IRR \cdot \eta_{\text{photosynthesis}} \cdot 0.9327 \tag{5.3}$$

with:
IRR = average solar irradiation [GJ/(ha·year)]

According to Lems (2009), the exergy efficiency of the photosynthesis process itself equals 41% at a 680 to 700 nm wavelength of the photons, but he also says that the average overall efficiency of the capturing of solar energy by plants during a year is much lower and that this efficiency strongly depends on the amount of solar radiation, its wavelength and the temperature on earth. The theoretical maximum efficiency of capturing solar energy by means of photosynthesis is 10.8 per cent (Sharma-Natu and Ghildiyal, 2005). In the CEENE method, it is assumed to be 2% (Dewulf et al., 2007). According to Turkenburg (2000); Archer and Barber (2004); Schiermeier et al. (2008), the maximum efficiency of photosynthesis during a short time can be 5%, but on average a value between 0.5 and 1 per cent is more realistic. In previous publications about this research (e.g. Stougie and Van der Kooi (2014)), it was assumed that the efficiency of capturing solar energy via photosynthesis equals 0.75%.

The average solar irradiation in Western Europe has been calculated at about 2.78 kWh/m^2 per day based on the international solar irradiation database (Lowell, 2011; Dewulf et al., 2007). This results (Equation 5.3) in an exergy loss due to land use of 256 GJ exergy/ha·year for industrial areas. Table 5.2 presents the calculated average solar irradiation per continent. The country of which the highest average solar irradiation has been calculated is Namibia, i.e. 6.52 kWh/m^2 per day. The arctic area has the lowest average solar irradiation, i.e. 1.97 kWh/m^2 per day according to the data provided by Lowell (2011).

Table 5.2: Average solar irradiation per continent calculated from data provided by Lowell (2011).

Continent	Average solar irradiation [kWh/m^2 per day]
Africa	5.42
Antarctica	2.42
Asia	4.76
Central America	5.15
Europe	3.37
North America	4.10
Oceania	5.03
South America	4.57

Alvarenga et al. (2013) present an alternative to the way of calculating the exergy loss caused by land use introduced by Dewulf et al. (2007). This new method makes use of the natural potential Net Primary Production (NPP), i.e. 'the net amount of carbon assimilated in a given period by vegetation' (Haberl et al., 2007, p.12942), when this land is not occupied and a biomass exergy conversion factor that equals 42.9 MJ$_{\text{ex}}$ per kg of carbon on average. An advantage of the use of the NPP compared to the previous method is that the NPP takes into account aspects like climate and soil quality and that detailed data about the NPP is available, i.e. with a grid size of 5' geographical resolution (about 10 by 10 km at the equator) for the year 2000 (Haberl et al., 2007). Alvarenga et al. (2013) calculated characterization factors in MJ$_{\text{ex}}$/m^2 per year at the same detailedness, as well as of the continents and at a country level. The world average of the characterization factor amounts to 21.5 MJ/m^2 per year. It is learned from comparing this characterization factor with the method applied in CEENE (Equation 5.3) that both methods result in equal amounts of exergy loss caused by land use if the efficiency of photosynthesis is assumed to be 0.63 instead of 0.75 per cent. This implies that the effect of choosing one or the other method on the results of the case studies is small. In this research, the exergy loss caused by land use is based on the method of Alvarenga et al. (2013).

In environmental sustainability assessment, e.g. the ReCiPe method (Section 4.2.1, a distinction is made between the several types of land used by technological systems. E.g., the impact of land used for industrial installations is higher than the impact of land used for forests. The TCExL method includes the calculation of the amount of exergy that cannot be captured via photosynthesis as a result of land that has become unavailable to the ecosystem. This implies that land that is used by a technological system for the growing of trees or another type of biomass should not be taken into account in the calculation of the exergy loss (or in other words: prevention of exergy capture) caused by land use. Furthermore, considering the land used for growing biomass would lead to double-counting because the use of biomass (as resource/input) is already considered in the calculation of the internal exergy loss caused by the technological system. In addition, the land use types related to marine ecosystems are not taken into account because the fraction of solar exergy captured is negligible according to Dewulf et al. (2007). This means that the following types of land use are not considered in the calculation of the exergy loss caused by land use: ‘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’. Land transformation is not considered in this research because the TCExL method is meant for calculating the total cumulative exergy loss caused by a technological system compared to the situation in which the ecosystem is not hindered by a technological system. I.e., only the type of land occupation by the technological system counts and not whether the type of land had been e.g. forest or industrial area before the technological system was constructed.

5.1.6 Discussion

The newly developed TCExL method calculates the exergy loss caused by technological processes. Internal exergy losses are caused by driving forces (Section 2.1.1). The larger the driving force that gets a process running, the more spontaneously that process will take place and the more difficult it will be to run that process in the opposite direction or to reach the initial state via an alternative route. Reaching the initial state is important from a sustainability point of view, with the closing of material cycles as an example. In short, the larger the exergy loss caused by a process or system, the less sustainable this process or system is.

Based on the definition and components of the TCExL method, the TCExL increases with the use of raw materials and energy carriers, the amounts of emissions and the use of land. The components of sustainability of the list of requirements that can only indirectly be considered are the decrease of natural resources and the economic and social aspects of sustainability. I.e., the decrease of natural resources results in higher exergy losses accompanied with the extraction of resources that are scarcer. The economic aspect is for example related to the amounts of raw materials and products, which represent an amount of exergy, to the man-hours needed to extract or process these inputs and outputs, and to the land used. The social aspect of the list of requirements belongs to the number of man-hours, which are related to amounts of exergy as described before, and originates from the notion that exergy loss influences the environmental, economic and social sustainability because exergy is needed for all processes and activities. A differentiation between the man-hours with regard to working conditions and other inequalities between human beings on a local level cannot be incorporated into the TCExL method via fundamental thermodynamic equations.

At the moment, only the abatement exergy losses of a few emissions are considered in the TCExL method because the abatement exergy losses of other emissions are not yet available. This means that the calculated TCExL is lower than it will be in reality.

The TCExL method is an improvement compared to existing exergy analysis methods in the sense that the TCExL method is solely based on the calculation of exergy losses and that it takes into account all exergy losses caused by a technological system during its life cycle. The TCExL method is also an improvement compared to regular, i.e. non-exergetic, sustainability assessment methods in the sense that the calculation of exergy losses is based on fundamental thermodynamic equations that do not change over time. The calculated TCExL is therefore timeless and not influenced by new insights into applied weighting factors, market prices etc.

The TCExL method is also relevant in view of 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' (WCED, 1987, p.43) because the TCExL method not only considers the exergy losses caused by a technological system but also includes the abatement of emissions and waste flows and the prevention of capturing new exergy from sunlight. The inclusion of abatement makes that the outputs of technological systems no longer influence the ecosystem nor human beings. With regard to the needs of present and future generations, all kinds of resources and materials can be made available via exploration and/or regeneration if enough exergy is available to do so. The lower the amount of exergy that is available on earth, the lower the ability of people to abate emissions and to meet their needs in the sense of e.g. materials they would like to use for their activities. Exergy that is not lost by a generation is available for future generations. This implies that the TCExL can be considered as an operationalization of the definition by the Brundtland commission.

Looking for similarities between the TCExL method and the environmental, economic and social life cycle assessment methods, i.e. LCA, LCC and S-LCA, it is noted that the TCExL as well as the (environmental) LCA are based on the inputs, outputs and land use of the technological system under consideration. The LCC method is based on the same variables, but depends on economic aspects like market prices and interest rates as well. The S-LCA method is based on variables like the number of employees and children working per amount of product, the wages for working hours and the compliance with regulations regarding health and safety (Valdivia et al., 2013; Valdivia and Sonneman, 2011; Benoît and Mazijn, 2009). Thus, S-LCA is based on the inputs and outputs of the technological system via the number of man-hours as well as on other aspects, which can be local ones like compliance with regulations regarding health and safety.

To be able to investigate the value of exergy analysis in sustainability assessment of technological systems, the results of the TCExL method will be compared with the results of regular sustainability assessment methods. Section 5.2 goes into detail about which other assessment methods will be used for this purpose.

5.2 Selection of the assessment methods to compare with

The value of exergy analysis in sustainability assessment of technological systems is investigated by comparing the results of the TCExL method with the results of regular, i.e. non-exergetic, methods that are applied and/or recommended for sustainability assessment. These regular methods have shortcomings with regard to the list of requirements, but comparison of the results of the TCExL method with the results of regular methods is the only way to investigate the value of the TCExL method. Sections 5.2.1, 5.2.2 and 5.2.3 deal with the selection of the environmental, economic and social sustainability assessment methods, respectively.

5.2.1 Environmental assessment method

The Endpoint indicator approach of ReCiPe (Section 4.2.1) has been chosen to analyse the environmental sustainability. This has been done because ReCiPe is the result of a thorough cooperation between experts in the field of LCA and because it is a recent development in this field. The reason for calculating Endpoint indicators is the need for a single environmental indicator. The software tool SimaPro in combination with the Ecoinvent database has been used to calculate the ReCiPe Endpoint indicators. A consequence of using the Ecoinvent database is that the ‘Emissions from the past (infrastructure construction), the present (e.g. heating) and the future (e.g. disposal options) are all included in the inventory analysis, virtually without temporal boundaries.’ (Frischknecht et al., 2007, p.9). Land occupation and land transformation are also considered in determining the Endpoint indicators. Land occupation is another name for land use and means the land that is occupied by an installation during a certain period of time for the production of products and services and is expressed in square metres times year. With ‘land transformation’, expressed in square metres, the conversion between a natural resort and industrial land is meant, e.g. clear-cutting of primary forests or active recultivation (Frischknecht et al., 2007).

5.2.2 Economic assessment method

In spite of the steady-state nature of the environmental life cycle assessment method (Section 4.2.2), it is not uncommon to calculate the Net Present Value (NPV) when performing environmental LCC (Swarr et al., 2011; Heijungs et al., 2013). The Net Present Value is a well-known economic metric, but it disregards the accompanying investment costs. As these investment costs are very important in choosing between systems, it was decided to use the Present Worth Ratio (PWR, Section 4.2.2) as the indicator of the economic sustainability in this research.

5.2.3 Social assessment method

As the method of social life cycle assessment (S-LCA) is not yet finalised (Section 4.2.3) and because it would be too time-consuming and costly to gather site-specific social data, it was decided to look for another way to determine the social sustainability of a supply chain. A literature research conducted in April 2012 in the Scopus database (www.scopus.com) after publications with the words 'sustainab*', 'social', 'indicator' and 'life cycle' or 'supply chain' in its title, abstract or keywords resulted in 147 publications, e.g. Hutchins and Sutherland (2008); Labuschagne and Brent (2008); Hunkeler (2006). What was learned from studying the abstracts, the full versions of interesting papers and related papers confirmed the idea that many indicators, indices and frameworks for the assessment of social sustainability have been developed, that no consensus exists about which one to use and that the required data are difficult to obtain. Overviews of indicators, frameworks and guidelines in this field and their characteristics are provided by several researchers, e.g. Labuschagne et al. (2005); Labuschagne and Brent (2006); Jørgensen et al. (2008); Klöpffer (2008). The range of these indicators, frameworks and guidelines varies from global frameworks, like the indicator framework of the UN (UN, 2007) and the Global Reporting Initiative (GRI) Reporting Framework (Global Reporting Initiative, 2011) to corporate sustainability indices like the Dow Jones Sustainability Index (SAM and S&P Dow Jones Indices, 2012). The difficulty with those indicators etc. is the limited availability of site-specific and/or corporate social data and the qualitative nature of many social aspects.

Hunkeler (2006) proposes to apply a societal assessment method that makes use of labour hours for the comparison between systems. He determines the employment hours related to every unit of the life cycle inventory that results from the environmental LCA, e.g. employment hours related to extraction of fuels and materials, carbon dioxide emissions etc., and takes into account the geographical region where the activities take place. From the number of employment hours per country and the average wage in a country, he calculates the access to four midpoint categories, i.e. housing, health care, education and necessities. A weakness of his approach is the assumption that employees spend their money equally on the four categories, i.e. 25% on housing etc.

In an attempt to make the social assessment method used in this research as objective as possible, it was decided to look for a single social-based indicator that can be used in combination with the number of employment hours per country. Ideally, indicator values of all countries of the world are available. Studying a number of overview publications in this field (Van de Kerk and Manuel, 2008; Phillis et al., 2011, 2010; Parris and Kates, 2003; Hass et al., 2002; Hutchins and Sutherland, 2008) resulted in a large number of indices and indicators on a national level, e.g. (in alphabetical order): CSD Indicators, Commitment to Development Index, Ecological Footprint, Environmental Sustainability Index, Environmental Performance Index, Genuine Progress Indicator, Human Development Index, Index for Sustainable Economic Welfare, Indicators for the EU Sustainable Development Strategy, Millennium Development Indicators, Multiple Criteria and Fuzzy Logic and Corporate Sustainability, Pressure-State-Response Indicators of the OECD, Sustainability Assessment by Fuzzy Evaluation (SAFE), Wellbeing of Nations (Barometer of Sustainability).

The following indicators and indices of the previous list focus on the social aspect of sustainability and are available for a large number of countries:

- Human Development Index (HDI): The HDI per country is presented annually by the United Nations Development Programme (UNDP). The UNDP states that ‘It is now almost universally accepted that a country’s success or an individual’s well-being cannot be evaluated by money alone. Income is of course crucial: without resources, any progress is difficult. Yet we must also gauge whether people can lead long and healthy lives, whether they have the opportunity to be educated and whether they are free to use their knowledge and talents to shape their own destinies.’ (Klugman, 2010, p.iv). The HDI, which was launched in 1990, is based on the average achievements in a country in the fields of ‘a long and healthy life’, ‘access to knowledge’ and ‘a decent standard of living’. The HDI is calculated as the geometric mean of the three normalised indices representing the aforementioned dimensions of human development. To correct for inequalities in human development across the population of a country, the UNDP has also developed the Inequality-adjusted Human Development Index (IHDI). The aspects of which the inequality in distribution of the HDI dimensions has been estimated are ‘life expectancy’, ‘years of schooling and household income (or consumption)’ and ‘the inequality in standard of living dimension’. Political participation and social cohesion are components of human development that have not yet been accounted for in the HDI and IHDI (Klugman, 2010).

- Human Sustainability component of the Sustainability Assessment by Fuzzy Evaluation (SAFE) model: The SAFE model has been developed by the Technical University of Crete, Greece, and combines an ecological sustainability component (ECOS) with a societal or human sustainability component (HUMS) (www.sustainability.tuc.gr). The HUMS component comprises political aspects, economic welfare, health and education (Phillis et al., 2010, 2011) and has been calculated for about 130 countries. The SAFE model applies fuzzy logic, i.e. if-then-rules, to calculate the ECOS, HUMS and overall OSUS indices from the 75 basic indicators per country instead of applying weighting methods. The presented ECOS, HUMS and OSUS indices are not applicable to one year, but cover the period 1990 to 2005. In September 2012 the aforementioned website did not present more recent data.

- Human Well-Being component of the Wellbeing of Nations index (HWI): In 2001 the HWI was introduced by the International Union for the Conservation of Nature (IUCN). It is stated that 'The HWI is a more realistic measure of socioeconomic conditions than narrowly monetary indicators such as the GDP and covers more aspects of human well-being than the Human Development Index.' (Prescott-Allen, 2001, p.3). A disadvantage of the Human Well-Being index is that the index is not published yearly, i.e. the last and only known publication dates back to 2001 (Prescott-Allen, 2001).
- Sustainable Society Index (SSI): The SSI has been developed by the Dutch Sustainable Society Foundation (www.ssfindex.com) and is based on the following extension of the well-known Brundtland definition: 'A sustainable society is a society that meets the needs of the present generation, that does not compromise the ability of future generations to meet their own needs, in which each human being has the opportunity to develop itself in freedom, within a well-balanced society and in harmony with its surroundings.' (Van de Kerk and Manuel, 2008, p.229) The SSI consists of 22 indicators that are grouped into 5 categories, i.e. Personal development, Clean environment, Well-balanced society, Sustainable use of resources and Sustainable world. The SSI has yet been calculated of about 150 countries, makes use of publicly available data only and is updated two-yearly (2006, 2008, 2010) as per September 2012.

The problem with the Human Sustainability component of the SAFE model and the HWI is the lack of recent data. An advantage of the SSI is its broad definition of sustainability, but this has the accompanying disadvantage that it also considers aspects that belong to the technological part of the assessment, e.g. the sustainable use of resources. Furthermore, the SSI is calculated of fewer countries than the HDI and IHDI. The IHDI has the additional advantage that it considers the inequality between people. On the basis of the aforementioned advantages and disadvantages, it was decided to take into account the social aspect of sustainability by means of the Inequality-adjusted Human Development Index (IHDI) as reported by the UNDP (Klugman, 2010). This is done by calculating the number of man-hours of the different stages of the production chains (e.g. exploration, conversion, transport) and dividing these hours between the countries the employees originate from, which is followed by aggregating the number of man-hours per country over the whole production chain. Finally, the overall IHDI can be calculated by summing the products of the percentage of man-hours per country and the IHDI of that country over all countries, as shown in Equation 5.4.

$$IHDI_{\text{overall}} = \frac{\sum_{i=1}^{i=n} perc.man\text{-}hrs_i \cdot IHDI_i}{100} \tag{5.4}$$

with:
$perc.man\text{-}hrs_i$ = percentage of man-hours per country
$IHDI_i = IHDI$ of country i

The calculation method of the $\text{IHDI}_{\text{overall}}$ implies that the social sustainability decreases with an increasing number of man-hours spent by people originating from countries with a low IHDI, which is in line with the general notion that the social sustainability decreases with the living conditions of the people involved. This is not meant to say that less man-hours should be spent by people originating from less-developed countries, but that the living conditions of the employees have room for improvement. The calculation of the $\mathrm{IHDI}_{\mathrm{overall}}$ does not have an added value anymore when the IHDIs of the current less-developed countries have increased to the same level as the developed countries, but the same would hold for an indicator based on local sustainability aspects when differences between local sustainability aspects no longer exist. A limitation of calculating the social sustainability indicator from more general indicators like the IHDI is that local aspects like working conditions of the individual employees are not considered.

Summarising, the TCExL method is compared with an LCA method that calculates ReCiPe endpoint indicators, an environmental LCC method based on calculating the PWR and a newly developed social LCA method that makes use of the Inequality-adjusted HDI reported by the UNDP. Section 5.3 elaborates on the method that is used for the comparison of the results of the four assessment methods.

5.3 Method for comparing the results of the assessments

The value of exergy analysis in sustainability assessment of technological systems can be investigated by conducting case studies that comprise several systems, in this case power generation systems, followed by comparing the results of the assessment methods with and without exergy of these systems.

In general, two methods of comparing the results of the assessments with and without exergy can be distinguished. One method is to combine the results of the environmental, economic and social assessments into one overall sustainability indicator and to compare the results of the TCExL assessment method with this overall indicator. However, combining the three sustainability indicators into one overall indicator is subjective and leads to a loss of information. The other method of comparing is by confronting the separate results of the environmental, economic, social and exergetic assessments of the systems with each other. The latter method is applied in this research by conducting two case studies that each consist of three different systems for power generation.

On the basis of the results of the assessments it can be concluded which system of a case study is preferred from an environmental point of view, which system is preferred from an economic point of view, etc. Table 5.3 presents an example of the ranking of the systems of a case study. According to this table, system A is preferred on the basis of the results of methods 1 and 2, and the systems B and C are preferred based on the results of methods 3 and 4, respectively. It can also be concluded what the consequences of choosing the system that is preferred from an exergetic point of view are with regard to the environmental, economic and social sustainability of the case study. E.g., in case the system is chosen that is preferred according to the results of method 1, i.e. system A, this has no consequences for the sustainability of the case study from the viewpoint of method 2, but the sustainability from the viewpoint of method 3 is less and even worst from the viewpoint of method 4.

Table 5.3: Example of the ranking of the several systems of a case study per assessment method.

Systems	Method 1	Method 2	Method 3	Method 4
System A	1	1	2	3
System B	2	3	1	2
System C	3	2	3	1

During the case studies, the results of the assessment methods are also studied in more detail by investigating which processes of the systems contribute most to the overall scores of the sustainability assessment methods.

Summarising, this chapter introduced the exergy analysis method that is used in this research, as well as the three sustainability assessment methods that this exergy analysis method is compared with. Furthermore, it elaborated on the way of comparing the results of the four methods.

Chapter 6 discusses the choice of the case studies in this research and provides additional information regarding the applied calculation methods and data.

Chapter 6

Introduction to the case studies

This chapter starts with the choice of the case studies in Section 6.1 and provides information about calculation methods and data that are used in all case studies in Section 6.2. The results of applying the methods to the case studies are described in Chapters 7 and 8.

6.1 Choice of the case studies

As already described in Section 1.3, this research focuses on central, large-scale power generation and is limited to systems that are applicable in the Netherlands, i.e. it is not realistic to take into account enormous hydropower installations. Examples of power generation systems that are applied or considered in the Netherlands are coal, gas and nuclear power plants, wind farms, small-scale photovoltaic installations and biomass installations. An important requirement introduced in Chapter 5 is that each case study comprises a number of alternative systems that can be compared, e.g. different types of coal power plants. The transport, distribution, use and storage of the produced electricity are not considered since these would be the same for all case study systems.

The answer to the fifth research question, i.e. 'What is learned from the case studies about the value of exergy analysis in sustainability assessment of technological systems?', can best be found when the case studies are diverse. It was therefore decided to conduct a case study that deals with different types of installations using the same source of energy and a case study that compares power generation from fossil and renewable energy sources. The systems of the case studies have been chosen on the basis of information about current and future power generation systems that are topical in the Netherlands. The choice of the subjects of the case studies and the systems that are part of the case studies is not meant to indicate that these system or systems are preferable and/or desirable.

The subject of the case study that deals with different types of installations using the same source of energy is power generation in combination with Liquefied Natural Gas (LNG) evaporation. Reasons for choosing this subject are that it is a topical issue in the Netherlands and that different systems exist. According to the current plans, the waste heat of the power plant will be used to evaporate the LNG, but also an alternative system is (De Buck et al., 2008) in which an oxyfuel power plant is combined with LNG evaporation and air separation. Furthermore, in literature systems can be found in which the LNG cold is used to generate electricity by means of an Organic Rankine Cycle (ORC), e.g. Tsatsaronis and Morosuk (2010); Szargut and Szczygiel (2009); Liu et al. (2009); Lu and Wang (2009); Deng et al. (2004). The third system that is studied comprises LNG evaporation in combination with an ORC and a separate power plant.

The systems of the case study that compares power generation from fossil and renewable energy sources are topical in the Netherlands as well. Co-firing of biomass is regarded as a way to make power generation more sustainable. In this case study, the co-firing in a power plant of biomass from abroad is compared with the fermentation of Dutch verge grass to bioethanol and subsequent combustion in a power plant. Another way of making the Dutch power generation more sustainable is the use of wind energy. Therefore, the third system of this case study considers a wind farm.

Summarising, the case studies are the following:

- Power generation in combination with LNG evaporation
  - Waste heat from a coal power plant is used for LNG evaporation
  - Oxyfuel coal power plant combined with air separation and LNG evaporation
  - Stand-alone coal power plant and LNG evaporation combined with an ORC

- Fossil versus renewable energy sources for power generation
  - Co-firing of coal and wood pellets
  - Wind farm
  - Combustion of bioethanol from verge grass

Chapters 7 and 8 describe the two case studies. General information about the calculation methods and data that are used in both case studies can be found in Section 6.2, which deals successively with the environmental, economic, social and exergetic sustainability assessments.

6.2 General calculation methods and data

Some of the assessed systems produce other products in addition to electricity, e.g. process heat in the Co-firing system. In such a case, only the impact of the overall system that is allocated to the produced electricity is considered. The allocation is done on an exergy basis, i.e. the impact of the overall system is multiplied by a factor that is equal to the amount of exergy represented by the produced electricity over the total amount of exergy of all products (electricity and other products).

The Sections 6.2.1 to 6.2.4 deal with the environmental, economic, social and exergetic assessments applied in the case studies, respectively.

6.2.1 Environmental assessment

The environmental sustainability of the systems is assessed by determining ReCiPe endpoint indicators (Section 5.2.1). During this research, these indicators are calculated with the software tool SimaPro version 7.3 (PRé, n.d.) in combination with the Ecoinvent database version 2.2 (Ecoinvent Centre, n.d.). The SimaPro software tool can be used to combine the three ReCiPe Endpoint indicators, i.e. 'damage to human health', 'damage to ecosystem diversity' and 'damage to resource availability' into one single indicator. Different normalisation/weighting sets can be used for calculating this overall Endpoint indicator, i.e. normalisation values of Europe or the World and the weighting set belonging to the chosen perspective (I/H/E) or the average (A) weighting set. When calculating the ReCiPe endpoint indicators, the default endpoint method and normalisation/weighting set, i.e. 'ReCiPe Endpoint (H) V1.04' and 'Europe ReCiPe H/A', is used because there is no reason to deviate from the default method and because the 'Europe ReCiPe H/A' normalisation/weighting set is recommended by the developers of SimaPro. According to this weighting set the weighting factors of the Endpoint indicators 'Ecosystems', 'Human Health' and 'Resources' are 40, 40 and 20 per cent respectively when calculating one overall Endpoint indicator.

The main processes of the systems of the case studies are modelled in SimaPro and are connected to the Ecoinvent database that is included in SimaPro via the inputs and outputs of the main processes. In this way the whole supply chains of the systems can be analysed. The resulting ReCiPe score is expressed in Points (Pt). The higher the score, the higher the environmental impact is. SimaPro also offers the possibility to calculate the contribution of the individual processes of a system to the ReCiPe score and to get an overview of the resources that are used and the components that are emitted by the system.

In SimaPro/Ecoinvent, the use of infrastructure like power plants and wind turbines is listed under the 'Materials/fuels' needed for the unit process and is expressed as the number of installations needed per amount of product that is produced by this unit process. This number is calculated from the amount of product, e.g. 1 kg or m^3, and the total production capacity of the installation used for the production of this product during its lifetime. E.g., when the unit process describes the production of 1 ton of product A and the installation needed for the production of product A can produce 10 tons of product A per year during a lifetime of 20 years, then $1/(10{\cdot}20) = 0.005$ pieces of that installation are needed for the production of 1 ton of product A. The number of installations needed for the main processes of the systems is calculated accordingly.

6.2.2 Economic assessment

The indicator that is calculated to assess the economic sustainability is the Present Worth Ratio (PWR, Section 5.2.2) of the systems. The PWR considers all costs and benefits from a life cycle point of view, e.g. investment costs and yearly costs. The discount rate used in calculating the PWR is specified at 8 per cent, which is in line with the discount rate used for private effects in social cost-benefit analyses in the

Netherlands (Warringa et al., 2012). The influence of the discount rate on the PWR of the case study systems is investigated by calculating the PWR at discount rates of 6 and 10 per cent as well. The lifetime of the installations after construction is assumed to be 20 years.

Furthermore, it is assumed that it takes 5 years to build a large scale power plant, i.e. with a capacity of about 1000 MWe, and that 3 years are needed to build the other installations mentioned in the case studies. The investment costs are assumed to be spread over the construction period. In accordance with De Buck et al. (2008), the yearly operation and maintenance costs (OpEx) are estimated at 4 per cent of the investment costs.

The chapters about the case studies describe of which installations the investment costs are considered. The costs of R&D and decommissioning related to these installations are assumed to be low compared to the other costs and are therefore not considered. The effect of this assumption is discussed in Chapters 7 and 8. The investment and other life cycle costs to produce other inputs and outputs are assumed to be incorporated in the price of these inputs and outputs. Table 6.1 presents an overview of the prices used in this research.

Table 6.1: Prices of inputs and outputs used in the economic calculations.

Inputs		
Coal [€/GJ]	2.65	(CBS StatLine, n.d.)
Outputs		
Electricity [€/MWh]	60	(Zicht op Energie, n.d.)
Carbon dioxide [€/ton]	20	

In some cases, the capacity of the main installation differs from the capacity needed to produce the amount of the functional unit. When the installation is too large, the investment costs of the installation of the appropriate size are assumed to be proportional to the original investment costs. The other way round, the investment costs of a larger installation are calculated by applying the well-known six-tenths rule.

6.2.3 Social assessment

The method to assess the social sustainability of the systems makes use of the Inequality-adjusted Human Development Index (IHDI) reported by the UNDP (Malik, 2013) and the man-hours along the chain, as explained in Section 5.2.3. It is assumed that the employees that take care of exploration and processing of raw materials originate from the country where these activities take place. Table 6.2 presents an overview of the IHDIs used in this research.

The contributions of the various processes to the $\text{IHDI}_{\text{overall}}$ scores of the systems are calculated from the $\text{IHDI}_{\text{overall}}$ scores of the processes and the number of man-hours of the processes relative to the total number of man-hours spent in that system.

Table 6.2: IHDIs of countries used in this research (Malik, 2013).

Country	IHDI	Country	IHDI	Country	IHDI
Algeria	0.713[1]	Greece	0.760	Russian Federation	0.670[3]
Australia	0.864	India	0.392	South Africa	0.411[4]
Bangladesh	0.374	Indonesia	0.514	South Korea	0.758
Brazil	0.531	Latvia	0.726	Sri Lanka	0.607
Bulgaria	0.704	Lithuania	0.727	Turkey	0.560
Canada	0.832	Maldives	0.515	Ukraine	0.672
China	0.543	Myanmar	0.498[1]	United Kingdom	0.802
Colombia	0.519	Netherlands	0.857	USA	0.821
Croatia	0.683	Pakistan	0.356	Venezuela	0.549
Eastern Europe[2]	0.740	Philippines	0.524	Viet Nam	0.531
Eqypt	0.503	Romania	0.687	Yugoslavia[5]	0.631
Estonia	0.770				

[1] HDI instead of IHDI

[2] Poland

[3] Klugman (2011)

[4] Klugman (2010)

[5] The Former Yugoslav Republic of Macedonia

6.2.4 Exergetic assessment

The exergetic assessment concerns the calculation of the Total Cumulative Exergy Loss (TCExL, Section 5.1). This TCExL is the summation of the internal exergy loss, the exergy loss related to emission abatement and the exergy loss caused by land use. This section elaborates on the calculation of the three components of the TCExL with the help of the software tool SimaPro.

Internal exergy loss

SimaPro cannot only be used to calculate ReCiPe endpoint indicators, but offers the possibility to calculate an exergy indicator as well, which is the Cumulative Exergy Demand (CExD, Section 3.4). Hereto SimaPro makes use of the CExD factors listed in Appendix A. The CExD calculated with the help of SimaPro is the overall exergy input of the systems. The internal exergy loss can be calculated from the CExD and the amounts of exergy of the products and emissions as depicted in Equation 6.1.

$$Ex_{\text{loss,internal}} = CExD - Ex_{\text{product}} - Ex_{\text{emissions}} \tag{6.1}$$

The exergy values of the products are calculated manually, in the way as described in Appendix A. The amount of exergy represented by the emissions is calculated from the amounts of emissions reported by SimaPro and the standard chemical exergy values of the emissions. These standard chemical exergy values of the emissions originate from and/or are calculated from thermodynamic data reported by Szargut (2007); Rivero and Garfias (2006); Stretton (2004a,b) and are listed in Appendix A as well. The total list of emissions reported by SimaPro counts more than 600 emissions. Because it is too time-consuming to calculate the exergy values of all emissions of which no exergy value could be found in literature, it was decided to calculate the exergy values of the largest emissions until at least the exergy values of 99 % by mass of all emissions are known. When calculating the exergy values of waste heat flows, it is assumed that the temperature of waste heat emitted to air, water and soil is equal to 110, 30 and 30 ℃, respectively. The temperature of waste heat emitted to air is based on the temperature of flue gases from a power plant and the temperature of waste water is set at the allowed maximum temperature of waste water emitted to surface water in the Netherlands. The temperature of waste heat to soil is assumed to be equal to the temperature of waste water. SimaPro provides an overall list of emissions and their amounts. As SimaPro does not report which emissions belong to the same waste flow, the effects of mixing of components on the exergy value of emissions are not considered and therefore the calculated exergy value of the emissions is somewhat higher than in reality. This means that the calculated internal exergy losses are somewhat lower than in reality, but it is assumed that the difference is negligible because the exergy values of emissions are usually small compared to the exergy values of the inputs and products.

Not only the internal exergy losses of the main processes themselves are calculated, but also the internal exergy losses of the constituting processes. This is done in the same way as described above, with the exception that now also material and fuel inputs to the individual processes have to be considered to be able to calculate realistic internal exergy losses of these processes. The amounts of exergy represented by the (intermediate) material and fuel inputs cancel out when calculating the internal exergy loss of the system, as illustrated by calculating the internal exergy loss of the imaginary system of Figure 6.1 and its constituting processes.

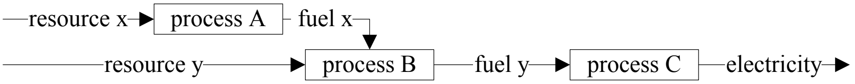

Figure 6.1: An imaginary system including its processes.

The internal exergy losses of the processes and the overall system of Figure 6.1 can be calculated with the help of Equations 6.2 to 6.7. These equations show that the amounts of exergy represented by the material and fuel inputs cancel out in the calculation of the overall internal exergy loss of the system.

$$Ex_{\text{loss,int.,A}} = Ex_{\text{resource x}} - Ex_{\text{fuel x}} \tag{6.2}$$

$$Ex_{\text{loss,int.,B}} = Ex_{\text{resource y}} + Ex_{\text{fuel x}} - Ex_{\text{fuel y}} \tag{6.3}$$

$$Ex_{\text{loss,int.,C}} = Ex_{\text{fuel y}} - Ex_{\text{electricity}} \tag{6.4}$$

$$Ex_{\text{loss,int.,system}} = Ex_{\text{loss,int.,A}} + Ex_{\text{loss,int.,B}} + Ex_{\text{loss,int.,C}} \tag{6.5}$$

$$\begin{aligned}Ex_{\text{loss,int.,system}} = Ex_{\text{resource x}} - Ex_{\text{fuel x}} + Ex_{\text{resource y}} + Ex_{\text{fuel x}} \\ - Ex_{\text{fuel y}} + Ex_{\text{fuel y}} - Ex_{\text{electricity}} \quad (6.6)\end{aligned}$$

$$= Ex_{\text{resource x}} + Ex_{\text{resource y}} - Ex_{\text{electricity}} \quad (6.7)$$

It is important to stick to the structure of the network modelled in SimaPro/Ecoinvent when calculating the TCExL of the individual processes because of the wish to compare these results with the results of the environmental assessment of the same processes. The inputs of the processes are divided into 'resources' and 'materials/fuels'. The outputs are the emissions to air, water and soil, final waste flows and waste to treatment. The connections between the processes of a network in SimaPro are made via 'materials/fuels' and 'waste to treatment'. The following types of materials/fuels can be distinguished:

- materials/fuels that are processed in the process, e.g. 'diesel, at regional storage'
- materials/fuels that are processed in another connected process, e.g. 'hard coal, burned in power plant'
- transport related to the process, e.g. 'transport, freight, rail'
- infrastructure processes, e.g. 'gas power plant'

When calculating the internal exergy losses of a process, only the materials/fuels are considered as inputs that, according to SimaPro, are processed in the process itself, i.e. the materials/fuels with names like '[material x or fuel y], [at or in], [certain location]'. Inputs with 'verbs' in their names like 'Natural gas, burned in gas motor, for storage/DZ U' are not regarded as an input to the process under consideration because this type of name indicates that in SimaPro/Ecoinvent a separate process exists in which this transformation takes place. The resources, product/products, emissions to air, water and soil as well as the final waste flows are also considered when calculating the internal exergy loss of a process. Processes with names like '[fuel y], [burned in], [certain location]' do not have a product as output because the purpose of that process is to burn this product (fuel). Appendix A presents an overview of the exergy values of the products and the materials and fuels used in the calculations.

A point of attention when calculating the internal exergy losses of the processes is that the amount of mass entering a process modelled in SimaPro/Ecoinvent not always equals the amount of mass exiting that same process and that the composition of the inputs and outputs is not always clear. For example, the amount and composition of the biowaste input to the process 'Biogas, from biowaste, at storage/CH U' are not known, while various components are listed as emissions. In this case, it is assumed that the amount of exergy represented by the ingoing mass flows equals the amount of exergy represented by the outgoing mass flows.

The natural gas production processes ‘Natural gas, at production onshore/DZ U, m^3’ and ‘Natural gas, at production onshore/RU U, m^3’ seem to produce 1 m^3 of natural gas out of 1 m^3 of ‘natural gas, in ground’, without consuming materials/fuels but with the emission of components to air. This results in negative internal exergy losses, which is impossible. In this case it is assumed that the produced natural gas has a somewhat lower exergy value, i.e. about 0.5 per cent, so that the internal exergy loss of these processes equals zero.

A special category of processes in SimaPro/Ecoinvent are the processes named ‘Disposal, [material x or component y], [to certain location/processing]’, because these processes have no inputs. The input of the process named ‘Disposal, plastics, mixture, 15.3% water, to municipal incineration/CH U’ is assumed to be the disposed plastic waste, i.e. the ‘product’ of this process according to the Ecoinvent database. The same holds for the process ‘Blast furnace gas, burned in power plant/RER U’. The composition of the disposed material of the other disposal processes is unknown and it is therefore not possible to calculate its exergy value and to regard this amount as the exergy input. Instead, it is assumed that the exergy input of these processes equals the exergy output represented by the emissions, i.e. the internal exergy loss of these processes is zero.

The physical part of the exergy values of the mass flows of the SimaPro/Ecoinvent processes cannot be taken into account because of the lack of data, but usually the physical exergy value of a component is much smaller than its chemical exergy value. Appendix A explains the calculation of the physical and chemical exergy values of mass flows.

The abatement exergy of the processes is calculated from the emissions of the processes reported by SimaPro and the abatement exergy values of Table 5.1. The types and amounts of land occupation per process reported by SimaPro are used for the calculation of the exergy loss caused by land use like described in Section 5.1.5.

This chapter elaborated on the choice of the case studies and provided general information related to the calculation methods and data that are used in all case studies. The Chapters 7 and 8 deal with these case studies.

Chapter 7

Case study Power generation in combination with LNG evaporation

The purpose of this case study is investigating the value of exergy analysis by applying the four assessment methods to systems that use the same feedstocks and produce the same products, but which apply a different technology. The choice of power generation in combination with LNG evaporation as the subject of this case study does not mean that it is preferable and/or desirable to combine power generation and LNG evaporation. Previous versions of this case study have already been published by Stougie and Van der Kooi (2010, 2011b, 2013, 2014).

The three systems of the case study are described in Section 7.1. Section 7.2 elaborates on the assessment of the three systems and Section 7.3 presents the results. In addition to the original case study, Section 7.4 deals with a variant in which the H-gas supply chain is excluded from the systems. The chapter concludes with discussion and conclusions in Section 7.5.

7.1 Description of the systems of the case study

LNG, short for Liquefied Natural Gas, is produced to make it easier to transport natural gas over large distances by tankers. The volume of 1 ton of LNG is about 1/600 of the volume of 1 ton of natural gas. LNG is transported at atmospheric pressure and a temperature of -162 °C. At the place of destination, the LNG is stored in large tanks and evaporated, also known as regasification, to natural gas when needed. Usually, the evaporation is carried out by heating with seawater in ‘open rack vaporizers’ and/or by combustion of natural gas in ‘submerged combustion vaporizers’ (Tarakad, 2003). Instead of using heat for evaporating the LNG, the LNG cold can be used in power generation, air separation etc., like they do in Japan (Sugiyama, n.d.). Advanced systems for LNG evaporation in combination with power generation have been described by e.g. Tsatsaronis and Morosuk (2010); Szargut and Szczygiel (2009); Liu et al. (2009); Lu and Wang (2009); Deng et al. (2004).

This case study deals with the following three systems for LNG evaporation: using the waste heat from a power plant, integrating the LNG terminal with an air separation unit and an oxyfuel power plant, and combining the evaporation process with an Organic Rankine Cycle to produce electricity plus a separate power plant. These three systems are expected to be appropriate for the situation in Rotterdam (Netherlands). After evaporation of the LNG, nitrogen is added to obtain H-gas, a gas mixture of about 91 mass% methane and 9 mass% nitrogen. This H-gas is used by large-scale gas consumers in the Netherlands.

7.1.1 Use of waste heat from a coal-fired power plant

The residual heat of a new coal-fired power plant in the Rotterdam port area of the Netherlands will be used by an LNG import terminal, as depicted in Figure 7.1. The power plant is an ultra-supercritical power plant with an electrical efficiency of about 47 per cent, which is of the same type as the Avedøre II and Nordjyllandsvaerket III power plants in Denmark (De Buck et al., 2008). The power plant uses ultra-supercritical steam of about 600 ℃ and 300 bar, and the steam is reheated twice during the expansion stage. In this case study, the carbon dioxide resulting from the combustion of coal is captured with monoethanolamine (MEA) absorption for reasons of comparability of the three systems of the case study. This system is called the 'Waste heat system'.

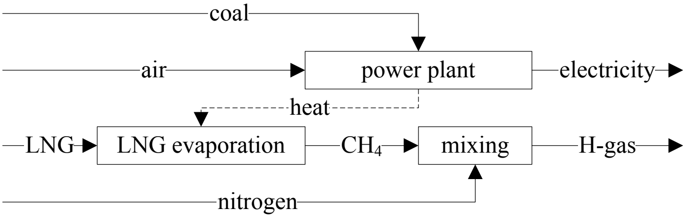

Figure 7.1: Use of waste heat from a coal-fired power plant.

7.1.2 Integration with air separation and a coal-fired oxyfuel power plant

The coal-fired oxyfuel power plant is based on the 30 MWe pilot plant in Schwarze Pumpe (Germany) and is described by De Buck et al. (2008). The power plant has an electrical efficiency of about 45 per cent. The use of pure oxygen in the combustion would result in a very high flame temperature, but by recirculating 65 to 70 per cent of the flue gases, the flame temperature is kept at about 1600 ℃. The integration between LNG evaporation, air separation and electricity production, as described by De Buck et al. (2008); SenterNovem (2008), is depicted in Figure 7.2.

In contrast with their description, the compression of the captured carbon dioxide is not taken into account in this research, as this is not part of the other systems either.

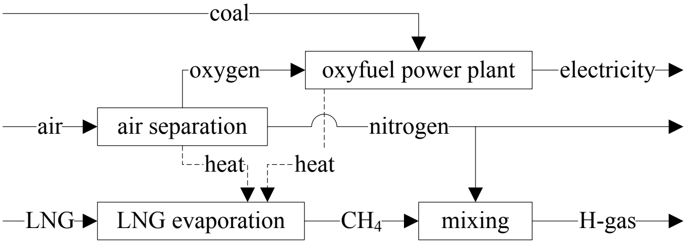

Figure 7.2: Integration with air separation and an oxyfuel power plant.

7.1.3 Electricity production through an Organic Rankine Cycle

This system makes use of the same ultra-supercritical power plant as the Waste heat system. Instead of using the residual heat of the power plant for evaporating the LNG, the LNG cold is used for electricity production through an Organic Rankine Cycle (ORC), as depicted in Figures 7.3 and 7.4. The possibility of using LNG cold for producing electricity through an ORC is also described by Tsatsaronis and Morosuk (2010); Szargut and Szczygiel (2009). Assuming that LNG consists of pure methane, the theoretical amount of work that can be obtained from the transition of LNG at 1 bar and -162 ℃ to natural gas at 70 bar and 2 ℃, the conditions in the Dutch pipelines for gas transport, can be calculated at 383 kJ/kg LNG from the data provided by Zagoruchenko and Zhuravlev (1970).

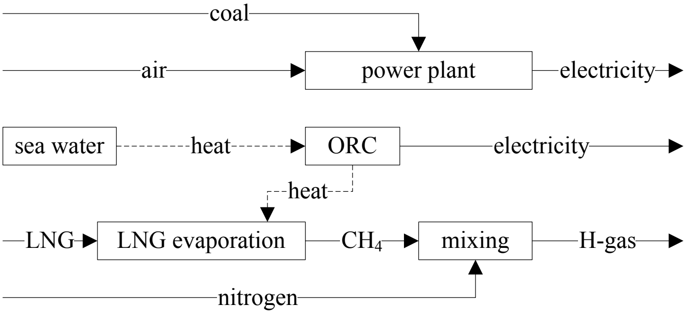

Figure 7.3: Combination with electricity production through an ORC.

In this case study system, the LNG is first compressed to 39 bar, then evaporated in the ORC, and finally compressed to the required 72 bar. Seawater of 10 ℃ acts as the high temperature heat source in the ORC. The selected working fluid of the ORC is ethane, as it was learned from calculations with nitrogen, methane, ethylene and ethane as working fluids that ethane is the most suitable.

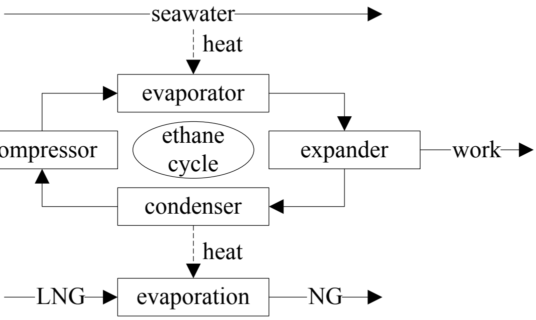

Figure 7.4: The principle of an Organic Rankine Cycle (ORC).

7.2 Assessment

The functional unit and the system boundaries applied in this case study are described in Section 7.2.1. This is followed by the data used for the assessments in Section 7.2.2.

7.2.1 Functional unit and system boundaries

The functional unit was defined as the production of 27 PJ of electricity, 12 Mton of H-gas and 15.3 Mton of nitrogen (Figure 7.5). The 27 PJ of electricity is the net amount of electricity produced, i.e. the internal electricity consumption of processes like LNG compression and air separation has been accounted for. The reason for including nitrogen as one of the by-products is the comparability of the three systems since the Oxyfuel system includes air separation and therefore produces a net amount of nitrogen. This extension of the functional unit is called 'system enlargement' and implies that the net production of the same amount of nitrogen is included in the Waste heat and ORC systems.

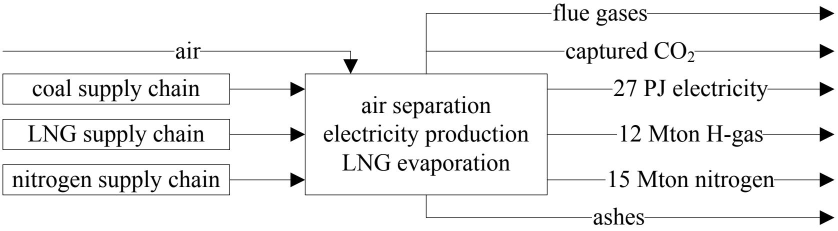

Figure 7.5: Assessed overall system with a net electricity production of 27 PJ, 12 Mton of H-gas and 15 Mton of nitrogen.

The assessment included the extraction, processing and transport of coal, natural gas, LNG and nitrogen. As the captured carbon dioxide from the power plant is not emitted to the environment, this flow was not regarded as an emission. In line with the rules of the European union carbon dioxide emission trading system (EUTS) in

2013, credits were obtained by selling the rights not needed because of carbon dioxide capture, although the subsequent storage of carbon dioxide was not considered in this case study. The use of ethane as a working fluid in the ORC system, the use of seawater for heating and cooling purposes and all other auxiliary substances not mentioned in the following subsections were not taken into account, because it was assumed that the effects on the results are negligible compared to the other effects.

7.2.2 Data

This case study is based on a large number of data from various data sources, completed with additional calculations and educated guesses. The most important data are presented, as it is impossible to present all data in this chapter.

Environmental sustainability

Table 7.1 gives an overview of the inputs and outputs of the three systems modelled in SimaPro. A more detailed overview can be found in Appendix D.

Table 7.1: Overview of the main inputs and outputs of the three systems.

	Waste heat	Oxyfuel	ORC
Inputs[1]			
Coal [Mton]	2.9	2.6	2.7
Nitrogen [Mton]	16	-	16
Hard coal power plant [p]	0.12	0.10	0.11
Products[2]			
Captured CO_2 [Mton]	5.5	5.6	5.6
Emissions to air			
CO_2 [Mton]	1.0	0.30	0.91
NO_x [kton]	1.4	0.0	1.3
SO_x [ton]	11	0.0	10
N_2 [Mton]	26	0.0	24
O_2 [Mton]	2.5	0.72	2.3
H_2O [Mton]	1.4	0.98	1.3
Final waste flows			
Waste heat to river [PJ]	22	21	29
Slags and ashes [Mton]	0.35	0.30	0.32

[1] Inputs of all systems are 10.9 Mton of LNG and 0.88 pieces of the Liquid storage tank modelled in Ecoinvent.

[2] Products of all systems are 27 PJ of electricity, 12 Mton of H-gas and 15.3 Mton of nitrogen.

The ultra-supercritical power plant, the oxyfuel power plant including air separation unit, the ORC and the LNG terminal were modelled on the basis of the references mentioned in Section 7.1. The coal and LNG supply chains were modelled in SimaPro by selecting the Ecoinvent unit processes ‘Hard coal supply mix/NL’ and ‘Natural gas, liquefied, at freight ship/DZ’, respectively.

The ‘Hard coal supply mix/NL’ considers the exploration, processing and transport of hard coal as used in the Netherlands. The ‘Natural gas, liquefied, at freight ship/DZ’ describes the environmental effects of LNG originating from Algeria, including exploration, liquefaction and transport. It appeared from studying the LNG supply chain in SimaPro/Ecoinvent in more detail that the preceding unit process called ‘Natural gas, at production onshore/DZ U’ applies a natural gas drying process that is based on the situation in Norway. Because this led to an unexpected use of hydropower installations, these processes were modified as described in Appendix D.

The nitrogen production of the Waste heat and ORC systems was modelled by selecting the Ecoinvent unit process ‘Nitrogen, via cryogenic air separation, production mix, at plant, gaseous EU-27 S’. The installations of the power plant and LNG terminal were modelled by selecting the Ecoinvent unit processes ‘Hard coal power plant/RER/I U’ and ‘Liquid storage tank, chemicals, organics/CH/I U’, respectively. Based on the Ecoinvent documentation, an assumed electrical efficiency of 42%, a lifetime of 20 years and 7500 operation hours per year, it was calculated that $1.7 \cdot 10^{-12}$ power plant per processed MJ of coal is needed. It was also calculated from the Ecoinvent documentation that $6.3 \cdot 10^{-5}$ liquid storage tank is needed per m^3.

Economic sustainability

The data needed for calculating the life cycle costs originate from Tarakad (2003); De Buck et al. (2008); FW (2004); Coulson and Richardson (1983); DACE (2006). The extra costs associated with the very low (cryogenic) temperatures and high pressures in the installations have been taken into account (De Buck et al., 2008). The coal power plant of the Waste heat and ORC systems has a capacity of 1070 MWe and the investment costs including a MEA unit for carbon dioxide capture were calculated at 1.8 billion euros. The oxyfuel power plant has a capacity of 1000 MWe and its investment costs, including air separation unit, are 1.5 billion euros. The LNG terminal of the Waste heat and Oxyfuel systems has a capacity of 12 BCM (billion cubic metre) and costs 0.8 billion euros. The LNG terminal of the ORC system has the same capacity and its investment costs were calculated at 0.8 billion euros as well. More detailed numbers can be found in Appendix D.

Table 7.2 presents an overview of the investment costs of the systems and the operational expenses. The investment and operational costs of the air separation unit have only been taken into account in the Oxyfuel system, because in the other two systems it was assumed that the nitrogen needed for bringing the evaporated LNG to H-gas conditions was bought from another company. The costs and revenues related to the ‘production’ of the 15 Mton of nitrogen in the Waste heat and ORC options have not been included in Table 7.2, because they cancel each other out in the calculation of the PWR. The price of nitrogen was estimated at €0.017/kg (Haynes, 2013, p.4-24). This price was also used to calculate the revenues of the nitrogen produced by the Oxyfuel system. The costs of carbon dioxide capture with

MEA absorption were assumed to be €5/ton CO_2 (De Buck et al., 2008). The price of LNG was calculated at €6.8/GJ, which is based on the US$10.45/MMBTU reported by McKay (2013), and the price of H-gas was estimated at €6.7/GJ (Zicht op Energie, 2013). According to these prices, which are of February 2013, it was not profitable to import LNG at that moment.

Table 7.2: Overview of economic data of the three systems.

	Waste heat	Oxyfuel	ORC
Investment costs [10^8 €]	26	23	25
Operation and maintenance costs [10^7 €/year]	10	9.1	10
Costs of fuels/feedstocks [10^8 €/year]	43	42	43
Revenues of carbon credits [10^7 €/year]	11	11	11
Revenues of products [10^8 €/year]	44	47	44

Social sustainability

The man-hours per stage of the production chain in Table 7.3 were estimated on the basis of many references (Biofuels Center, n.d.; World Investment News, 2001; Sonatrach, n.d.; EIA, 2003; SBH, n.d.; Alderton and Lane, 2001; GATE, n.d.; EIA, 2010; Dones et al., 2007; DSF, n.d.; RTV Noord, 2010; Stellinga and Sanders, 2009), completed with educated guesses and calculations. The number of man-hours for operating the coal power plants was assumed to be equal for the three systems. The man-hours needed for construction and decommissioning of the installations, equipment and infrastructure were not considered because of lack of data. The man-hours related to the transport of natural gas by pipeline to the liquefaction plant, the loading/unloading of LNG and coal, and the storage of coal were neglected as well. The calculated number of man-hours for the exploration and processing of natural gas is very low compared to the other numbers, therefore the influence of a higher number on the $IHDI_{overall}$ scores was investigated during the case study.

Table 7.3: Overview of man-hours in the production chain.

	Coal	LNG
Exploration/processing [man-hours/PJ coal or LNG]	$8 \cdot 10^3$	$1 \cdot 10^0$
Liquefaction [man-hours/PJ LNG]	-	$8 \cdot 10^3$
Deep sea transport [man-hours/PJ coal or LNG]	$3 \cdot 10^3$	$7 \cdot 10^4$
LNG terminal [man-hours/year]	-	$8 \cdot 10^3$
Power plant [man-hours/year]	$4 \cdot 10^4$	-

It was assumed that the people that are responsible for the extraction and processing of coal and the production of LNG originate from the country where these activities take place. The same holds for the operation of the power plants in the Netherlands. The man-hours needed for deep-sea transport (of coal, LNG) were divided over the countries the crew originate from according to literature.

7.3 Results

The results of the environmental, economic, social and exergetic sustainability assessments are presented in Sections 7.3.1 to 7.3.4, respectively. Section 7.3.5 compares the results of the assessments.

7.3.1 Environmental sustainability

Table 7.4 presents the ReCiPe endpoint indicators of the three systems. As becomes clear from this table, the Oxyfuel system resulted in the best ReCiPe score of the three systems, while the scores of the other two systems are comparable. The ReCiPe damage categories ‘Human health’, ‘Ecosystems’ and ‘Resources’ account for about 14, 9 and 77 per cent of the ReCiPe score of the systems, respectively. A main difference between the three systems is the amount of coal used. It was therefore investigated how the ReCiPe score of the Oxyfuel system is affected by increasing the amount of coal and the emissions resulting from the combustion of coal by 10 per cent, which is about the same amount of coal use as in the other two systems. According to Table 7.4, the effect is negligible and the Oxyfuel system remains the preferred system.

Table 7.4: ReCiPe scores of the three systems per ReCiPe damage category and of the Oxyfuel system with 10% higher coal consumption and emissions.

[GPt]	Waste heat	Oxyfuel	ORC	Oxyfuel plus 10%
Human Health[1]	0.37	0.29	0.36	0.30
Ecosystems[1]	0.21	0.17	0.21	0.17
Resources[1]	1.88	1.82	1.87	1.84
Total	2.46	2.28	2.44	2.31

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

It was also investigated which processes of the whole supply chain contribute most to the ReCiPe score of the three systems. Figure 7.6 presents the contributions to the ReCiPe scores of the main process, i.e. the Power plant/LNG terminal, and of the processes that are responsible for at least 80 per cent of the ReCiPe scores. A table with the numbers can be found in Appendix D. This figure clearly shows that the production of natural gas is the main contributor to the ReCiPe score and therefore the natural gas production process itself was analysed in more detail. It appeared that 91 per cent of the overall ReCiPe score of the natural gas production process is caused by the extraction of natural gas from the earth.

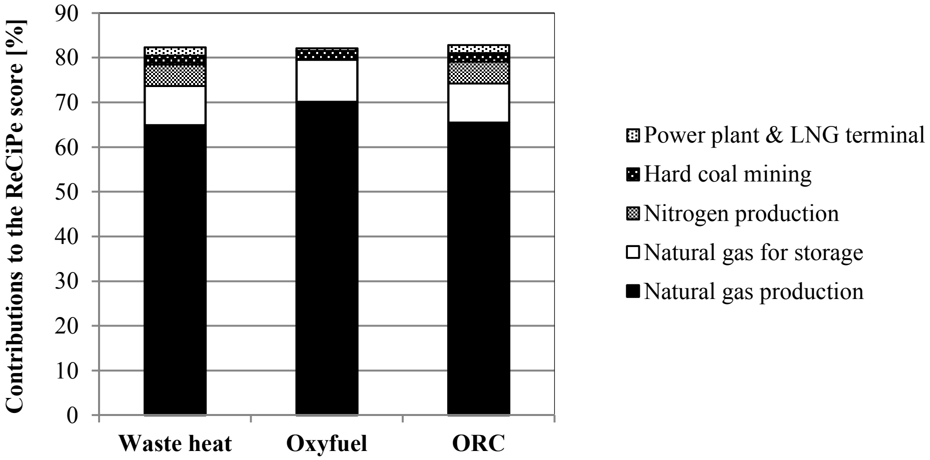

Figure 7.6: Process contributions to the ReCiPe scores of the three systems.

7.3.2 Economic sustainability

The results of the economic assessment are presented in Table 7.5. As becomes clear from these numbers, the Oxyfuel system is the preferred system and the only profitable system at the considered prices of energy carriers and carbon credits. If the coal consumption of the Oxyfuel system is increased by 10 per cent, i.e. to approximately the same amount as the other two systems, the Oxyfuel system is still preferable. Table 7.5 shows the PWR scores of the three systems at discount rates of 6 and 10 per cent as well. As expected, the systems become more profitable at a lower discount rate and the ranking of the systems remains the same. The costs of R&D and decommissioning are assumed to be low compared to the other costs and were not taken into account. The effect of this assumption was investigated by increasing the investment costs by 25 per cent. This resulted in lower PWR scores, but it did not influence the ranking of the systems.

Table 7.5: Life Cycle Costs of the three systems and of the Oxyfuel system with 10% higher coal consumption and emissions.

8% discount rate	Waste heat	Oxyfuel	ORC	Oxyfuel plus 10%
NPV [10^9 €]	-1.3	1.4	-1.2	1.3
Investment costs [10^9 €][1]	2.2	1.9	2.1	1.9
PWR [-]	-0.62	0.75	-0.57	0.69
PWR at 6 % discount rate [-]	-0.54	1.12	-0.48	
PWR at 10 % discount rate [-]	-0.68	0.47	-0.64	

[1] Present value of investment costs.

The contributions of the investment costs and yearly costs and revenues to the PWR are depicted in Figure 7.7. A table with the numbers can be found in Appendix D. Figure 7.7 shows that the costs of LNG and the revenues of H-gas largely influence the PWR value. The costs of the LNG supply chain contribute for about 90 per cent to the costs part of the PWR. No detailed investigation was carried out of the cost structure of the LNG supply chain, but according to Praet (2009), the production of natural gas is responsible for 15 to 20 per cent of the costs, the liquefaction for 30 to 45 per cent, the shipping 10 to 30 per cent and the evaporation including storage and distribution accounts for 15 to 25 per cent. Thus the average contributions of the production of natural gas, liquefaction, shipping and evaporation/storage/distribution to the costs part of the PWR are 16, 34, 18 and 18 per cent, respectively.

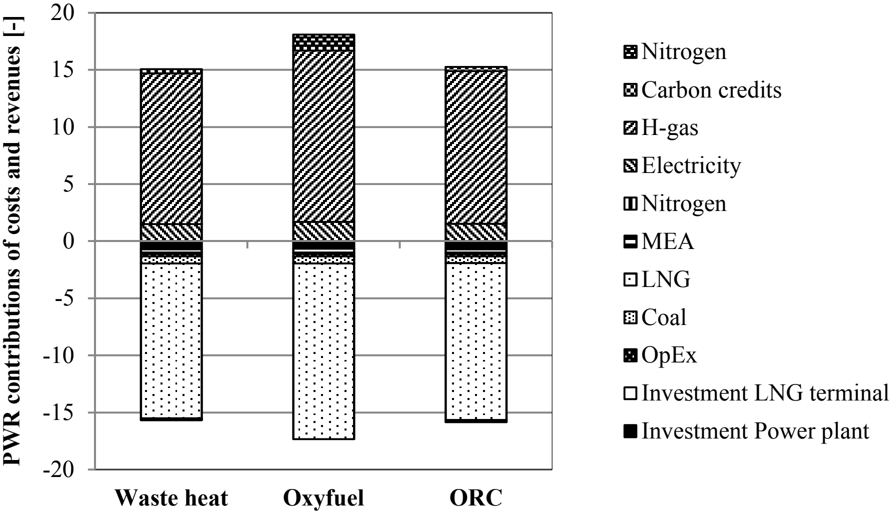

Figure 7.7: Contributions to the PWR scores of the three systems.

7.3.3 Social sustainability

Table 7.6 shows that the difference in the overall Inequality-adjusted Human Development Index ($\text{IHDI}_{\text{overall}}$) between the three systems is negligible. This is understandable because the coal and LNG used in the three systems originate from the same countries. The slight difference in the three $\text{IDHI}_{\text{overall}}$ scores is caused by the difference in the amounts of coal used in the three systems. If the coal consumption of the Oxyfuel system is increased by 10 per cent, its overall IHDI is lower because of the lower IHDI of the processes of the coal supply chain. The effect of the calculated number of man-hours for the exploration and processing of natural gas on the $\text{IHDI}_{\text{overall}}$ scores was investigated by increasing this number from its low value of 1 man-hour/PJ LNG to a value of the same order of magnitude as the exploration and processing of coal, i.e. 1000 man-hours/PJ. This resulted in a less than 0.1% increase of the scores, thus the effect is negligible.

Table 7.7 presents the $\text{IHDI}_{\text{overall}}$ along the supply chains. An overview of the origin of most employees of the three systems can be found in Appendix D. Figure 7.8 shows the contributions of the processes to the overall IHDI scores. The numbers

Table 7.6: Results of the social LCA of the three systems and of the Oxyfuel system with 10% higher coal consumption and emissions.

[-]	Waste heat	Oxyfuel	ORC	Oxyfuel plus 10%
$\text{IHDI}_{\text{overall}}$	0.619	0.620	0.619	0.619

used in this figure can be found in Table 7.10 (Oxyfuel system) and in Appendix D (Waste heat and ORC systems).

Table 7.7: $\text{IHDI}_{\text{overall}}$ along the supply chains.

[-]	Coal supply chain	LNG supply chain
Extraction	0.617	0.713
Liquefaction		0.713
Transport	0.562	0.583
Coal power plant	0.857	
LNG terminal		0.857

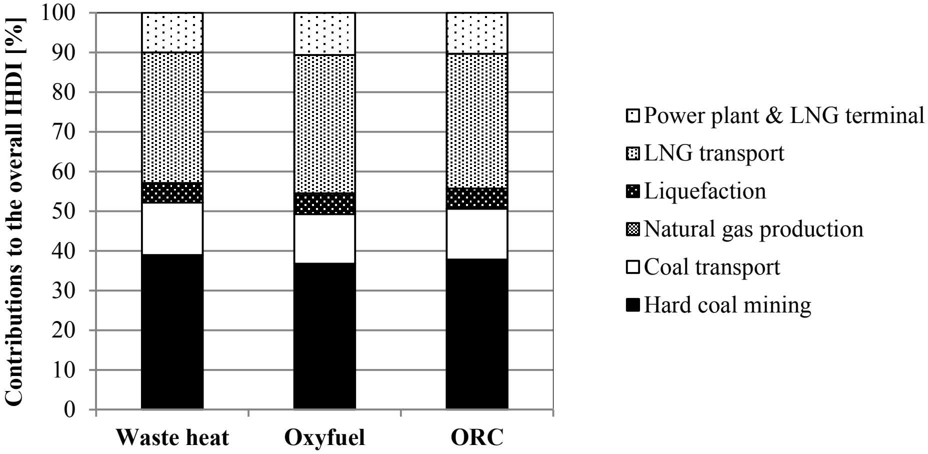

Figure 7.8: Process contributions to the $\text{IHDI}_{\text{overall}}$ scores of the three systems.

7.3.4 Exergetic sustainability

Table 7.8 presents the results of the exergetic assessment. According to the results, the Oxyfuel system is preferred and the ORC system is second-best, although the difference between the ORC and Waste heat systems is not very large. The Oxyfuel system with a 10 per cent higher coal consumption is still preferable compared to the other two systems.

A difficulty in determining the exergy value of the emissions was that the composition of two of the waste flows that belong to the first 99 mass% of the emissions

Table 7.8: Total Cumulative Exergy Loss of the three systems and of the Oxyfuel system with 10% higher coal consumption and emissions.

[PJ]	Waste heat	Oxyfuel	ORC	Oxyfuel plus 10%
CExD	859	806	849	820
Exergy of products	608	608	608	608
Exergy of emissions	51	36	50	36
Internal exergy loss[1]	200	163	191	175
Abatement exergy	47	42	46	42
Exergy loss land use	1.3	1.2	1.3	1.3
Total Cum. Exergy Loss[2]	248	206	239	219

[1] The internal exergy loss is equal to the CExD minus the exergy of products and emissions.

[2] The Total Cumulative Exergy loss is the sum of the internal exergy loss, abatement exergy and exergy loss caused by land use.

(Section 6.2.4) is unknown, i.e. the waste flows called ‘mineral waste, from mining’ and ‘slags and ashes’. It is expected that the exergy value of these flows is quite low, therefore it was assumed that these flows have an exergy value of zero. Even if the exergy value of these flows amounts to 1000 kJ/kg, the Oxyfuel system is preferred because this results in a TCExL of 207 PJ for the Oxyfuel system compared to 244 and 235 PJ for the Waste heat and ORC systems, respectively. The results of Table 7.8 are based on an exergy value of zero for both waste flows. According to Table 7.8, the influence of land use is almost negligible compared to the other exergy losses, i.e. about 1 per cent compared to the 80 and 19 per cent caused by the internal exergy losses and abatement exergy losses, respectively.

SimaPro does not offer the possibility to calculate the contribution of the processes to the TCExL, and the CExD calculated by SimaPro is no measure of the TCExL (Section 3.4). To be able to compare the ReCiPe and TCExL scores along the supply chains in Section 7.3.5, it was decided to calculate the TCExL of the processes with the highest contributions to the ReCiPe scores of the three systems (Section 7.3.1). The results are shown in Figure 7.9. According to this figure, the use of natural gas for storage (of LNG) contributes most to the TCExL scores of the three systems and is followed by the main process, i.e. the power plant and LNG terminal. A table with the process contributions to the TCExL and CExD scores of the three systems can be found in Appendix D.

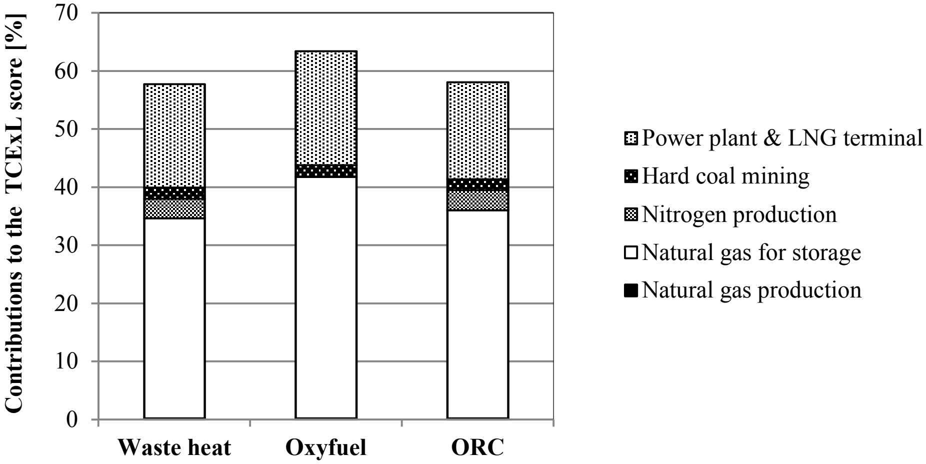

Figure 7.9: Process contributions to the TCExL scores of the three systems.

7.3.5 Comparison of the results

The results of applying the four methods of assessment to the three systems are summarised in Table 7.9. This table presents an overview of the grading of the systems as well. If two systems had the same score, they were rated the same. According to this table, the Oxyfuel system is the preferred system of this case study. The difference between the other two systems is small.

Table 7.9: Overview of the assessment results of the systems.

	Waste heat		Oxyfuel		ORC	
	absolute	ranking	absolute	ranking	absolute	ranking
ReCiPe [GPt]	2.46	2 (3)	2.28	1	2.44	2
PWR [-]	-0.62	2 (3)	0.75	1	-0.57	2
$\text{IHDI}_{\text{overall}}$ [-]	0.619	1 (3)	0.620	1	0.619	1 (2)
TCExL [PJ]	248	2 (3)	206	1	239	2

Figure 7.10 presents the environmental, economic and social sustainability of the three systems versus the TCExL caused by each system. Hereto, the ReCiPe indicator of Table 7.9 has been modified into a dimensionless indicator that increases with the environmental sustainability. This was done by multiplying the inverse of the ReCiPe indicator of each system with the ReCiPe score of the Oxyfuel system, i.e. the system with the highest environmental sustainability. According to Figure 7.10, the environmental sustainability slightly decreases with an increasing exergy loss, which is in accordance with the expected relationship of Figure 3.7. The economic sustainability decreases with an increasing exergy loss as well, which is in line with the right part of the line representing the relationship between economic sustainability and exergy losses of Figure 3.7. The social sustainability very slightly decreases with exergy loss as well. This decrease is understandable because the social

sustainbility indicator and the exergy losses are related to the amount of input.

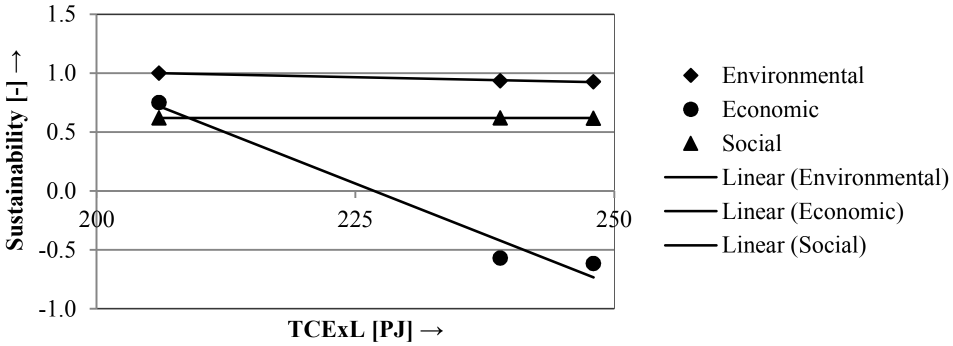

Figure 7.10: The environmental, economic and social sustainability of the systems of the LNG case study versus the exergy losses caused by these systems.

To be able to investigate the differences between the four methods in more detail, Table 7.10 presents the contributions of the processes to the total score of the Oxyfuel system. The tables of the other two systems can be found in Appendix D. According to Table 7.10, the LNG supply chain contributes the most to the ReCiPe, PWR and TCExL scores of the three systems. The coal and LNG supply chains contribute about equally to the $\mathrm{IHDI}_{\mathrm{overall}}$ of the systems. The natural gas production process of the LNG supply chain accounts for two-thirds to three-quarters of the total ReCiPe score, while this process hardly contributes to the TCExL score.

The influence of the H-gas supply chain on the results of the assessments is quite large, while it is only the physical part, i.e. the evaporation of LNG to NG, that is of importance to the production of electricity in this case study. To enable a thorough comparison of the differences between the three systems of the case study, Section 7.4 considers the systems without the LNG and nitrogen supply chains and H-gas production, in short the systems ‘excluding H-gas supply chain’.

Table 7.10: Contributions of supply chains and processes to the scores of the Oxyfuel system.

[%]	ReCiPe	PWR	$\mathrm{IHDI}_{\mathrm{overall}}$	TCExL
Coal supply chain				
Hard coal mining[1]	2.0		37	2.0
Coal transport			12	
Purchase of coal		3.5	-	
subtotal	*(2.0)*	*(3.5)*	*(49)*	*(2.0)*
LNG supply chain				
Natural gas production[2]	70		0	0.23
Liquefaction			5.2	
Natural gas for storage[3]	9.4			42
LNG transport			35	
Purchase of LNG		89		
subtotal	*(80)*	*(89)*	*(40)*	*(42)*
Power plant and LNG terminal				
Power plant and LNG terminal	0.59		11	20
Investment costs power plant		3.9		
Investment costs LNG terminal		1.9		
OpEx		2.0		
MEA costs		-		
subtotal	*(0.59)*	*(7.8)*	*(11)*	*(20)*
Total	82	100[4]	100	63

[1] Ecoinvent process 'Hard coal, at mine/ZA U'. The fact that about 2% of the ReCiPe and TCExL numbers contributes to the LNG supply chain is neglected.

[2] Ecoinvent process 'Natural gas, at production onshore/DZ U' (adapted)'

[3] Ecoinvent process 'Natural gas, burned in gas motor, for storage/DZ U'

[4] Costs only, because of the opposite signs of costs and revenues.

7.4 Case study excluding H-gas supply chain

In the previous sections, the case study comprised the production of electricity in combination with LNG evaporation, followed by mixing the resulting natural gas with nitrogen to obtain the H-gas used in the Netherlands. It appeared that this H-gas supply chain largely influences the results of the assessments. This section deals with the three systems 'excluding H-gas supply chain' to be able to better investigate the influence of e.g. an increased coal consumption on the sustainability of the systems.

The systems 'excluding H-gas supply chain' consist of the same power plant and LNG terminal as before, but do no longer take into account the supply chains of LNG and nitrogen and the production of H-gas. The resulting overall system is depicted in Figure 7.11. The new functional unit was the production of 27 PJ of electricity. A difficulty when comparing the three systems excluding H-gas supply chain is the production of nitrogen by the air separation unit that is part of the Oxyfuel system. Various ways exist to deal with this. System enlargement (including the production of a certain amount of nitrogen in the functional unit) was not chosen because of the wish to compare the systems of this case study with other power generation systems. From comparing the results of applying the alternative methods ‘applying allocation’ and ‘regarding nitrogen as an avoided product’ (the latter means that the impacts of producing this product in the regular way are subtracted from the impacts of the process under consideration, which is known as the ‘avoided burden’ or ‘substitution’ method) in SimaPro, it was learned that the allocation method leads to the most realistic results. Like described in Section 6.2, the allocation in this research is based on the exergy values of the products. It was assumed that the conditions of the produced nitrogen equal 5 bar and -150 ℃, like described by De Buck et al. (2008), which led to an exergy value of 0.24 PJ/Mton nitrogen, i.e. 4.0 PJ/year, based on the data provided by Zagoruchenko and Zhuravlev (1970). As a result 87 per cent of the impact of the Oxyfuel system, i.e. 27/(27+4), was allocated to the electricity that was produced.

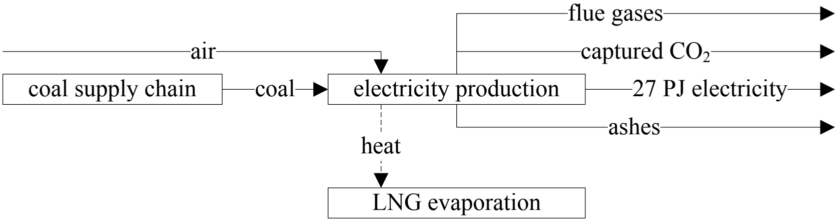

Figure 7.11: Assessed overall system with a net electricity production of 27 PJ.

Section 7.4.1 presents the results of the assessments of the overall system depicted in Figure 7.11. Furthermore, the influence of increasing the coal consumption and emissions was investigated by increasing both with 10 per cent without increasing the amount of electricity that is produced.

7.4.1 Results of the assessments

Tables 7.11 to 7.14 present the results of environmental, economic, social and exergetic assessments of the three case study systems excluding H-gas supply chain, respectively. When calculating the TCExL, the evaporation of LNG to natural gas was accounted for by considering the decrease in exergy of evaporated LNG (i.e. NG) compared to LNG as an input of exergy. Assuming that 10.9 Mton of LNG was evaporated, this extra input of exergy was calculated at 4.1 PJ on the basis of data provided by Zagoruchenko and Zhuravlev (1970). Tables 7.11 to 7.14 present the results with a 10 per cent higher coal consumption and emissions from combustion of coal as well.

Table 7.11: ReCiPe scores of the three systems excluding H-gas supply chain.

[GPt]	Waste heat	Oxyfuel	ORC
Human Health	0.11	0.07	0.10
Ecosystems	0.04	0.02	0.04
Resources	0.20	0.15	0.19
Total	0.34	0.24	0.32
Total plus 10%[1]	0.38	0.27	0.35

[1] 10% higher coal consumption and emissions.

Table 7.12: PWR of the three systems excluding H-gas supply chain.

[-]	Waste heat	Oxyfuel	ORC
excluding H-gas supply chain	-0.20	0.41	-0.15
idem, plus 10%[1]	-0.28	0.35	-0.22

[1] 10% higher coal consumption and emissions.

Table 7.13: $\mathrm{IHDI}_{\mathrm{overall}}$ of the three systems excluding H-gas supply chain.

[-]	Waste heat	Oxyfuel	ORC
excluding H-gas supply chain	0.633	0.636	0.634
idem, plus 10%[1]	0.630	0.633	0.632

[1] 10% higher coal consumption and emissions.

Table 7.14: TCExL of the three systems excluding H-gas supply chain.

[PJ]	Waste heat	Oxyfuel	ORC
CExD[1]	159	124	150
Exergy of products	27	27	27
Exergy of emissions	9.6	6.2	9.1
Internal exergy loss	122	91	114
Abatement exergy	9.4	4.4	8.9
Exergy loss land use	1.3	1.0	1.2
TCExL[2]	133	96	124
TCExL plus 10%[3]	148	108	138

[1] The internal exergy loss is equal to the CExD minus the exergy of products and emissions.

[2] The Total Cumulative Exergy loss is the sum of the internal exergy loss, abatement exergy and exergy loss caused by land use.

[3] TCExL with 10% higher coal consumption and emissions.

7.4.2 Comparison of the results

The results of the assessments are summarised in Table 7.15. This table presents the absolute scores as well as the results of grading the systems. The preferred system per assessment method was assigned the value ‘1’, the second best ‘2’ etc. If two systems had about the same score, they were rated the same. According to this table, the Oxyfuel system is the preferred system and the difference between the other two systems is small.

Table 7.15: Overview of the assessment results of the systems excluding H-gas supply chain.

	Waste heat		Oxyfuel		ORC	
	absolute	ranking	absolute	ranking	absolute	ranking
ReCiPe [GPt]	0.34	2 (3)	0.24	1	0.32	2
PWR [-]	-0.20	2 (3)	0.41	1	-0.15	2
$\text{IHDI}_{\text{overall}}$ [-]	0.633	1 (3)	0.636	1	0.634	1 (2)
TCExL [PJ]	133	2 (3)	96	1	124	2

Table 7.16 presents the effect of increasing the coal consumption and emissions by 10 per cent on the results of the systems including and excluding H-gas supply chain. E.g., if the coal consumption and emissions of the Oxyfuel system including H-gas supply chain increase by 10%, the ReCiPe score increases from 2.28 to 2.31 (Table 7.4) and this is represented by 101 ($= 2.31/2.28 \cdot 100\%$) in Table 7.16. It appears that when the H-gas supply chain is excluded, the environmental, economic and exergetic sustainability are more sensitive to increasing the coal consumption and emissions. The effect on the social sustainability is negligible.

Table 7.16: Scores of the Oxyfuel system with 10% higher coal consumption and emissions relative to the score of the standard Oxyfuel system, including and excluding H-gas supply chain.

[-]	Including H-gas supply chain	Excluding H-gas supply chain
Environmental	101	110
Economic[1]	109	118
Social	100	100
Exergetic	106	112

[1] The PWR decreases with an increase of coal consumption, therefore the economic percentages have been calculated from the original PWR scores over the plus 10% PWR scores.

An advantage of assessing the systems of the LNG case study without the H-gas supply chain is that the resulting systems produce only one product, electricity, which makes it easier to compare these systems with other power generation systems, like those of the other case study. The ReCiPe and TCExL scores of the 1 PJ systems are equal to the scores of the systems that produce 27 PJ of electricity divided by 27. The PWR scores of the 1 PJ systems are the same as the scores of the 27 PJ systems because of the linearity of all costs and revenues, including the investment costs as explained in Section 6.2.2. The $\text{IHDI}_{\text{overall}}$ scores are the same as the $\text{IHDI}_{\text{overall}}$ scores of the 27 PJ systems because it was assumed that the ratio between the number of man-hours per country is not influenced by the amount of electricity produced. On the basis of the aforementioned, the ReCiPe, PWR, $\text{IHDI}_{\text{overall}}$ and TCExL of the Oxyfuel system producing 1 PJ of electricity equal 9.0 MPt, 0.41 [-], 0.636 [-] and 3.6 PJ, respectively.

7.5 Discussion and conclusions

It can be concluded from the results of this case study including the H-gas supply chain, i.e. the original systems, that the environmental, economic and exergetic assessment methods prefer the Oxyfuel system and that the difference between the other two systems is too small to decide which system is the second-best. The difference in the outcomes of the social assessment is too small to choose between the three systems, which is caused by the similarity between the supply chains of the systems. The Oxyfuel system is still preferred when the coal consumption of this system including the emissions caused by the combustion of coal are increased by 10 per cent, which coal consumption is comparable to that of the other two systems. With regard to the results of the economic assessment, it should be noted that the costs of back-up installations have not been taken into account. This is especially important in the case of the Oxyfuel system because of the continuous operation of the power plant and the discontinuity in the send-out of the LNG terminal. The LNG terminal is expected to send out natural gas about 60 per cent of the time, depending on the weather conditions. Looking at the interdependency between the installations, the ORC system is preferred because of the absence of interconnections between the LNG terminal and the power plant.

From the detailed analysis of the systems including the H-gas supply chain, it becomes clear that different processes contribute most to the total scores of the methods. For example, the natural gas production process is responsible for two-thirds to three-quarters of the ReCiPe score but this process hardly contributes to the TCExL score. The LNG supply chain also largely influences the results of the economic assessment, but hard coal mining and LNG transport both contribute about one third to the score of the social assessment. It can therefore be concluded that the methods differ a lot when looking into more detail at the systems. As the TCExL of the individual processes is not calculated automatically and it was too time-consuming to calculate the TCExL of the approximate 2000 processes that are part of the systems, it is unknown which processes contribute most to the TCExL of the three systems. The contributions to the scores of the economic and social assessment methods could not be investigated at the same level of detail as with the environmental and exergetic assessments.

Excluding the H-gas supply chain from the systems resulted in an improved environmental, economic, social and exergetic performance of the systems except for the economic sustainability of the Oxyfuel system. The latter is caused by the production of nitrogen as a valuable by-product of the Oxyfuel system and its exclusion from the functional unit of the assessments when the H-gas supply chain was not considered. As expected, the differences between the scores of the systems were larger when the H-gas supply chain was excluded. The Oxyfuel system remained the preferred system and the ranking of the three systems remained the same as well. Increasing the coal consumption and resulting emissions of the Oxyfuel system without H-gas supply chain by 10 per cent resulted in a 10 per cent higher ReCiPe score and a 12 per cent higher TCExL. The effect on the social sustainability was very small and the PWR decreased by about 18 per cent.

Instead of excluding the H-gas supply chain, it would also have been possible to calculate the environmental and exergetic impacts related to the production of electricity by applying allocation factors in SimaPro. However, this is not regarded as a realistic option because of the large amount of H-gas compared to the amount of electricity, i.e. the amounts of exergy represented by the produced electricity, H-gas and nitrogen are 4, 95 and 1 per cent, respectively. Furthermore, the production of electricity and H-gas are not related, except for the exchange of heat between the power plant and the LNG terminal.

It is not surprising that the Oxyfuel system is preferred because the three systems use the same feedstocks and the Oxyfuel system is the system with the lowest coal consumption and emissions. Although the difference between the scores of the Waste heat and ORC systems including and excluding H-gas supply chain is small, the Waste heat system tends to be the least preferred system. This implies that the cold of LNG should be considered as a valuable input instead of a ‘problem’ that needs to be solved.

Chapter 8

Case study Fossil versus renewable energy sources for power generation

The purpose of this case study is investigating the value of exergy analysis by applying the four assessment methods to systems that use fossil and/or renewable sources for power generation. The choice of the power generation systems of this case study does not mean that these systems are preferable and/or desirable. Previous versions of this case study have already been published by Stougie et al. (2012); Stougie and Van der Kooi (2014).

The three systems of the case study are described in Section 8.1. Section 8.2 elaborates on the assessment of the three systems and Section 8.3 presents the results. The chapter concludes with discussion and conclusions in Section 8.4.

8.1 Description of the systems of the case study

The three energy supply systems compared in this case study are the following: co-firing of wood pellets originating from Georgia (USA) in the 'Amercentrale' power plant located in Geertruidenberg (Netherlands), a wind farm consisting of 86 wind turbines in the Dutch 'Noordoostpolder' area, and the production of bioethanol from verge grass and its subsequent combustion in a combined cycle power plant, located in the Netherlands as well.

8.1.1 Co-firing of coal and wood pellets

The Co-firing system is depicted in Figure 8.1. This system is based on the current situation in the Netherlands, i.e. the 'Amercentrale' power plant located in Geertruidenberg (Essent, 2010b), Netherlands. This power plant has a capacity of

1,245 MWe and 600 MWth. The production of heat, which is used for the heating of houses, greenhouses etc., did not belong to the functional unit of the assessment. The power plant co-fires about 30 mass% of biofuels and adaptations are being made to increase this number to 50 mass% in 2015 and even further. Apart from wood pellets from the Georgia Biomass plant (Gabiomass, n.d.) in Waycross, Georgia (USA), which is the main source of biomass, also other sources of biomass like biocoal are co-fired in the Amercentrale power plant. In this case study, it was assumed that all biomass consists of wood pellets originating from the Georgia Biomass plant. The Georgia Biomass plant has an annual capacity of approx. 750,000 tons of wood pellets and was commissioned by the owner of the Amercentrale power plant because of the limited availability of biofuels in Europe.

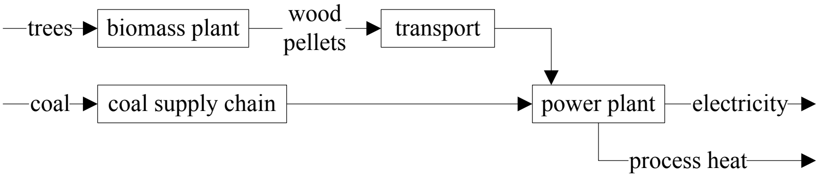

Figure 8.1: Co-firing of coal and wood pellets.

8.1.2 Wind farm

The Wind farm system is based on the construction of a wind farm in the 'Noordoostpolder' area in the Netherlands (Koepel Windenergie Noordoostpolder, n.d.). The wind farm is planned to be operational in 2015 and is expected to produce 1.4 billion kWh of electricity per year. The planned wind farm consists of 38 onshore wind turbines with a capacity of 7.5 MW (type Enercon E126) and 48 offshore wind turbines with a capacity of 3 MW (Siemens SWT3.0).

8.1.3 Combustion of bioethanol from verge grass

The third system of this case study (Figure 8.2) is based on the research conducted by De Vries (1999). In this system, verge grass is fermented into bioethanol (96 mass% in water) with fibres and proteins as by-products, followed by combustion of the bioethanol in a combined cycle power plant. The production of grass fibres and proteins did not belong to the functional unit of the assessment. The capacity of the power plant is about 30 MWe.

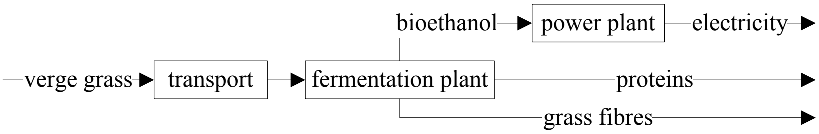

Figure 8.2: Combustion of bioethanol from verge grass.

8.2 Assessment

The functional unit and the system boundaries applied in this case study are described in Section 8.2.1. This is followed by a description of the data used for the assessments in Section 8.2.2.

8.2.1 Functional unit and system boundaries

The functional unit was set at the production of a net amount of 1 PJ of electricity. Reasons for choosing 1 PJ of electricity were that electricity is the main product of the three systems, all three systems can produce this amount of electricity and that it is a practical unit to use when comparing systems of the different case studies. The Co-firing and Bioethanol systems produce additional products, like process heat, proteins and grass fibres. The allocation of the impact of these systems to the various products was done on an exergy basis, like described in Section 6.2.

The assessment included the extraction, processing and transport of coal, the growing and thinning of trees up and including the arrival of wood pellets in the Netherlands, the mowing and transport of verge grass and so on, like schematically shown in Figures 8.1 and 8.2.

The ashes resulting from the Amercentrale power plant were regarded as by-products without an economic value. It is common practice to use these ashes in road construction. The use of river water for cooling purposes and all other auxiliary substances not mentioned in this chapter were not taken into account, because it was assumed that the effects thereof are negligible compared to the other effects.

8.2.2 Data

This case study is based on a large number of data from various data sources, completed with additional calculations and educated guesses. It is impossible to present all data in this chapter, therefore only the most important data are presented.

Environmental sustainability

Table 8.1 presents an overview of the main inputs and outputs of the three systems. A more detailed overview can be found in Appendix E. The Co-firing system delivers 0.17 PJ of heat by-product per PJ of electricity. The Bioethanol system results in 0.14 Mton of grass fibres and 0.17 Mton of proteins per PJ of electricity. The numbers presented in Table 8.1 are the amounts allocated to the production of electricity. This allocation was done on an exergy basis, as described in Section 6.2.

The Co-firing system was modelled on the basis of data about the Amercentrale (Essent, 2010c; Boudewijn and Koopmans, 2001; Didde, 2010; Arthers et al., 2011; Essent, 2010a, 2011), the Georgia Biomass plant (Essent, 2010b; Van der Voet et al., 2008; Sims, 2002) and several unit processes from the Ecoinvent database v2.2 (Ecoinvent Centre, n.d.). The coal consumption was modelled by selecting the Ecoinvent

Table 8.1: Overview of the main inputs and outputs of the three systems. The numbers are the amounts allocated to the production of 1 PJ of electricity.

	Co-firing	Wind	Bioethanol
Inputs			
Coal [kton]	87		
Trees [kton]	37		
Wind energy [PJ]		2.4	
Verge grass [kton][1]			490
Emissions to air[2]			
CO_2 fossil [Mton]	0.15		
CO_2 biogenic [Mton]	0.042		0.17
NO_x [kton]	0.12		0
SO_2 [ton]	37		
PM10 [ton]	3.5		
Final waste flows[2]			
Waste heat to river [GJ]	5.1		
Slags and ashes [kton]	15		

[1] 40% dry matter content.

[2] Main process only.

unit process ‘Hard coal supply mix/NL’. One cubic meter of wood used for producing pellets in Georgia (in short: Georgia wood) was assumed to consist of the following Ecoinvent unit processes: 0.65 m^3 of ‘Round wood, softwood, under bark, u=70% at forest road/RER’, 0.235 m^3 of ‘Industrial wood, softwood, under bark, u=140%, at forest road/RER’ and 0.115 m^3 of ‘Residual wood, softwood, under bark, u=140%, at forest road/RER’. The production of wood pellets from wood was based on the unit process ‘Wood pellets, u=10%, at storehouse/RER’ and the Ecoinvent processes that connect this process with the aforementioned ‘Georgia wood’. The unit processes were adapted to the situation in the USA as much as possible, e.g. by adapting the transport distances and ways of transport. The power plant itself was modelled by selecting the Ecoinvent unit process ‘Hard coal power plant/RER/I U’.

The wind turbines are modifications of the largest onshore and offshore wind turbines modelled in the Ecoinvent database, i.e. ‘Electricity, at wind power plant 800kW/RER U’ and ‘Electricity, at wind power plant 2 MW, offshore/OCE U’. The capacity and size of the turbines was adapted on the basis of several information sources (Enercon, 2010; Siemens, 2011; EEN, 2010; Pondera, 2009; Van Grinsven, 2009). It was assumed that the material composition of the moving and fixed parts of the wind turbines is the same as in the Ecoinvent unit processes. The capacity factor of the wind turbines was assumed to be 0.45 on average, based on an average wind speed of 8.3 to 8.7 m/s (Enercon, 2010; Siemens, 2011; Van Grinsven, 2009). At the time of modelling the wind turbines in SimaPro, it was not yet known whether the capacity of the offshore wind turbines would be 3 MW (Siemens SWT3.0) or 3.6 MW (Siemens SWT3.6) and it was decided to model the 3.6 MW wind turbines. Later on, it appeared that the offshore wind turbines applied in the

Noordoostpolder area have a capacity of 3 MW, but this has no consequences for the results of this case study since there is a large difference between the environmental and exergetic sustainability of the Wind farm system on the one hand and the Co-firing and Bioethanol systems on the other hand, and because the size of the wind turbines was not included in the calculation of the economic and social sustainability indicators.

The fermentation plant of the Bioethanol system was based on the Ecoinvent unit process 'Ethanol, 95% in H_2O, from grass, at fermentation plant/CH' in which verge grass instead of grass from meadows was used as a feedstock. The data for modelling the combined cycle power plant originate from De Vries (1999). The power plant itself was modelled by selecting the Ecoinvent unit process 'Gas power plant, 100 MWe/RER/I U', because of the resemblance of the Bioethanol power plant with a gas power plant.

Economic sustainability

Table 8.2 presents an overview of the investment costs, the operation and maintenance costs, and the costs and revenues of fuels, feedstocks and products.

Table 8.2: Overview of the economic data of the three systems related to the production of 1 PJ of electricity.

	Co-firing	Wind	Bioethanol[1]
Investment costs [10^6 €]	47	198	86
O&M costs [10^6 €/year]	1.9	7.9	3.5
Costs of fuels/feedstocks [10^6 €/year]	6.8		-7.4
Revenues of electricity [10^6 €/year]	17	17	17
Subsidy [10^6 €/year]		12	

[1] Fermentation plant and power plant.

The investment costs of the wood pellet and coal power plants were calculated at 137 million euros (Gabiomass, n.d.) and 1100 million euros (Croezen et al., 2006), respectively. The investment costs of the Wind turbines are 1 billion euros (Koepel Windenergie Noordoostpolder, n.d.) and the investment costs of the fermentation and power plant of the Bioethanol system amount to 80 million euros (De Vries, 1999). The capacities of the systems differ from the functional unit of this case study, i.e. the capacities of the Co-firing, Wind farm and Bioethanol systems are 27, 5.04 and 0.876 PJ per year, respectively. The investment costs related to a capacity of 1 PJ per year were calculated in the way as described in Section 6.2.2.

The costs of the trees were calculated from the feedstock costs of the wood pellet plant (Gabiomass, n.d.). The disposal of verge grass costs about 20 euros per ton (Huizing and Hillebrand, 2005), therefore the costs of fuels/feedstocks in the bioethanol system is a negative number. It was assumed that 75% of the disposal costs, i.e. 15 euros per ton of verge grass, is received in the Bioethanol system.

The Wind farm will be subsidised by the Dutch government. On the basis of the information provided by RVO (2014), the subsidy allocated to 1 PJ of power generation was calculated at 12 million euros per year for 15 years.

Social sustainability

The man-hours per stage of the co-firing production chain (Table 8.3) were calculated on the basis of many references (Gabiomass, n.d.; BLS, n.d.; Alderton and Lane, 2001; EIA, 2010; DSF, n.d.; RTV Noord, 2010), completed with educated guesses. The man-hours needed for loading/unloading and storage of coal were neglected. The man-hours of the Wind farm and Bioethanol systems have not been calculated because it was assumed that all employees, including the employees occupied with the construction and decommissioning of the installations, originate from the Netherlands, which means that the IHDI of the Netherlands is applicable in both systems.

Table 8.3: Overview of man-hours of the Co-firing system.

[Man-hours/Mton]	Coal	Wood pellets
Exploration/processing	$2{\cdot}10^5$	
Wood pellet plant		$2{\cdot}10^5$
Deep sea transport	$7{\cdot}10^4$	$3{\cdot}10^5$
Coal power plant	$2{\cdot}10^4$	-

8.3 Results

8.3.1 Environmental sustainability

The results of the environmental assessment are presented in Table 8.4. The preferred system is the Wind farm system and the second-best system is the Bioethanol system. It was expected that the ReCiPe score of the Wind farm system largely depends on the construction of the Wind farm. This was investigated by calculating the ReCiPe score of the Wind farm system without infrastructure processes. The ReCiPe score decreased from 0.54 to 0.0059 MPt when the infrastructure processes were excluded, so it is true that the ReCiPe score of the Wind farm system is mainly caused by infrastructure processes. If the verge grass of the Bioethanol system was no longer regarded as a waste product and, as a consequence, the land needed for the growing of verge grass was taken into account, the ReCiPe score of the Bioethanol system increased from 8.0 to 33 MPt.

It was also investigated which processes of the whole supply chain are responsible for at least 80 per cent of the ReCipe scores of the three systems. Figure 8.3 presents the processes that contribute at least 5 per cent to the total ReCiPe score. A more detailed overview can be found in Appendix E. As becomes clear from Figure 8.3 and the data in the appendix, many processes are responsible for the first 80 per cent of the ReCiPe scores of the three systems.

Table 8.4: ReCiPe scores of the three systems per ReCiPe damage category.

[MPt]	Co-firing	Wind farm	Bioethanol
Human Health	7.2	0.27	3.3
Ecosystems	5.5	0.10	1.7
Resources	6.4	0.17	2.9
Total[1]	19	0.54	8.0

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

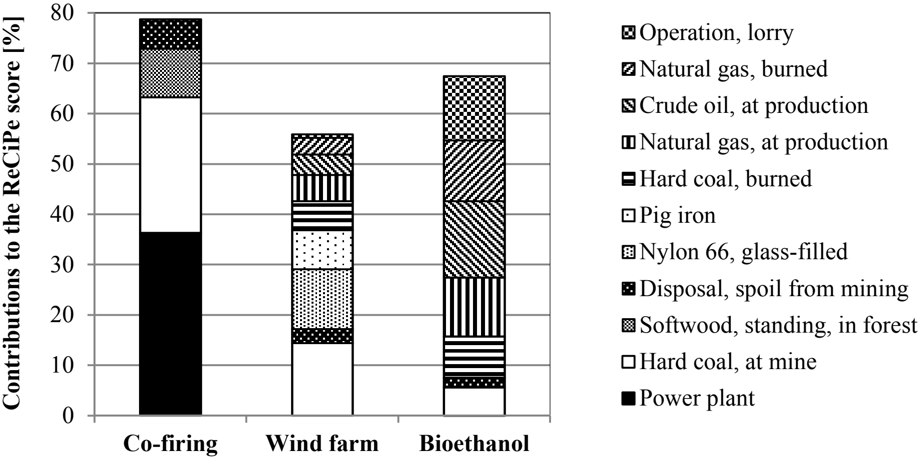

Figure 8.3: Process contributions to the ReCiPe scores of the three systems.

8.3.2 Economic sustainability

Table 8.5 presents the Net Present Value (NPV) and Present Worth Ratio (PWR) of the three systems based on the production of 1 PJ of electricity. The PWR of the Wind farm is presented with and without considering subsidy. The influence of the subsidy appeared to be quite large, but it is very reasonable to assume that the Wind farm is subsidised. In this research, it was assumed that the revenues of processing verge grass equal 15 euros per ton. The influence of the (negative) price of verge grass was investigated by calculating the life cycle costs of the Bioethanol system when the revenues of processing verge grass are 7.5 instead of 15 euros per ton. It can be concluded from the results that the Bioethanol system is preferred and that the second-best system is the Co-firing system. Table 8.5 presents the PWR scores of the three systems at discount rates of 6 and 10 per cent as well. As expected, the systems become more profitable at a lower discount rate and the ranking of the systems remains the same. The Wind farm system becomes profitable at a discount rate of 6 per cent. The costs of R&D and decommissioning are assumed to be low compared to the other costs and were not taken into account. The effect of this assumption was investigated by increasing the investment costs by 25 per cent, which resulted in lower PWR scores, but did not influence the ranking of the systems. The contributions of the investment costs and yearly costs and revenues to the PWR are depicted in Figure 8.4. A table with the numbers can be found in Appendix E.

Table 8.5: Life Cycle Costs of the three systems related to the production of 1 PJ of electricity.

8% discount rate	Co-firing	Wind farm	Bioethanol
Investment costs [10^6 €][1]	40	184	80
NPV [10^6 €]	17	-23	94
PWR [-]	0.42	-0.12	1.2
Variants			
NPV [10^6 €]		-111[2]	62[3]
PWR [-]		-0.6[2]	0.79[3]
PWR at 6 % discount rate [-]	0.72	0.029	1.6
PWR at 10 % discount rate [-]	0.18	-0.24	0.84

[1] Present value of investment costs.

[2] Without subsidy.

[3] With revenues for processing verge grass of €7.5/ton instead of €15/ton.

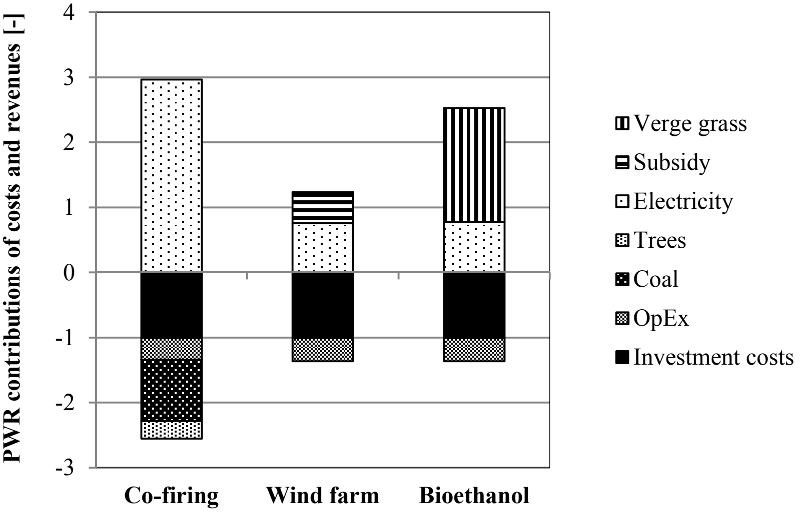

Figure 8.4: Contributions to the PWR scores of the three systems.

8.3.3 Social sustainability

The Wind farm and Bioethanol systems have the IHDI of the Netherlands as these systems take place in the Netherlands and it was assumed that all employees, including the employees occupied with the construction and decommissioning of the installations, originate from the Netherlands as well. As a result, the Wind farm and Bioethanol systems are preferred compared to the Co-firing system. Table 8.6 presents the $IHDI_{overall}$ of the three systems. It was also investigated how the $IHDI_{overall}$ varies along the supply chain of the Co-firing system. The results thereof are presented in Table 8.7. The transport of coal and wood pellets has the lowest $IHDI_{overall}$, closely followed by the extraction of coal. Figure 8.5 presents the contributions of the processes to the overall IHDI score of the Co-firing system.

Table 8.6: Results of the social LCA of the three systems.

[-]	Co-firing	Wind farm	Bioethanol
$IHDI_{overall}$	0.639	0.857	0.857

Table 8.7: $IHDI_{overall}$ along the supply chains of the Co-firing system.

[-]	Coal supply chain	Wood pellet supply chain
Extraction/production	0.617	0.821
Transport	0.562	0.562
Coal power plant	0.857	

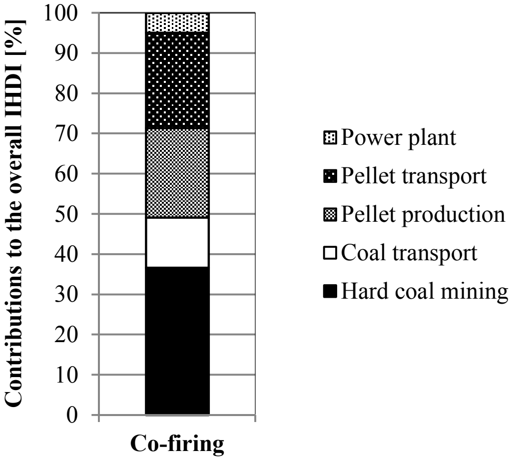

Figure 8.5: Process contributions to the $IHDI_{overall}$ score of the Co-firing system.

8.3.4 Exergetic sustainability

The results of the exergetic sustainability assessment are presented in Table 8.8. It appears that the Wind farm system is preferred from an exergetic point of view. Table 8.8 also shows that most of the exergy loss is caused by internal exergy losses and that the exergy loss caused by land use is quite small.

Table 8.8: Total Cumulative Exergy Loss caused by the three systems.

[PJ]	Co-firing	Wind farm	Bioethanol
CExD	8.9	3.1	11
Exergy of products	1.0	1.0	1.0
Exergy of emissions	0.32	0.026	0.90
Internal exergy loss	7.6	2.1	9.1
Abatement exergy	1.0	0.028	0.46
Exergy loss land use	0.053	0.00094	0.023
Total Cumulative Exergy Loss	8.7	2.1	9.5

SimaPro does not offer the possibility to calculate the contribution of the processes to the TCExL, and the CExD calculated by SimaPro is no measure of the TCExL (Section 3.4). To be able to compare the ReCiPe and TCExL scores along the supply chains in Section 8.3.5, the TCExL of the processes with the highest contribution to the ReCiPe scores of the three systems (Section 8.3.1) and of the main processes were calculated. Figure 8.6 shows the aforementioned processes that contribute at least 1 per cent to the TCExL score of one of the three systems. Tables with the process contributions to the TCExL and CExD scores of the three systems can be found in Appendix E.

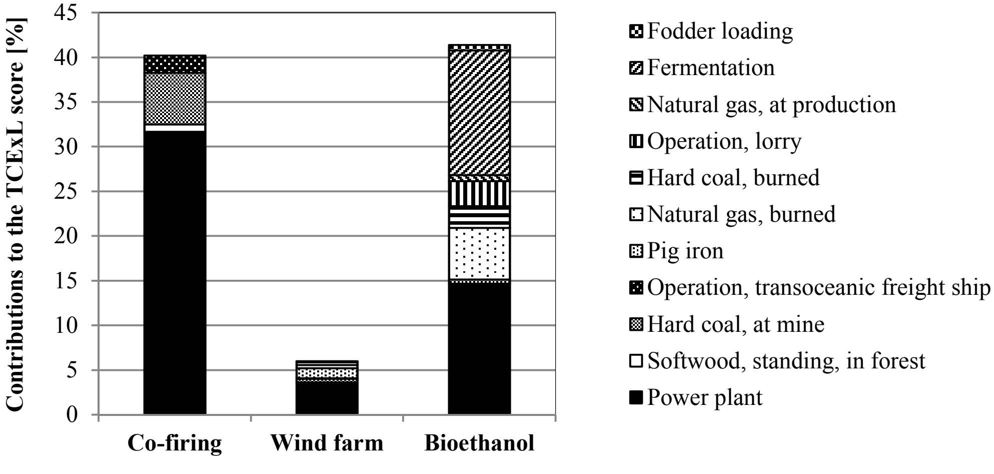

Figure 8.6: Process contributions to the TCExL scores of the three systems.

According to Figure 8.6, the power plant itself is responsible for about one third of the TCExL of the Co-firing system. The processes of the Wind farm system of which the TCExL was calculated contribute to a small extent to the overall TCExL score. The power plant of the Bioethanol system contributes for about 15 per cent to the TCExL and the fermentation of verge grass to bioethanol for about 14 per cent.

8.3.5 Comparison of the results

The results of the environmental (ReCiPe), economic (PWR) and social ($\mathrm{IHDI}_{\mathrm{overall}}$) sustainability assessments as well as the results of the exergetic life cycle assessment are presented in Table 8.9. This table also presents an overview of the grading of the systems. If two systems had the same score, they were rated the same.

Table 8.9: Overview of the assessment results of the systems.

	Co-firing		Wind farm		Bioethanol	
	absolute	ranking	absolute	ranking	absolute	ranking
ReCiPe [MPt]	19	3	0.54	1	8.0	2
PWR [-]	0.42	2 (1)[1]	-0.12	3	1.17	1
$\mathrm{IHDI}_{\mathrm{overall}}$ [-]	0.64	3	0.86	1	0.86	1
TCExL [PJ]	8.7	2	2.1	1	9.5	3

[1] If the disposal costs of verge grass are assumed to be cut in half, the economic sustainability of the Co-firing and Bioethanol systems are comparable.

From the results in Table 8.9, it can be concluded that the Wind farm system is preferred from an environmental, social and exergetic point of view and that the Bioethanol system is preferred from an economic point of view. The profitability of the Bioethanol system is to a large extent caused by the 20 euros per ton disposal costs of the verge grass, of which 75% (i.e. €15/ton) is received in this system. As already mentioned in Section 8.3.2, the PWR of this system decreases to 0.79 if the disposal costs are cut in half, making the distinction between the PWR of the Co-firing and Bioethanol systems relatively small.

According to the results of the regular sustainability assessment methods, the Co-firing system is the least preferred system, except for its economic sustainability. The Co-firing system is the second-best system according to the results of the exergetic assessment. An explanation of the fact that the ReCiPe scores of the Co-firing and Bioethanol systems are very different while the TCExL scores are quite similar is that the use of verge grass has no environmental impact but still contributes to the TCExL score because of the exergy value of verge grass. If the verge grass is no longer considered a waste product and, as a consequence, the land used for the growing of verge grass is accounted for in the sustainability assessments, the ReCiPe score increases from 8.0 to 33 MPt but the TCExL score remains the same. Thus, the ReCiPe score is to a large extent influenced by the choice whether verge grass is a waste product or not while the TCExL is not. The social sustainability scores and rating of the Wind farm and Bioethanol are the same because it was assumed that all activities take place in the Netherlands and that the employees originate from the Netherlands as well.

Figure 8.7 presents the environmental, economic and social sustainability of the three systems versus the TCExL caused by each system. Hereto, the ReCiPe indicator of Table 8.9 has been modified into a dimensionless indicator that increases with the environmental sustainability. This was done by multiplying the inverse of the ReCiPe indicator of each system with the ReCiPe score of the Wind farm system, i.e. the system with the highest environmental sustainability. Figure 8.7 clearly shows that the environmental and economic sustainability of the Wind farm system are very different from the two other systems. In accordance with the expected relationships of Figure 3.7, the environmental sustainability decreases with increasing exergy loss. The economic sustainability indicator increases with increasing exergy loss because of the high investment costs of the Wind farm system compared to the other systems. This is in line with the left part of the line representing this relationship in Figure 3.7, but the technological differences between the Wind farm system and the two other systems are too large to draw conclusions about the relationship between exergy losses and the economic sustainability. The relationship between social sustainability and exergy loss is not clear because of the assumptions with regard to the social sustainability of the Wind farm and Bioethanol systems.

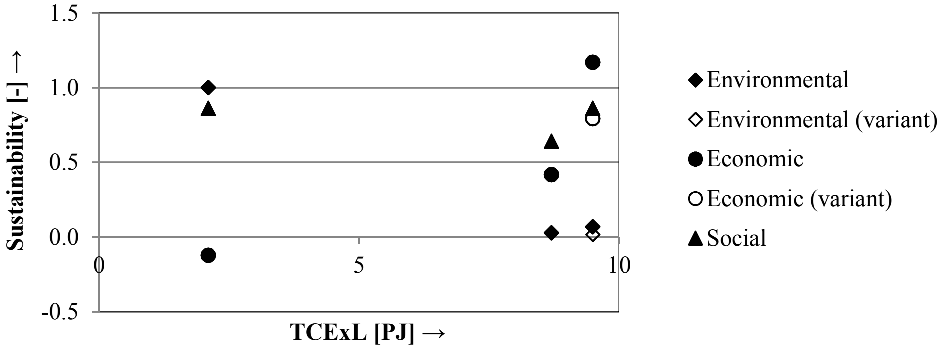

Figure 8.7: The environmental, economic and social sustainability of the systems of the fossil versus renewable case study versus the exergy losses caused by these systems.

To be able to investigate the differences between the four methods in more detail, Tables 8.10 to 8.12 present the contributions of the processes to the total scores of the systems.

It appears from Tables 8.10 to 8.12 that different parts of the systems contribute most to the scores of the systems. E.g., the coal supply chain and the power plant of the Co-firing system both contribute about one third to the ReCiPe score, about half of the PWR costs is caused by the power plant, the coal and wood pellets supply chains each cause about half of the $IHDI_{overall}$ and the power plant is the main contributor to the TCExL, but with the remark that the TCExL has only been calculated of the processes that contribute most to the ReCiPe score. The total of the processes that cause at least 80 per cent of the ReCiPe scores of the

Table 8.10: Contributions of supply chains and processes to the total scores of the Co-firing system.

[%]	ReCiPe	PWR	$IHDI_{overall}$	TCExL
Coal supply chain				
Hard coal mining	27		37	5.8
Disposal, spoil from coal mining	5.8			0
Coal transport, transoceanic	3.6		12	1.5
Purchase of coal		37	-	
subtotal	*(36)*	*(37)*	*(49)*	*(7.3)*
Wood pellets supply chain				
Growing of trees	9.7	11		0.82
Wood pellet production			22	
Wood pellet transport, transoceanic	1.0		24	0.42
subtotal	*(11)*	*(11)*	*(46)*	*(1.2)*
Power plant				
Power plant	36		4.9	32
Investment costs		39		
OpEx		13		
subtotal	*(36)*	*(52)*	*(4.9)*	*(32)*
Total	83[1]	100[2]	100	40[1]

[1] The ReCiPe and TCExL scores of the processes that cause at least 80 per cent of the ReCiPe score have been calculated only. The infrastructural part of these processes is very small, i.e. only 0.25 and 0.05 per cent of the total ReCiPe and TCExL scores, respectively.

[2] Costs only, because of the opposite signs of costs and revenues.

three systems and the main processes 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 8.11: Contributions of supply chains and processes to the total scores of the Wind farm system.

[%]	ReCiPe	PWR	$\text{IHDI}_{\text{overall}}$	TCExL
Construction				
Construction	80			3.9
Investment costs		73		
subtotal	*(80)*	*(73)*	*(n/a)*	*(3.9)*
Operation				
Operation	0.56			3.6
OpEx		27		
subtotal	*(0.56)*	*(27)*	*(n/a)*	*(3.6)*
Total	80[1]	100[2]	100	7.5[1]

[1] The ReCiPe and TCExL scores of the processes that cause at least 80 per cent of the ReCiPe score and of the operation of the wind turbines have been calculated only.

[2] Costs only, because of the opposite signs of costs and revenues.

Table 8.12: Contributions of supply chains and processes to the total scores of the Bioethanol system.

[%]	ReCiPe	PWR	$\text{IHDI}_{\text{overall}}$	TCExL
Verge grass supply chain				
Mowing	2.0			0.40
Transport	29			3.8
Other	5.4			0.32
subtotal	*(36)*		*(n/a)*	*(4.5)*
Fermentation and combustion				
Fermentation	0.018			14
Heat supply fermentation	4.2			2.1
Electricity supply fermentation	40			7.8
Power plant	0.085			15
Investment costs		73		
Total OpEx		27		
subtotal	*(45)*	*(100)*	*(n/a)*	*(39)*
Total	80[1]	100[2]	100	43[1]

[1] The ReCiPe and TCExL scores of the processes that cause at least 80 per cent of the ReCiPe score and of the fermentation and combustion process have been calculated only. The infrastructural part of these processes is 5.9 and 0.29 per cent of the total ReCiPe and TCExL scores, respectively.

[2] Costs only, because of the opposite signs of costs and revenues.

8.4 Discussion and conclusions

It can be concluded from this case study that the four assessment methods are not unanimous about the system that is preferable. The environmental and exergetic assessment methods prefer the Wind farm system. From an economic point of view the Bioethanol system is preferred. The $\mathrm{IHDI}_{\mathrm{overall}}$ of the Wind farm and Bioethanol systems are the same because it was assumed that their $\mathrm{IHDI}_{\mathrm{overall}}$ is equal to the IHDI of the Netherlands. As a result, the Co-firing system has the lowest $\mathrm{IHDI}_{\mathrm{overall}}$. The growing of verge grass was not considered in the sustainability assessments because verge grass was regarded as a waste product. The results of this case study make clear that the ranking of the options according to the regular sustainability assessment methods depends on choices and/or opinions with regard to the value, or lack of value, of inputs and products, on market prices and the like. This does not hold for the TCExL method because the calculation of exergy values and exergy losses is based on fundamental thermodynamic equations.

The discontinuity in electricity production by the Wind farm system caused by too low or too high wind speeds has not been considered. Back-up systems will have a negative influence on its sustainability, but it is expected that this system is still preferable from the environmental and exergetic points of view because of the large difference with the scores of the two other systems.

The methods differ in the processes that contribute most to the total score of the method. E.g., the coal supply chain contributes about one-third to the ReCiPe score of the Co-firing system but these processes cause less than 10 per cent of the TCExL score. The processes that are responsible for 80 per cent of the ReCiPe score of the Wind farm system cause about 8 per cent of the TCExL score. The TCExL caused by the processes of the Bioethanol system that are responsible for 80 per cent of the ReCiPe score is about 43 per cent. It was too time-consuming to calculate the TCExL of all processes that are part of the systems, so it is unknown which process contributes the most to the TCExL. The PWR and $\mathrm{IHDI}_{\mathrm{overall}}$ scores could not be calculated at the same level of detail as the ReCiPe and TCExL scores, but they lead to different results with regard to which process or part of a system contributes most to the total score as well.

Chapter 9

Back to the research questions

This chapter provides the answers to the research questions of Chapter 1, followed by the underpinning of the answers. The foundation of the answers can be found in the sections and/or chapters that are mentioned in brackets after each answer.

1. What is known about the relationship between exergy and sustainability?

   Researchers in the field of exergy and sustainability claim that exergy losses should be decreased when striving for sustainability (Sections 3.1 and 3.3).
   The researchers qualitatively explain the relationship between exergy and environmental sustainability, e.g. resource degradation and waste exergy emissions. However, an unambiguous quantitative underpinning of the relationship between exergy and sustainability has not been found in literature. Some of the researchers mention that no single metric will be completely satisfactory when assessing sustainability because it provides too little information and they recommend using exergy analysis in addition to other assessment methods. From a study into the use of exergy as a measure in environmental policy making, it was concluded that exergy loss is at least a qualitative measure of the environmental impact of technological processes.

   A reason to decrease exergy losses is that exergy, also known as 'work potential', is needed for all processes and activities that take place in our society, i.e. every process and activity is accompanied with the loss of exergy. The only source of new exergy to replenish the amount of exergy on earth is solar and/or tidal energy.

   Exergy analysis has a wide variety of application areas and can be used to pinpoint where the largest potential for improvement is and to calculate the distance to the thermodynamic optimum (Sections 2.3 to 3.1).
   Examples of application areas of exergy analysis are engineering applications, analysis of countries or regions, its combination with environmental and economic aspects and in the field of sustainable development. Conducting an

exergy analysis clearly pinpoints where exergy is lost and where the largest potential for improvement is. Furthermore, exergy analysis can be used to determine the distance to the thermodynamic optimum of a process or activity and it can be used for the comparison of processes and activities. The thermodynamic optimum of a process or activity is zero exergy loss, but when it is supposed that the exergy losses of certain parts of a process, e.g. the chemical reactions, are inevitable, a new target value can be calculated that takes into account these inevitable losses.

Exergy values can be calculated of mass as well as energy flows, which makes the use of weighting factors superfluous (Section 2.1.1).
An advantage of exergy analysis in sustainability assessment is that no (subjective) weighting factors are needed to consider amounts or flows of mass and energy in an exergy analysis. A drawback of exergy analysis is that it is not always easy to determine the chemical exergy value of amounts of mass. However, it depends on the desired kind of exergy analysis results whether the chemical exergy values of amounts of mass have to be considered or not, and the calculation of chemical exergy values is facilitated by the increasing number of tabulated standard chemical exergy values of components.

Exergy loss is an objective and timeless performance indicator (Sections 2.1, 3.5 and 5.1.6.
The calculation of exergy losses is based on fundamental thermodynamic equations for the determination of exergy values of mass and energy flows. Regular sustainability assessment methods make use of contested models and weighting factors and are dependent on market prices etc. Furthermore, the results of regular assessment methods change over time because of new insights and developments regarding the applied calculation methods. Another characteristic of exergy losses is that they are caused by driving forces. The larger the driving force that gets a process running, the more spontaneously that process will take place and the more difficult it will be to run that process in the opposite direction or to reach the initial state via an alternative route. Reaching the initial state is important from a sustainability point of view, with the closing of material cycles as an example. Thus, the larger the exergy loss caused by a process or system, the less sustainable this process or system is. The higher the amount of exergy that is available on earth, the better present and future generations can meet their needs. From a sustainability point of view, it is therefore important to use exergy wisely.

2. What requirements do methods for the assessment of the sustainability of technological systems have to meet?

   A commonly accepted operationalization of sustainability could not be found in literature, but in general, sustainability is considered as having an environmental, an economic and a social component. Furthermore, it is considered important to assess the sustainability of a system from a life cycle perspective (Section 4.1).
   Several definitions of 'sustainability' and 'sustainable development' have been proposed in an attempt to operationalise the concept of sustainability. Not always a distinction is made between 'sustainability' and 'sustainable devel-

opment'. Regardless the lack of a commonly accepted operationalization of sustainability, it is common knowledge that sustainability consists of three pillars or components, i.e. an environmental, an economic and a social component, although some researchers are of the opinion that the technological component should be considered separately as well. The technological component is related to the other components, especially the environmental component, and is not considered separately in this research to prevent double-counting of technological aspects.

It was learned from the literature research that it is important to take a life cycle point of view when assessing technological systems, because in this way problem shifting between different life cycle phases and/or sustainability aspects is prevented. However, whether it is a true life cycle assessment depends on the subject of analysis. In literature, an assessment is called a life cycle assessment when the phases of construction, operation and decommissioning of a technological system and its supply chains are included in the analysis, but in fact it would be better to call it a cradle to grave assessment when the transformation of the outputs to the required inputs is not included in the assessment.

Sustainability assessment methods should consider the phases of construction, operation and decommissioning of the installations, equipment and infrastructure, the amounts of inputs and outputs, 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, economic and social aspects (Section 4.3.1).
A list of requirements that analysis methods for the assessment of the sustainability of technological systems have to fulfil has been drawn up on the basis of knowledge gathered from studying literature about the definition of sustainability and sustainability assessment methods, as well as research into exergy as a measure in environmental policy making. Common to all assessment methods are the operational phase of installations, equipment and infrastructure, and the amounts of inputs and outputs to and from the installations, equipment and infrastructure. The requirements that have to be met and that are not common to all assessment methods are the following: phase of construction of the installations, equipment and infrastructure, phase of decommissioning of the installations, equipment and infrastructure, 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, economic aspects and social aspects. The aforementioned list of requirements plus the 'operational phase' and the components 'inputs' and 'outputs' is appropriate because it considers all interactions between a technological system and its surroundings.

Methods applied for the calculation of sustainability indicators should be objective and sufficient data should be available to calculate these indicators (Section 4.3.2).
Like all assessment methods, the methods applied in this research for the calculation of sustainability indicators should be objective and enough data

should be available to calculate these indicators. A method is for example not regarded as objective if different views exist about how its indicators should be calculated, if it makes use of variables that are disputable, e.g. weighting factors, and/or if the results of a method change over time because of market influences and the like. Strictly speaking, the latter is not a consequence of the method itself, but the result of variations in one or more of the input variables used by that method. In this research, both aspects have been grouped into 'objectivity' for reasons of simplicity.

The requirement that the applied methods for calculating sustainability indicators are objective is different from pursuing an objective overall sustainability assessment method that takes into account regular environmental, economic and social sustainability indicators as well as exergy losses. The importance that is attached to each of these four aspects is a subjective, and likely political, consideration.

3. Which methods, with and without exergy, are suitable for the assessment of the sustainability of technological systems?

   The sustainability assessment methods found in literature have shortcomings with regard to the assessment of the sustainability of a technological system (Section 4.4).
   The common method to assess the environmental sustainability from a life cycle perspective is called environmental life cycle assessment (LCA). The economic assessment method that is recommended for use in combination with environmental LCA is known as environmental Life Cycle Costing (LCC). A method for social LCA (S-LCA) is under development. However, none of these assessment methods meets all aforementioned requirements because the methods consider only the aspects of sustainability they are meant for, e.g. the environmental LCA method does not consider economic and social aspects of sustainability. The problem with combining the three assessment methods into an overall Life Cycle Sustainability Assessment (LCSA) method is that weighting and/or adding up of the three components is subjective and leads to a loss of transparency because a high score of one of the three aspects can compensate for a low score of another aspect. The possibility that an aspect compensates for another aspect is called 'weak sustainability'.

   The environmental LCA method does not fully meet the requirement 'objectivity of the method', because it makes use of models for the calculation of the impact of e.g. emissions while in some cases there is no consensus about which model to use. Another disadvantage is that weighting factors are needed to calculate one overall environmental indicator. Neither does the environmental LCA method consider exergy losses.

   The economic method has the disadvantage that it does not include all indirect costs and that the indicators change over time because of market developments, governmental decisions and consumer confidence.

   A problem of social LCA is the limited availability and qualitative or semi-quantitative nature of many data, which makes it difficult to calculate aggregated indicators.

The exergy analysis methods found during the literature research into ‘exergy’ and ‘sustainability’ have shortcomings as well, i.e. they do not consider all components of sustainability and/or they make use of indicators, equations and weighting factors that are not objective.

The Total Cumulative Exergy Loss (TCExL) method has been developed as an alternative to existing exergy analysis methods (Section 5.1).
The shortcomings of current exergy analysis methods in combination with the notion that exergy losses should be minimised when striving for sustainability, led to the design of a new exergy analysis method that is based on fundamental scientific equations and that takes into account as many of the designated components of sustainability as possible. This newly designed exergy analysis method is called the Total Cumulative Exergy Loss (TCExL) method. The total cumulative exergy loss of the TCExL method is the summation of the internal exergy loss caused by irreversibilities within the technological system including its supply chains, the exergy loss caused by abatement of emissions and the exergy loss related to the land occupied by the technological system including its supply chains. The latter is relevant because land use prevents capturing new exergy from sunlight by the ecosystem.

The TCExL method can be regarded as a combination of, or extension to, the existing exergy analysis methods called Cumulative Exergy Consumption (CExC), Cumulative Exergy Consumption and Abatement (CExCA), Cumulative Exergy Extraction from the Natural Environment (CEENE), and Exergetic Life Cycle Assessment (ELCA).

A component of sustainability of which no exergy losses can be calculated is the decrease of natural resources, because depletion and scarcity are facts instead of technological processes. However, the TCExL method indirectly considers the decrease of natural resources by taking into account the exergy losses caused by the extraction of these resources. It is very likely that the scarcer a resource, the higher the exergy loss will be that is caused by the extraction of that resource. Other components of sustainability that cannot directly be considered by the TCExL method are the economic and social aspects of sustainability. Like exergy losses, the economic aspect is related to the amounts of inputs and outputs and land use, but it also depends on immaterial aspects like market prices and wages. The social aspect of sustainability is indirectly considered via the amounts of inputs and outputs and the man-hours related to these amounts, but the social sustainability depends on aspects like working conditions as well. Somehow incorporating the economic and social aspects of sustainability in the exergy analysis method would ‘pollute’ the method, therefore no attempts have been made to incorporate these aspects. Nevertheless, the loss of exergy can be regarded as having economic and social components because exergy (work potential) is needed for all processes and activities.

The newly developed Total Cumulative Exergy Loss (TCExL) method is an improvement compared to existing exergy analysis methods in the sense that the TCExL method is solely based on the calculation of exergy losses and that it takes into account all exergy losses caused by a technological system during its life cycle. However, until now, the abatement exergy loss of only a few emissions is included in the TCExL method because abatement exergy values of other emissions are not yet available.

The inclusion of the abatement of emissions makes that the outputs of technological systems no longer influence the ecosystem nor the health of human beings. The abatement of emissions results in exergy losses. It must be realised that all inputs of technological systems can be regenerated if enough exergy is available to do so. From a sustainability point of view, it is therefore important to use exergy wisely. Exergy that is not lost by a generation is available for future generations. The lower the amount of exergy that is available on earth, the lower the ability of people to abate emissions and to meet their needs in the sense of e.g. materials they would like to use for their activities. This implies that the TCExL can be used as a fundamental indicator in the operationalization of the definition of sustainable development by the Brundtland commission.

The environmental sustainability is assessed by determining ReCiPe Endpoint indicators (Section 5.2.1).
To investigate the value of exergy analysis in sustainability assessment, regular, i.e. non-exergetic, sustainability assessment methods have been used in this research as well. The method applied for the environmental sustainability assessment is the environmental LCA method that results in ReCiPe endpoint indicators. The reason for choosing this method is that ReCiPe is the result of a thorough cooperation between experts in the field of LCA and because it is a recent development in this field.

The Present Worth Ratio (PWR) is calculated to determine the economic sustainability (Section 5.2.2).
The economic sustainability assessment method that has been chosen is the calculation of the Present Worth Ratio (PWR) because the PWR takes into account the net present value of costs and revenues during a life cycle as well as the investment costs of a technological system.

A newly developed method based on man-hours and the Inequality-adjusted Human Development Index (IHDI) is used to assess the social sustainability (Section 5.2.3).
This new method has been developed because a standard method for social LCA is still under development and because it would be too time-consuming and costly to gather site-specific social data. The method embroiders on other societal assessment methods that make use of labour hours for the comparison between systems and is based on the man-hours along the supply chain, the country of origin of those people and the Inequality-adjusted Human Development Index (IHDI) reported by the UNDP (United Nations Development Programme). The reasons for using the IHDI instead of other social indicators are that it is available for many countries and that it takes into account the possible inequality between inhabitants of a country. A limitation of calculating the social sustainability indicator from more general indicators like the IHDI is that local aspects like working conditions of the individual employees are not considered. The calculation of the $\mathrm{IHDI}_{\mathrm{overall}}$ does not have an added

value anymore when the IHDIs of the current less-developed countries have increased to the same level as the developed countries, but the same would hold for an indicator based on local sustainability aspects when differences between local sustainability aspects no longer exist. An advantage of calculating the $\text{IHDI}_{\text{overall}}$ over the standard social LCA method that is under development is that no qualitative or semi-quantitative data that are difficult to aggregate are needed.

4. Which method can be used to compare the results obtained from applying the selected methods, with and without exergy, in case studies?

   The value of exergy analysis in sustainability assessment of technological systems can be investigated by conducting case studies that comprise several systems and subsequently comparing the results of assessment methods with and without exergy of these systems (Section 5.3).
   An important requirement to these systems is that they are comparable, i.e. they produce the same product in the same amount and they use the same feedstocks or they take into account the whole supply chain to produce the feedstocks from resources available on earth. In this research, each case study comprises three systems for fulfilling the demand for energy carriers.

   The TCExL and the chosen environmental LCA, LCC and S-LCA methods are used to assess the systems of each case study, despite the shortcomings of the non-exergetic methods. On the basis of the results of the assessments, it can be concluded which system of a case study is preferred from an environmental point of view, which system is second-best, etc., which system is preferred from an economic point of view, etc. The advantage of comparing the results of the separate methods instead of combining the results of the methods into one overall assessment result is that it is a transparent way of comparison, there is no need for weighting factors and no information is lost.

   From the ranking of the systems based on the results of the four assessment methods, conclusions can be drawn with regard to the value of exergy analysis in sustainability assessment of technological systems. E.g., what does it mean for the environmental sustainability of the subject of the case study if the system is chosen that is preferred from an exergetic point of view instead of the system that is preferred from an environmental point of view? And what does it mean for the economic and social sustainability if the system is chosen that is preferred from an exergetic point of view?

   The differences between the four methods can be investigated in more detail by examining which part or process of a technological system contributes most to the overall score of each method (Section 5.3).
   It can also be investigated whether the same process contributes most to the scores of all four methods or that different processes contribute most to these scores. In this way the value of exergy analysis in sustainability assessment of technological systems can be investigated in more detail.

5. What is learned from the case studies about the value of exergy analysis in sustainability assessment of technological systems?

   The sustainability of our society can be improved by applying exergy analysis in the assessment of technological systems, but in the case of comparing technological systems with different inputs, a technological system that is preferred from an exergetic point of view is not always preferred from the economic and social points of view (Chapters 7 and 8).

   The environmental impact of a technological system can be traced back to the use of raw materials, energy carriers and other inputs, emissions and land use. It follows from the LNG case study and especially from the variant excluding H-gas supply chain that an increase of the amounts of inputs, e.g. raw materials and energy carriers, and emissions is accompanied with an increase of the Total Cumulative Exergy Loss (TCExL). This is understandable because the exergy loss caused by a technological process is proportional to the amount that is processed by that process. It follows from the definition of the TCExL that the same holds for land use, i.e. a larger area of land occupation results in a higher TCExL. According to the results of the Fossil versus renewable case study, the environmental and TCExL methods prefer the same system as well, but they differ in the system that is considered second-best. Both methods would result in the same ranking of the three systems if the environmental method took into account the land needed for the growing of the inputs that are regarded as waste products, i.e. verge grass. The TCExL score is not influenced by the choice whether an input is regarded as a waste product or not. Both case studies contribute to the notion that a lower environmental impact of a technological system is accompanied with a lower TCExL. This is in line with the relationship between environmental sustainability and exergy losses that is mentioned in Sections 3.1 and 3.5.

   According to the LNG case study, the system with the highest economic sustainability has the lowest TCExL. This is understandable because the three systems of the LNG case study make use of the same raw materials and energy carriers for power generation and have comparable investment costs, while the preferred system requires the lowest amount of raw materials and energy carriers. Thus, in the case of systems that use the same inputs and have comparable investment costs, the system with the highest economic sustainability causes the lowest TCExL. The systems of the Fossil versus renewable case study apply technologies that make use of different energy carriers for power generation. The investment costs of the system with the lowest TCExL are much higher than the investment costs of the two other systems and the low variable costs of this system do not outweigh the higher fixed costs. As a result, this system causes the lowest TCExL, but has the lowest economic sustainability. Thus, when comparing systems that apply different technologies and make use of different energy carriers for power generation, the system with the lowest TCExL is not always the system with the highest economic sustainability. This is in line with Sections 3.2 and 3.5 where it was already suspected that the relationship between economic sustainability and exergy loss is not straightforward. The results of both case studies contribute to the notion that the economic sustainability is lower at lower exergy losses (large installations with high investment costs) and at higher exergy losses (large amount of inputs), but the technological differences between the systems of the Fossil versus renewable case study and between the case studies themselves are too large to draw conclusions about the entire relationship between economic sustainability and exergy losses. A disadvantage of economic indicators compared to a physical property like exergy loss is that economic indicators do not always include all costs, especially not all indirect costs, and are largely influenced by market developments, governmental decisions and consumer confidence.

It was learned from the LNG case study, especially from its variant without the H-gas supply chain, that the rating of the systems according to their social sustainability is the same as the rating according to the exergetic sustainability. This is understandable because the applied social sustainability indicator as well as the exergy losses are related to the amounts of inputs. I.e., a larger amount of inputs is accompanied with a higher exergy loss as well as a higher demand for those inputs and this higher demand leads to more raw materials and/or energy carriers to be extracted, which is a less-preferred job that is usually carried out by people originating from countries with a low IHDI. The systems of the Fossil versus renewable case study are very different, but again the system with the lowest social sustainability causes the highest TCExL. It is understandable that the system with the highest TCExL of this case study also has the lowest social sustainability because of the origin of the inputs of this system, but no relationship between the TCExL and the social sustainability of systems that use different inputs from different countries is known. No additional information could be obtained from comparing the two other systems because it was assumed that all employees of those two systems originate from the Netherlands. It was already mentioned in Section 3.2 that it is not known whether social sustainability and exergy losses are related. According to the results of the case studies, a relationship exists between the TCExL and the $\mathrm{IHDI}_{\mathrm{overall}}$ when the systems make use of the same inputs and when these inputs are extracted/processed by people originating from countries with a lower IHDI than the IHDI of the Netherlands. Local social sustainability aspects like working conditions of the individual employees are not considered by the TCExL and $\mathrm{IHDI}_{\mathrm{overall}}$ methods.

Summarising, the results of the case studies contribute to the notion that a relationship exists between exergy losses and environmental sustainability, as well as between exergy losses and the calculated economic and social sustainability indicators of systems that use the same inputs and have comparable investment costs. In the case of comparing technological systems with different inputs or with inputs from different locations, the calculation of a social sustainability indicator like the $\mathrm{IHDI}_{\mathrm{overall}}$ indicator introduced in this research can have an added value compared to calculating only the TCExL.

The TCExL method leads to more fundamental insights into which process or part of a system has the largest potential for improvement than regular sustainability assessment methods (Section 5.1 and Chapters 7 and 8).
When looking into more detail at the technological systems and the processes that contribute most to the overall scores of the four assessment methods,

it is learned that there is a large difference at this point. E.g., the natural gas production process of the systems of the LNG case study causes about two-thirds of the ReCiPe score, about 16 per cent of the costs included in the PWR, zero per cent of the $\text{IHDI}_{\text{overall}}$ and less than one per cent of the TCExL. Although the contributions of the processes to the scores of the economic and social assessment methods have not been calculated in the same detail as with the environmental assessment method, it is clear that the results are very different. The same holds for the process contributions to the TCExL, although it was not yet doable to calculate the TCExL of all, about 2000, processes by hand and is therefore unknown which process contributes most to the TCExL of the systems of the case studies. Of the processes of which the TCExL has been calculated, the use of natural gas for storage contributes the most to the TCExL of the systems of the LNG case study, i.e. about one third.

The processes of the Co-firing system (of the Fossil versus renewable case study) that are responsible for at least 80 per cent of the ReCiPe score cause about 40 per cent of the TCExL score. The contribution of the power plant to both scores is about one third, but again large differences exist. e.g. the hard coal mining contributes for more than one quarter to the ReCiPe score, but only 6 per cent to the TCExL score. About half of the costs is related to the power plant, while the power plant hardly contributes to the IHDI score. The total of the processes that contribute 80 per cent to the ReCiPe score of the Wind farm and Bioethanol systems and the main processes of these systems cause only 7.5 and 43 per cent of the TCExL score, respectively, etc.

Because of the advantages of the TCExL method compared to the regular sustainability assessment methods, which have been explained before, the TCExL method leads to more fundamental insights into which process or part of a system has the largest improvement potential.

Applying exergy analysis in the LNG case study does not lead to other conclusions with regard to the preferred system, but the exergetically preferred system of the Fossil versus renewable case study and of both case studies together has a lower economic sustainability (Chapters 7 and 8).

According to the results of the LNG case study, the Oxyfuel system is the preferred system, although the differences between the IHDI scores of the three systems are very small. The Wind farm system is the preferred system of the Fossil versus renewable case study, except for its economic sustainability and with an $\text{IHDI}_{\text{overall}}$ score equal to that of the Bioethanol system. The system with the highest economic sustainability of the Fossil versus renewable case study is the Bioethanol system, but its score highly depends on the disposal costs of the verge grass that is processed by this system.

All systems of both case studies have been compared by calculating the assessment results of the systems related to the production of 1 PJ of electricity, thus excluding the H-gas supply chain from the systems of the LNG case study. Nevertheless, there are still differences between the systems of both case studies, like the inclusion of an LNG terminal in the systems of the LNG case study.

It is concluded from the assessment results of both case studies that the Wind farm system is the preferred system, except for its economic sustainability and with the remark that back-up installations to overcome the discontinuity in power generation by the Wind farm system caused by too low or too high wind speeds have not been considered.

The choice of the systems of the case studies and the choice of central versus decentral power generation systems is not meant to indicate that the assessed power generation systems are preferable and/or desirable compared to other ways of power generation. Neither that it is more important to focus on power generation systems than on the transport, distribution, use and/or storage of electricity.

Chapter 10

Discussion and conclusions

This chapter provides an overview of the conclusions, followed by a brief discussion of each conclusion.

- The sustainability of our society can be improved by applying exergy analysis in the assessment of technological systems, but in the case of comparing technological systems with different inputs, the technological system that is preferred from an exergetic point of view is not always preferred from the economic and social points of view.
- The designated components of sustainability related to the interaction between a technological system and its surroundings can all be expressed in terms of exergy loss, but the depletion and scarcity of natural resources and the economic and social sustainability aspects can only indirectly be considered.
- The newly developed Total Cumulative Exergy Loss (TCExL) method takes into account all exergy losses caused by a technological system during its life cycle.
- The TCExL can be used as a fundamental indicator in the operationalization of the Brundtland definition of sustainability.
- The newly developed social sustainability assessment method based on the Inequality-adjusted Human Development Index (IHDI) is a solution to the difficulties the standard social life cycle assessment method has with the availability and qualitative nature of social data.
- Exergy analysis leads to more fundamental insights into which process or part of a system has the largest potential for improvement than the standard sustainability assessment methods.

The sustainability of our society can be improved by applying exergy analysis in the assessment of technological systems, but in the case of comparing technological systems with different inputs, the technological system that is preferred from an exergetic point of view is not always preferred from the economic and social points of view.
The technological systems that have been investigated in this research belong to two case studies. The LNG case study consists of three different types of technological installations using the same source of energy and the Fossil versus renewable case study compares power generation from fossil and renewable energy sources. The Waste heat system of the LNG case study is the system that is used in the Rotterdam port area of the Netherlands. The sustainability of power generation at this location would be higher if the system is chosen that is preferred according to the results of the TCExL method (and the three other sustainability assessment methods as well), i.e. the Oxyfuel system. However, it must be noted that back-up installations for overcoming the discontinuity in the send-out of the LNG terminal have not been taken into account in this research. Although the difference between the scores of the Waste heat and ORC systems is small, it appears that also the ORC system is a better choice than the Waste heat system. As becomes clear from Figure 10.1, the environmental and economic sustainability decrease when the exergy loss increases. The social sustainability slightly decreases with an increasing exergy loss.

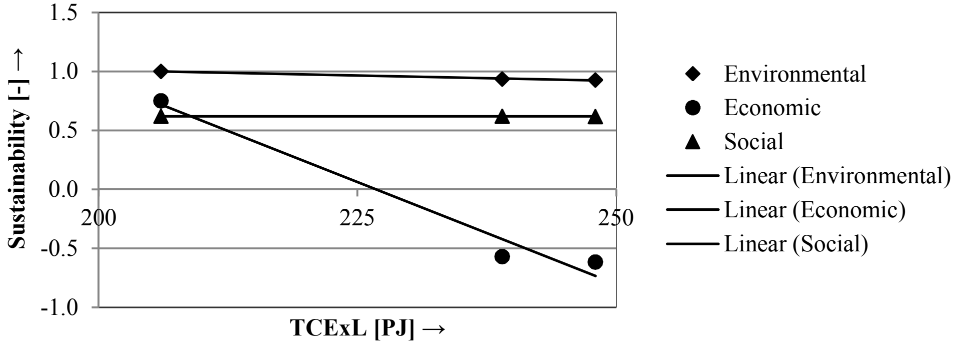

Figure 10.1: The environmental, economic and social sustainability of the systems of the LNG case study versus the exergy losses caused by these systems.

The Co-firing system of the other case study is one of the current power generation systems in the Netherlands but this is not the preferred system of this case study. The sustainability of power generation would improve if the Wind farm system instead of the Co-firing system is chosen, except for the economic sustainability of the Wind farm system and without considering back-up installations to overcome the discontinuity in power generation caused by too low or too high wind speeds. Figure 10.2 shows that the environmental sustainability is higher at a lower exergy loss and that the economic sustainability is lower at a lower exergy loss. The course of the social sustainability is unknown because it has been assumed that the social sustainability of the Wind farm and Bioethanol systems are equal each other. No trendlines have been added to Figure 10.2 because the systems of this case study are too different to draw conclusions about the relationship between the aspects of sustainability on the one hand and exergy losses on the other hand.

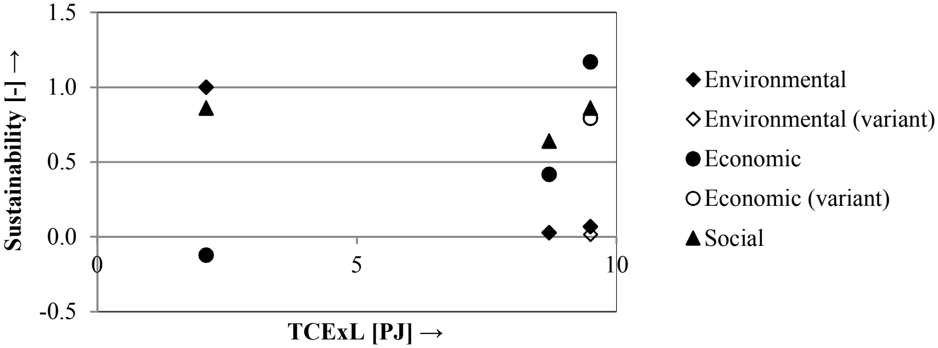

Figure 10.2: The environmental, economic and social sustainability of the systems of the Fossil versus renewable case study versus the exergy losses caused by these systems.

The functional units of both case studies are different because of the coproduction of H-gas (natural gas with a certain calorific value used by large-scale gas consumers in the Netherlands) and the larger size of the installations of the LNG case study. When the H-gas supply chain is excluded and the results of the LNG case study are allocated to the production of 1 PJ of electricity, like in the Fossil versus renewable case study, the comparability of the results of both case studies improves although still differences remain, e.g. the inclusion of the LNG terminal in the systems of the LNG case study. From comparing the results, it is learned that the Wind farm system is the preferred system of both case studies, but again except for its the economic sustainability and without considering back-up installations to overcome the discontinuity in power generation caused by too low or too high wind speeds.

Knowing that economic indicators do not include all indirect costs and change over time while exergy losses are based on fundamental scientific equations and are related to the consumption of raw materials and energy carriers, it is concluded that applying exergy analysis, especially the TCExL method, in the assessment of technological systems can contribute to a more sustainable society. In the case of comparing technological systems with different inputs or with inputs from different locations, the calculation of a social sustainability indicator like the $\mathrm{IHDI}_{\mathrm{overall}}$ indicator introduced in this research can have an added value compared to calculating only the TCExL.

The choice of the systems of the case studies is not meant to indicate that these systems are preferable and/or desirable compared to other central or decentral power generation systems, nor that it is not important to look at the transport, distribution, use and/or storage of electricity. It must also be realised that the results of the case studies are based on models of the systems and on process and CExD data included in the SimaPro/Ecoinvent databases.

The designated components of sustainability related to the interaction between a technological system and its surroundings can all be expressed in terms of exergy loss, but the depletion and scarcity of natural resources and the economic and social sustainability aspects can only indirectly be considered.
On the basis of the interaction between a system and its surroundings during the life cycle of this system, a list of sustainability aspects that sustainability assessment methods have to deal with has been drawn up in order to cope with the lack of a commonly used operationalization of the term ‘sustainability’. All designated sustainability aspects can directly or indirectly be expressed in terms of exergy loss. E.g., the environmental impact of emissions and waste flows can be considered via the exergy loss caused by abatement of these emissions and waste flows. The same holds for the use of renewable and non-renewable natural resources. The impact of the use of land by technological installations and equipment can be considered via its influence on the possibility to capture new exergy from sunlight by the ecosystem. The depletion and scarcity of natural resources is indirectly expressed in terms of exergy loss via the expected higher exergy losses accompanied with the exploration of natural resources that are scarcer. The economic and social sustainability aspects are indirectly related to exergy loss via the use of natural resources, i.e. material resources and/or energy carriers.

The calculation of exergy losses is based on fundamental thermodynamic equations. The regular sustainability assessment methods used for the determination of environmental, economic and social sustainability indicators are not fully objective, i.e. no consensus exists about models for quantifying environmental impact, the economic indicators change over time etc. The same holds for an overall sustainability assessment method that combines the aforementioned sustainability indicators. Furthermore, the importance that is attached to exergy losses and regular environmental, economic and social sustainability indicators is a subjective, and likely political, consideration.

The newly developed Total Cumulative Exergy Loss (TCExL) method takes into account all exergy losses caused by a technological system during its life cycle.
Shortcomings of the exergy analysis methods found in literature are for example not taking a life cycle perspective and not considering the abatement of emissions and/or the use of land. In some cases, exergy analysis methods are extended with indicators and equations to cover economic and social aspects of sustainability, but this leads to a decrease of the objectivity of these methods, because such extensions are not commonly accepted. The TCExL method is solely based on the calculation of exergy losses and totals all exergy losses caused by a technological system during its life cycle. A point of improvement is that, until now, the abatement exergy losses of only a few emissions have been included in the TCExL method because of the lack of data regarding other emissions.

Although it is common practice to call an assessment a life cycle assessment whenever the phases of construction, operation and decommissioning are included, a true life cycle implies that technological installations for the transformation of the outputs to the required inputs, i.e. closing material cycles etc., are part of the assessed technological system. Preferably, already during the design of installations, equipment and products, attention is paid to the possibilities to repair, reuse and recycle these installations, equipment and products. When the transformation of outputs to the required inputs is included, the assessment is called a cradle to cradle assessment instead of a cradle to grave assessment. In fact, the systems of the case studies are cradle to grave systems as well. Since the TCExL method can be applied to all kinds of technological systems, it can also be used for the life cycle assessment of cradle to cradle systems.

Until now, the TCExL has been calculated from the CExD, emission and land use data of the systems reported by SimaPro/Ecoinvent. Implementing the TCExL method in a life cycle assessment software tool like SimaPro would facilitate the calculation of the TCExL.

The TCExL can be used as a fundamental indicator in the operationalization of the Brundtland definition of sustainability.
The TCExL method calculates all exergy losses caused by a technological system during its life cycle. Exergy losses are related to the environmental, economic and social dimensions of sustainability via the use of material resources, energy carriers etc. The calculation of exergy losses is based on fundamental thermodynamic equations, while the results of regular sustainability assessments change over time because of new insights into the calculation methods and because of changing needs, economic conditions and/or societal preferences. Every process and activity is accompanied with exergy loss. Exergy that is lost, is lost forever and the only source of new exergy to replenish the amount of exergy on earth is solar and/or tidal energy. From a sustainability point of view it is important to use exergy wisely.

Exergy is needed for the abatement of emissions, which makes that the outputs of technological systems no longer influence the ecosystem and the health of human beings. All inputs of technological systems can be regenerated if enough exergy is available to do so. Exergy that is not lost by a generation is available for future generations. The higher the amount of exergy that is available on earth, the better people will be able to meet their needs. This implies that the TCExL can be used as a fundamental indicator in the operationalization of the definition of sustainable development by the Brundtland commission.

The newly developed social sustainability assessment method based on the Inequality-adjusted Human Development Index (IHDI) is a solution to the difficulties the standard social life cycle assessment method has with the availability and qualitative nature of social data.
The standard social life cycle assessment method suffers from the limited availability and qualitative or semi-quantitative nature of the required data. This is not the case with the newly developed social sustainability assessment method which is based on the IHDI of the countries the employees originate from and the number of man-hours spent by those employees. However, the application of the IHDI values reported by the UNDP in the calculations leads to less specific indicators, for example local working conditions are not considered, and probably lower acceptance by experts in the field of social sustainability assessment. The method did not lead to distinguishing results when the compared systems use the same energy source or when all activities of the compared systems are assumed to take place in the same

country, but this is understandable and would also be the case with the standard social sustainability assessment method that is under development.

Exergy analysis leads to more fundamental insights into which process or part of a system has the largest potential for improvement than the standard sustainability assessment methods.
According to the results of the case studies, the four sustainability assessment methods lead to different results with regard to the processes that contribute most to the scores of the methods, i.e. the processes with the largest potential for improvement. The insights provided by the TCExL method are regarded as better because of the fundamental thermodynamic equations this method is based on, in contrary to the use of not commonly accepted models, market prices etc. by the standard sustainability assessment methods. It must be noted that the standard social sustainability assessment method, which is under development, is not applied in this research, but this method is also less fundamental than the TCExL method. This is caused by the inevitable use of weighting and other conversion factors for the calculation of a social sustainability indicator based on qualitative and semi-quantitative data.

Chapter 11

Recommendations

This chapter provides an overview of the recommendations, followed by a brief elucidation of each recommendation.

It is recommended that

- exergy losses be taken into account when striving for a more sustainable society,
- the Total Cumulative Exergy Loss (TCExL) method be used in decisions between technological systems,
- a working group be set up to investigate the possibilities for increasing the use of exergy analysis,
- the TCExL method be implemented in software tools.

It is recommended that exergy losses be taken into account when striving for a more sustainable society.
Every process and activity in real life is accompanied with the loss of exergy, also known as the loss of work potential. The higher the amount of exergy available on earth, the better the present and future generations will be able to meet their needs. Exergy that is lost, is lost forever and the only source of new exergy to replenish the amount of exergy on earth is solar and/or tidal energy. From a sustainability point of view it is therefore important to use exergy wisely. The designated components of sustainability related to the interaction between a technological system and its surroundings can all be expressed in terms of exergy loss, but the depletion and scarcity of natural resources and the economic and social sustainability aspects can only indirectly be considered when determining the exergy loss caused by a technological system. The results of the case studies contribute to the notion that a relationship exists between exergy loss and environmental sustainability, e.g. a higher consumption of natural resources is accompanied with higher exergy losses. The Fossil versus renewable case study shows that a lower exergy loss is not always accompanied with a higher economic and social sustainability, which is understandable. However, economic indicators do not include all indirect costs and economic

as well as social indicators change over time which makes it difficult to use them as a basis for long-term decisions and/or policy. Determining exergy losses leads to a more fundamental insight into which process or part of a system has the largest potential for improvement than the standard sustainability assessment methods.

It is recommended that the Total Cumulative Exergy Loss (TCExL) method be used in decisions between technological systems.
The TCExL method takes into account all exergy losses caused by a technological system during its life cycle as objectively as possible. This makes the TCExL method very suitable to assess technological systems like the systems that are to be realised and/or stimulated as a part of the 'Energy Agreement for Sustainable Growth' that was reached by the Dutch government and various Dutch parties in September 2013. For example, carbon dioxide capture and storage (CCS) is mentioned in this agreement, but the state-of-the-art CCS technology with amine capturing is exergy-intensive.

The current Dutch central government aims at making the economy of the Netherlands more sustainable by combining 'green' and 'growth' in its policy called 'Green Growth'. Instead of a policy based on growth, also other strategies have been defined to achieve a more sustainable society, like a 'Circular Economy' (China) and the 'Prosperity without Growth' concept. Especially in the case a policy is chosen that is based on growth, it is important to pay attention to exergy losses, because each new process and activity is accompanied with the loss of exergy. From a 'green' viewpoint, i.e. the viewpoint of the ecosystem, it is important to sustain or improve biodiversity, to minimise impact on natural cycles, to close material cycles and to store surplus minerals and/or metals until they are needed instead of combusting or land filling them.

The Dutch government wants to keep track of the progress of green growth via monitoring the sustainability of the Netherlands, named the 'Monitor Duurzaam Nederland', and the Green Growth indicators of the OECD. Decreasing exergy losses will have a positive effect on the indicators belonging to the 'Environment and resources' theme of this monitor and on the Green Growth indicators of environmental efficiency. It would even be better if an exergy indicator is added to the monitor and the Green Growth indicators.

It is recommended that a working group be set up to investigate the possibilities for increasing the use of exergy analysis.
The Ministry of Infrastructure and Environment, which is responsible for sustainability, is advised to take the initiative to set up such a working group. Potential members of this working group are officials from the aforementioned ministry, officials from the Ministry of Economic Affairs, businesses and knowledge institutes. These three parties (government, businesses and knowledge institutes) are mentioned as being essential to transitions and are known as 'The Golden Triangle'.

Measures to stimulate the use of exergy analysis the working group could think of are in the fields of information, stimulation and/or regulation. For example, more education about exergy at secondary schools, colleges and universities so that the concept of exergy will be known to future consultants, engineers, policy makers etc. The Netherlands Enterprise Agency ('Rijksdienst voor ondernemend Nederland', RVO) can inform companies via brochures, meetings etc. The knowledge institutes can disseminate the knowledge they obtain from carrying out research projects in the field of exergy. Exergy analysis can also be made more widely known by mentioning the TCExL method on the Dutch website dedicated to measuring of sustainability (www.metenvanduurzaamheid.nl), which is financed by the Dutch Ministry of Infrastructure and the Environment. The TCExL method is a method that can be used in decision making, assessment and monitoring with regard to technological systems on all levels, i.e. from products to the world as a whole.

The working group can consider financial measures in the sense of granting subsidies for research into technological systems that cause lower exergy losses than current technological systems. They can also think of introducing an obligation to assess the exergetic performance of technological systems to be constructed and making the granting of a permit for the construction and use of this technological system dependent on its exergetic performance against a standard. A similar system is already applied in the built environment where the Energy Performance Coefficient (EPC) of new dwellings has to be lower than a certain value. This system was introduced in 1995 and has led to better insulation of dwellings and energy saving. With regard to a level playing field, it is important to consult with other countries in the European Union, Europe and maybe even worldwide about legislation and other policy instruments regarding the use of exergy analysis, e.g. via The Green Growth Group and the relevant Directorates-General (DGs) of the European Union, i.e. the DGs for Climate Action, Energy and Environment.

The activities undertaken by this working group can inspire initiatives like The Sustainability Consortium (www.sustainabilityconsortium.org), the Exergy Development Group (www.exergydevelopment.com) and/or by companies and investors that pay attention to the Dow Jones Sustainability Indices (DJSI). Applying exergy analysis is expected to improve the sustainability performance of companies but its effect on the aggregated overall DJSI, which weights economic, environmental as well as social issues, would be small.

It is recommended that the TCExL method be implemented in software tools.
To facilitate the calculation of exergy losses, it is recommended that life cycle assessment software tools, e.g. SimaPro, be extended with the TCExL method. Besides implementing the TCExL calculation method itself, the standard chemical exergy values of products, emissions, final waste flows would have to be added to the database of the software tool. Adding the standard chemical exergy values of intermediate fuels and materials enables the calculation of the process contributions to the overall TCExL score of the technological system. Implementing the TCExL method in a life cycle assessment tool also facilitates the calculation of the exergy loss caused by the abatement of emissions of which not yet an abatement value is known. Increasing the amount of open data regarding technological processes, e.g. by facilitating the exchange of data between research institutes via a database system, would contribute to the development and use of software tools for the assessment of technological systems in general.

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Glossary

CDP	Cumulative Degree of Perfection. 34
CEENE	Cumulative Exergy Extraction from the Natural Environment. 32, 185
CExC	Cumulative Exergy Consumption. 33, 186
CExCA	Cumulative Exergy Consumption for Construction and Abatement. 34, 186
CExD	Cumulative Exergy Demand. 35, 186
CNEx	Net Exergy Consumption. 36, 192
ECEC	Ecological Cumulative Exergy Consumption. 35, 187
Eco-LCA	Ecologically Based LCA method. 35, 187
EEA	Extended Exergy Accounting. 36, 191
ELCA	Exergetic Life Cycle Analysis. 35, 189
H-gas	natural gas with a specific calorific value that is used by large-scale gas consumers in the Netherlands. 78
IHDI	Inequality-adjusted Human Development Index. 64
LCA	environmental Life Cycle Assessment or Life Cycle Assessment in general. 41
LCC	environmental Life Cycle Costing. 43
LCEA	Life Cycle Exergy Analysis. 36, 191
LNG	Liquefied Natural Gas. 77
MEA	monoethanolamine. 78
NPP	Net Primary Production. 59
NPV	Net Present Value. 44
ORC	Organic Rankine Cycle. 79
PWR	Present Worth Ratio. 44
ReCiPe	method for Life Cycle Impact Assessment. 42
S-LCA	social Life Cycle Assessment. 44
TCExL	Total Cumulative Exergy Loss. 53

Curriculum vitae

Lydia Stougie was born on 30 March 1969 in Gouda, Netherlands. She completed her pre-university education in 1987 at the J.C de Glopper School in Capelle aan den IJssel. Subsequently, she studied Chemical Engineering at the Delft University of Technology. In 1992, she was the first student at the Faculty of Chemical Engineering and Material Sciences to graduate in the field of exergy. Her thesis was titled 'Exergy Analysis for the Comparison of Processes - Case Study Methanol'.

In December 1992, she became a researcher at Interduct, the Delft University Clean Technology Institute, where she conducted several research projects, such as the research project 'Entropy or Exergy - a Measure for Environmental Policy Making?'. In 2000 she became a project coordinator at Interduct.

In 2004 she was appointed as a project leader at the Center for Port Innovation and Regional Development, which is part of the Faculty of Technology, Policy and Management of the Delft University of Technology. Since 2006 she has been involved in teaching third-year BSc students about 'Performance Analysis in Energy and Industry' and in 2007 she started her part-time PhD research into exergy and sustainability at the Energy and Industry Section of the Faculty of Technology, Policy and Management.

During her PhD research, she participated in several conferences in the field of energy efficiency, exergy, life cycle assessment and sustainability and wrote a journal paper about exergy and sustainability. Besides, she coordinates the activities of the informal interfaculty contact group 'Exergy Analysis TU Delft' which was set up in December 1994. The contact group aims to promote the contacts between the different researchers of TU Delft and to cluster the university's knowledge in the field of exergy.

Appendices

Appendix A

Exergy theory

This appendix elaborates on the calculation of the exergy values of electricity, heat and mass flows as well as the calculation of the internal exergy loss. This is followed by tables with data used in the calculations. Tables A.1 to A.4 present the Cumulative Exergy Demand (CExD) factors of resources that are used by SimaPro/Ecoinvent to calculate the Cumulative Exergy Demand of the systems of the case studies. The resources of which the CExD factor has been published in literature are listed only. Tables A.5 to A.7 present the exergy values of materials, fuels and products used for calculating the contributions of the processes to the TCExL score. The standard chemical exergy values of emissions and final waste flows are listed in Tables A.8 to A.12.

Calculation of exergy values
It was already mentioned in Chapter 1 that exergy is defined as the maximum amount of work that can be obtained when a substance, mass flow or other amount of energy is brought into total equilibrium with the reference environment. This reference environment consists of components existing in the atmosphere, oceans and earth that are in perfect equilibrium with each other at a temperature of usually 25 °C and a pressure of 1 atm. When calculating the exergy losses caused by e.g. heating and air conditioning of houses in the built environment, it is important to take into account the local and varying outer temperature (Jansen, 2013), but in this research the reference temperature and pressure can safely be assumed to be constant over time. Several models of the reference environment have been developed of which the reference environment by Szargut et al. (1988) is well-known and commonly applied. The CExD values of Bösch et al. (2007) and the other chemical exergy values applied in this research are based on the reference environment by Szargut et al. (1988) as well. The calculation of the exergy values of electricity, heat and mass flows is explained below.

Exergy value of electricity
Electricity is a kind of energy that fully represents work potential. By definition, the exergy value of electricity is equal to its energy value or in other words: electricity is 100% exergy.

Exergy value of heat
The maximum amount of work that can be obtained from an amount of heat has been determined by Sadi Carnot in 1824 and is shown in Equation A.1.

$$Ex_{\text{heat}} = Q \cdot (1 - T_0/T) \tag{A.1}$$

with:
Ex_{heat} = exergy value of heat [J]
Q = energy value of heat [J]
T_0 = temperature of the reference environment [K]
T = temperature of the heat [K]

The exergy value of 1000 joules of warm water at a temperature of 50 ℃ and an environmental temperature of 25 ℃ is calculated as an example. The temperature of the warm water and the environment are 50 ℃ + 273 = 323 K and 25 ℃ + 273 = 298 K, respectively. According to Equation A.1, the exergy value of the 1000 joules of warm water amounts to 1000 · (1 - 298/323) = 77 joules.

The exergy value of heat flows with a temperature that is lower than T_0, also known as cold, can be calculated from Equation A.2, as explained by Jansen and Woudstra (2010); Woudstra (2012); Jansen (2013).

$$Ex_{\text{cold}} = Q_{\text{c}} \cdot (1 - T_0/T) \tag{A.2}$$

with:
Ex_{cold} = exergy value of cold [J]
Q_{c} = energy value of cold [J] (this is a negative value because of thermodynamic sign conventions)
T_0 = temperature of the reference environment [K]
T = temperature of the cold [K]

Exergy value of mass flows
The exergy value of mass flows consists of several components of which the nuclear, magnetic, electrical and surface tension effects are usually excluded. The four remaining components are the kinetic, potential, physical and chemical exergy. The kinetic and potential exergy values of a mass flow equal the kinetic and potential energy value of this mass flow, respectively, and are usually negligible compared to the physical and chemical exergy values of the mass flow. The calculation of the physical and chemical exergy values is briefly described below, more information can be found in e.g. Szargut et al. (1988); Szargut (2005). The physical exergy value of a component is usually much smaller than its chemical exergy value.

The physical exergy value of a mass flow is a result of the first and second laws of thermodynamics and is calculated as follows (Equation A.3).

$$Ex_{\text{mass,phys}} = m((H - H_0) - T_0(S - S_0)) \tag{A.3}$$

with:
$Ex_{\text{mass,phys}}$ = physical exergy of a mass flow [J/s]
m = mass flow [kg/s]
H = specific enthalpy of the mass flow [J/kg]
H_0 = specific enthalpy of the mass flow at the pressure and temperature of the reference environment [J/kg]
T_0 = temperature of the reference environment [K]
S = specific entropy of the mass flow [J/(kgK)]
S_0 = specific entropy of the mass flow at the pressure and temperature of the reference environment [J/kgK]

The chemical exergy value of mass flows can be calculated from the chemical exergy values of its components. In case of a mass flow that consists of more than one component, the mixing of the components to the composition of the mass flow should be considered as well. The chemical exergy values of many components and chemical elements are tabulated, e.g. by Szargut (2007); Szargut et al. (1988); Rivero and Garfias (2006). Equation A.4 shows the calculation of the chemical exergy value of component i from the standard chemical exergy values of the elements tabulated by e.g. Szargut et al. (1988).

$$ex^0_{\text{chem,i}} = g_{\text{f,i}} + \sum N_{\text{e}} \cdot ex^0_{\text{chem,e}} \tag{A.4}$$

with:
$ex^0{}_{\text{chem,i}}$ = standard molar chemical exergy of component i [J/mole]
$g_{\text{f,i}}$ = molar Gibbs energy of formation of component i [J/mole]
N_{e} = number of moles of element e needed for the formation of one mole of component i [-]
$ex^0{}_{\text{chem,e}}$ = standard molar chemical exergy of element e [J/mole]

When a mass flow consists of more than one component, the mass flow has a somewhat lower exergy value because of the loss of work potential caused by the mixing of the components. Assuming that the mass flow is a homogeneous mixture, the exergy loss caused by mixing can be calculated from Equation A.5. The activity coefficients in this equation equal one in case of ideal mixing.

$$ex_{\text{mix}} = RT_0 \sum x_{\text{i}} \ln(\gamma_{\text{i}} x_i) \tag{A.5}$$

with:
ex_{mix} = exergy loss caused by mixing [J/mole mixture]
R = gas constant = 8.314 J/(mole K)
T_0 = temperature of the reference environment [K]
x_{j} = mole fraction of component i [-]
γ_{j} = activity coefficient of component i in the mixture [-]

The exergy value of a mass flow can then be calculated from the physical and chemical exergy values of this mass stream including, if applicable, the exergy loss caused by mixing, as displayed in Equation A.6.

$$Ex_{\mathrm{mass,total}} = Ex_{\mathrm{mass,phys}} + \sum_{\mathrm{i=1}}^{\mathrm{i=n}} n_{\mathrm{i}} ex^{0}_{\mathrm{chem,i}} + n_{\mathrm{tot}} ex_{\mathrm{mix}} \tag{A.6}$$

with:
$Ex_{\mathrm{mass,total}}$ = total exergy value of a mass flow [J/s]
$Ex_{\mathrm{mass,phys}}$ = physical exergy value of a mass flow [J/s]
n_{i} = mole flow of component i [mole/s]
$ex^{0}{}_{\mathrm{chem,i}}$ = standard molar chemical exergy of component i [J/mole]
n_{tot} = total mole flow of the mass flow [mole/s]
ex_{mix} = exergy loss caused by mixing [J/mole mixture]

Calculation of the internal exergy loss

As already mentioned in Section 2.1.1, the internal exergy loss is proportional to the total increase of entropy caused by that process or system (Equation A.7).

$$Ex_{\mathrm{loss}} = T_0 \Delta S_{\mathrm{total}} \tag{A.7}$$

with:
Ex_{loss} = exergy loss
T_0 = temperature of the reference environment
$\Delta S_{\mathrm{total}}$ = total entropy change

This implies that it is not necessary to calculate the (chemical and physical) exergy values of the ingoing and outgoing mass flows of a system, but that it is sufficient to know the absolute entropy values of the ingoing and outgoing mass flows.

Table A.1: CExD factors of resources (Bösch et al., 2007; Hischier et al., 2010; Rugani et al., 2011).

Name	Unit	CExD factor [MJ/unit]
in air		
Carbon dioxide, in air	kg	0
Energy, kinetic (in wind), converted	MJ	1
Energy, solar, converted	MJ	0.93
in biotic		
Energy, from wood	MJ	1.05
Energy, gross calorific value, in biomass	MJ	1.05
Peat, in ground	kg	10.3
Wood, soft, standing	m^3	0
Wood, unspecified, standing/m^3	m^3	0
in ground		
Aluminium, 24% in bauxite, 11%[1]	kg	5.73
Anhydrite, in ground	kg	0.06
Barite, 15% in crude ore, in ground	kg	4.2
Basalt, in ground	kg	0.28
Calcite, in ground	kg	0.01
Chromium, 25.5% in chromite, 11.6%[1]	kg	5.43
Cinnabar, in ground	kg	2.9
Clay, bentonite, in ground	kg	0.059
Clay, unspecified, in ground	kg	0.57
Coal, brown, in ground	kg	10.3
Coal, hard, unspecified, in ground	kg	19.7
Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3%[1]	kg	153
Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3%[1]	kg	143
Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3%[1]	kg	73.2
Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3%[1]	kg	33.5
Dolomite, in ground	kg	0.082
Energy, from coal	MJ	1.03
Energy, from coal, brown	MJ	1.04
Energy, from gas, natural	MJ	0.94
Energy, from oil	MJ	1.02
Energy, from peat	MJ	1.05
Energy, from uranium	MJ	1
Energy, geothermal, converted	MJ	0
Feldspar, in ground	kg	0.14

[1] in crude ore, in ground

Table A.2: CExD factors of resources (Bösch et al., 2007; Hischier et al., 2010; Rugani et al., 2011) - Continued.

Name	Unit	CExD factor [MJ/unit]
in ground		
Fluorspar, 92%, in ground	kg	0.15
Gas, mine, off-gas, process, coal mining/m^3	m^3	37.4
Gas, natural, in ground	m^3	36
Gold, Au 1.1E-4%, Ag 4.2E-3%, in ore, in ground	kg	346000
Gold, Au 1.3E-4%, Ag 4.6E-5%, in ore, in ground	kg	482000
Gold, Au 2.1E-4%, Ag 2.1E-4%, in ore, in ground	kg	295000
Gold, Au 4.9E-5%, in ore, in ground	kg	1290000
Gold, Au 1.4E-4%, in ore, in ground	kg	450000
Gold, Au 4.3E-4%, in ore, in ground	kg	147000
Gold, Au 6.7E-4%, in ore, in ground	kg	94000
Gold, Au 7.1E-4%, in ore, in ground	kg	88700
Gold, Au 9.7E-4%, Ag 9.7E-4%, Zn 0.63%, Cu 0.38%[1]	kg	58100
Granite, in ground	kg	0.068
Gravel, in ground	kg	0.068
Gypsum, in ground	kg	0.045
Indium, 0.005% in sulfide, In 0.003%, Pb, Zn, Ag, Cd[2]	kg	2770
Iron, 46% in ore, 25% in crude ore, in ground	kg	2.52
Kaolinite, 24% in crude ore, in ground	kg	2.63
Lead, 5.0% in sulfide, Pb 3.0%, Zn, Ag, Cd, In, in ground	kg	4.29
Magnesite, 60% in crude ore, in ground	kg	1.05
Manganese, 35.7% in sedimentary deposit, 14.2%[3]	kg	4.44
Metamorphous rock, graphite containing, in ground	kg	1.09
Molybdenum, 0.010% in sulfide, Mo 8.2E-3% and Cu 1.83%[3]	kg	209
Molybdenum, 0.014% in sulfide, Mo 8.2E-3% and Cu 0.81%[3]	kg	456
Molybdenum, 0.022% in sulfide, Mo 8.2E-3% and Cu 0.36%[3]	kg	955
Molybdenum, 0.025% in sulfide, Mo 8.2E-3% and Cu 0.39%[3]	kg	890
Molybdenum, 0.11% in sulfide, Mo 4.1E-2% and Cu 0.36%[3]	kg	639
Nickel, 1.13% in sulfide, Ni 0.76% and Cu 0.76%[3]	kg	56.1
Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	kg	60.58
Oil, crude, in ground	kg	46.49
Olivine, in ground	kg	0.78
Pd, Pd 2.0E-4%, Pt 4.8E-4%, Rh 2.4E-5%, Ni 3.7E-2%[4]	kg	48900
Pd, Pd 7.3E-4%, Pt 2.5E-4%, Rh 2.0E-5%, Ni 2.3%[5]	kg	13000
Phosphorus, 18% in apatite, 12% in crude ore, in ground	kg	5.25

[1] Pb 0.014%, in ore, in ground

[2] in ground

[3] in crude ore, in ground

[4] Cu 5.2E-2%, in ore, in ground

[5] Cu 3.2%, in ore, in ground

Table A.3: CExD factors of resources (Bösch et al., 2007; Hischier et al., 2010; Rugani et al., 2011) - Continued.

Name	Unit	CExD factor [MJ/unit]
in ground		
Pt, Pt 2.5E-4%, Pd 7.3E-4%, Rh 2.0E-5%, Ni 2.3%[1]	kg	25100
Pt, Pt 4.8E-4%, Pd 2.0E-4%, Rh 2.4E-5%, Ni 3.7E-2%[2]	kg	94800
Pumice, in ground	kg	0.6
Rh, Rh 2.0E-5%, Pt 2.5E-4%, Pd 7.3E-4%, Ni 2.3%[1]	kg	54400
Rh, Rh 2.4E-5%, Pt 4.8E-4%, Pd 2.0E-4%, Ni 3.7E-2%[2]	kg	205000
Sand, unspecified, in ground	kg	0.068
Shale, in ground	kg	0.57
Silver, 0.007% in sulfide, Ag 0.004%, Pb, Zn, Cd, In[3]	kg	961
Silver, 3.2ppm in sulfide, Ag 1.2ppm, Cu and Te[4]	kg	10300
Silver, Ag 2.1E-4%, Au 2.1E-4%, in ore, in ground	kg	5060
Silver, Ag 4.2E-3%, Au 1.1E-4%, in ore, in ground	kg	5940
Silver, Ag 4.6E-5%, Au 1.3E-4%, in ore, in ground	kg	8260
Silver, Ag 9.7E-4%, Au 9.7E-4%, Zn 0.63%, Cu 0.38%[5]	kg	996
Sodium chloride, in ground	kg	0.25
Sodium sulphate, various forms, in ground	kg	0.15
Sulfur, in ground	kg	19.0
Sylvite, 25% in sylvinite, in ground	kg	0.99
Talc, in ground	kg	0.039
Tellurium, 0.5ppm in sulfide, Te 0.2ppm, Cu and Ag[4]	kg	278
Tin, 79% in cassiterite, 0.1% in crude ore, in ground	kg	630
TiO2, 54% in ilmenite, 2.6% in crude ore, in ground	kg	24.2
TiO2, 95% in rutile, 0.40% in crude ore, in ground	kg	158
Uranium, in ground	kg	560000
Zinc, 9.0% in sulfide, Zn 5.3%, Pb, Ag, Cd, In, in ground	kg	6.79
Zirconium, 50% in zircon, 0.39% in crude ore, in ground	kg	162
land		
Occupation, construction site	m^2a	0
Occupation, dump site	m^2a	0
Occupation, forest, intensive, normal	m^2a	0
Occupation, industrial area	m^2a	0
Occupation, industrial area, vegetation	m^2a	0
Occupation, mineral extraction site	m^2a	0
Occupation, traffic area, road network	m^2a	0

[1] Cu 3.2%, in ore, in ground
[2] Cu 5.2E-2% in ore, in ground
[3] in ground
[4] in crude ore, in ground
[5] Pb 0.014%, in ore, in ground

Table A.4: CExD factors of resources (Bösch et al., 2007; Hischier et al., 2010; Rugani et al., 2011) - Continued.

Name	Unit	CExD factor [MJ/unit]
land		
Transformation, from forest, extensive	m^2	0
Transformation, from mineral extraction site	m^2	0
Transformation, from unknown	m^2	0
Transformation, to arable	m^2	0
Transformation, to dump site	m^2	0
Transformation, to forest, intensive, normal	m^2	0
Transformation, to industrial area	m^2	0
Transformation, to mineral extraction site	m^2	0
in water		
Energy, potential (in hydropower reservoir), converted	MJ	1
Water, cooling, unspecified natural origin/m^3	m^3	50
Water, river	m^3	50
Water, salt, ocean	m^3	0
Water, salt, sole	m^3	0
Water, unspecified natural origin/kg	kg	0.05
Water, unspecified natural origin/m^3	m^3	50
Water, well, in ground	m^3	50

[1] in ore, in ground

[2] in crude ore, in ground

Table A.5: Exergy values of materials, fuels and products used for calculating the contributions of the processes to the TCExL score.

Name	Unit	Exergy value [MJ/unit]
Ammonia, liquid, at regional storehouse/CH U	kg	22
Bauxite, at mine/GLO U	kg	1.1
Blast furnace gas, burned in power plant/RER U	MJ	0.98
Calcareous marl, at plant/CH U	kg	0.15
Cement, unspecified, at plant/CH U	kg	0.64
Chemicals inorganic, at plant/GLO U	kg	2.1
Chemicals organic, at plant/GLO U	kg	28
Chlorine, liquid, production mix, at plant/RER U	kg	1.8
Chromite, ore concentrate, at beneficiation/GLO U	kg	0.90
Chromium oxide, flakes, at plant/RER U	kg	0.24
Chromium steel 18/8, at plant/RER U	kg	7.2
Clay, at mine/CH U	kg	0.57
Clinker, at plant/CH U	kg	0.0066
Crude oil, at production/NG U	kg	47
Crude oil, at production offshore/GB U	kg	47
Crude oil, at production onshore/RAF U	kg	47
Crude oil, at production onshore/RME U	kg	47
Crude oil, at production offshore/NO U	kg	47
Diesel, at regional storage/CH U	kg	45
Diesel, at regional storage/RER U	kg	45
Diesel, burned in diesel-electric generating set/GLO U	MJ	1.0
Diesel, low-sulphur, at regional storage/CH U	kg	45
Disposal, plastics, mixture, 15.3% water[1]	kg	27
Disposal, spoil from coal mining[2]	kg	0.11
Disposal, spoil from lignite mining[2]	kg	0.10
Disposal, sulfidic tailings, off-site/GLO U	kg	0.30
Electricity, at cogen with biogas engine[3]	kWh	3.6
Electricity, at wind power plant 3.6MW, offshore U	MWh	$3.6{\cdot}10^3$
Electricity, at wind power plant 7.5MW onshore/RER U	MWh	$3.6{\cdot}10^3$
Electricity, high voltage, production UCTE[4]	kWh	3.6
Electricity, hydropower, at run-of-river power plant/CH U	kWh	3.6
Electricity, hydropower, at run-of-river power plant/RER U	kWh	3.6
Electricity, low voltage, production UCTE[4]	kWh	3.6
Electricity, medium voltage, at grid/CH U	kWh	3.6
Electricity, medium voltage, at grid/NL U	kWh	3.6
Electricity, medium voltage, production UCTE[4]	kWh	3.6
Ethanol, 95% in H2O, from fermentation of verge grass	kg	28

[1] to municipal incineration/CH U

[2] in surface landfill/GLO U

[3] allocation exergy/CH U

[4] at grid/UCTE U

Table A.6: Exergy values of materials, fuels and products used for calculating the contributions of the processes to the TCExL score - Continued.

Name	Unit	Exergy value [MJ/unit]
Ethylene glycol, at plant/RER U	kg	19
Ferrochromium, high-carbon, 68% Cr, at plant/GLO U	kg	11
Ferronickel, 25% Ni, at plant/GLO U	kg	6.0
Grass fibres, from fermentation of verge grass	kg	19
Hard coal supply mix/NL U	Mtn	$2.5{\cdot}10^{10}$
Hard coal, at mine/AU U	kg	20
Hard coal, at mine/EEU U	kg	20
Hard coal, at mine/RLA U	kg	20
Hard coal, at mine/RNA U	kg	20
Hard coal, at mine/WEU U	kg	20
Hard coal, at mine/ZA U	kg	20
Hard coal coke, at plant/RER U	MJ	1.1
Hard coal mix, at regional storage/UCTE U	kg	25
Hard coal supply mix/DE U	kg	25
Hard coal supply mix/NL U	kg	25
Hard coal supply mix/PL U	kg	25
Hard coal, at regional storage/WEU U	kg	25
Heat, at cogen with biogas engine, allocation exergy/CH U	MJ	0.17
Heat, at hard coal industrial furnace 1-10MW/RER U	MJ	0.22
Heavy fuel oil, at regional storage/CH U	kg	42
Heavy fuel oil, at regional storage/RER U	kg	42
Hydrochloric acid, 30% in H2O, at plant/RER U	kg	0.67
Iron (III) chloride, 40% in H2O, at plant/CH U	kg	0.58
Iron ore, 65% Fe, at beneficiation/GLO U	kg	1.6
Iron scrap, at plant/RER U	kg	6.7
Iron sulphate, at plant/RER U	kg	1.1
Light fuel oil, at regional storage/CH U	kg	42
Light fuel oil, at regional storage/RER U	kg	42
Lignite, at mine/RER U	kg	9.4
Lime, hydrated, loose, at plant/CH U	kg	0.72
Limestone, at mine/CH U	kg	0.010
Limestone, crushed, washed/CH U	kg	0.010
Limestone, milled, loose, at plant/CH U	kg	0.010
Limestone, milled, packed, at plant/CH U	kg	0.010
Lubricating oil, at plant/RER U	kg	47
Methanol, at regional storage/CH U	kg	22

Table A.7: Exergy values of materials, fuels and products used for calculating the contributions of the processes to the TCExL score - Continued.

Name	Unit	Exergy value [MJ/unit]
Natural gas, at production onshore/DZ U	m^3	36
Natural gas, at production onshore/DZ U[1]	m^3	36
Natural gas, at production onshore/NL U	m^3	36
Natural gas, at production offshore/NO U	m^3	36
Natural gas, at production onshore/RU U	m^3	36
Natural gas, burned in gas motor, for storage/DZ U[1]	MJ	1.0
Natural gas, high pressure, at consumer/CH U	MJ	1.0
Natural gas, high pressure, at consumer/NL U	MJ	1.0
Natural gas, high pressure, at consumer/RER U	MJ	1.0
NOx retained, in SCR/GLO U	kg	1.9
Nylon 66, glass-filled, at plant/RER U	kg	38
Oxygen, liquid, at plant/RER U	kg	0.75
Pellets, iron, at plant/GLO U	kg	6.7
Petroleum coke, at refinery/RER U	kg	27
Phosphoric acid, fertiliser grade, 70% in H2O[2]	kg	0.71
Pig iron, at plant/GLO U	kg	0.0088
Proteins, from fermentation of verge grass	kg	20
Quicklime, in pieces, loose, at plant/CH U	kg	2.0
Quicklime, milled, packed, at plant/CH U	kg	2.0
Refractory, basic, packed, at plant/DE U	kg	1.5
Refractory, fireclay, packed, at plant/DE U	kg	0.57
Refractory, high aluminium oxide, packed, at plant/DE U	kg	0.15
Sand, at mine/CH U	kg	0.068
Silica sand, at plant/DE U	kg	0.068
Sinter, iron, at plant/GLO U	kg	2.5
Sodium hydroxide, 50% in H2O, production mix[3]	kg	0.82
Softwood, standing, under bark, in forest/RER U	m^3	$9.6{\cdot}10^3$
SOx retained, in hard coal flue gas desulphurisation/RER U	kg	4.9
SOx retained, in lignite flue gas desulphurisation/GLO U	kg	4.9
Steel, electric, un- and low-alloyed, at plant/RER U	kg	6.7
Sweet gas, burned in gas turbine, production/m^3/NO U	m^3	36
Tap water, at user/RER U	kg	0
Titanium dioxide, production mix, at plant/RER U	kg	0.27
Water, completely softened, at plant/RER U	kg	0
Water, decarbonised, at plant/RER U	kg	0
Wood pellets at Savannah harbor	m^3	$1.3{\cdot}10^4$

[1] adapted

[2] at plant/GLO U

[3] at plant/RER U

Table A.8: Standard chemical exergy values of emissions and final waste flows. The data originate from and/or are calculated from thermodynamic data reported by Szargut (2007); Rivero and Garfias (2006); Stretton (2004b,a).

Name	Exergy value [MJ/kg]	Name	Exergy value [MJ/kg]
Emissions to air			
1,4-Butanediol	29	Calcium	21
1-Butanol	37	Carbon dioxide[1]	0.45
1-Pentanol	38	Carbon dioxide, fossil	0.45
1-Pentene	48	Carbon dioxide[2]	0.45
1-Propanol	34	Carbon disulfide	22
2-Butene, 2-methyl-	47	Carbon monoxide[1]	10
2-Methyl-1-propanol	37	Carbon monoxide, fossil	10
2-Nitrobenzoic acid	20	Chlorine	1.7
2-Propanol	33	Chloroacetic acid	10
Acenaphthene	42	Chlorosilane, trimethyl-	27
Acetaldehyde	26	Chromium	18
Acetic acid	15	Chromium VI	18
Acetone	31	Chrysene	41
Acetonitrile	29	Cobalt	12
Aluminium	40	Copper	6.8
Ammonia	20	Cumene	45
Aniline	35	Cyanide	24
Anthracene	41	Cyclohexane	47
Antimony	5.4	Diethanolamine	27
Arsenic	10	Diethylamine	43
Arsine	12	Dinitrogen monoxide	2.4
Barium	6.7	Ethane	50
Benzaldehyde	34	Ethanol	30
Benzene	42	Ethene	49
Benzene, 1,3,5-trimethyl-	44	Ethene, chloro-	21
Benzene, ethyl-	43	Ethene, tetrachloro-	7.3
Benzene, hexachloro-	10	Ethylamine	37
Benzo(b)fluoranthene	40	Ethylene oxide	29
Benzo(ghi)perylene	40	Ethyne	49
Beryllium	99	Fluorine	12
Boron trifluoride	3,1	Formaldehyde	18
Bromine	0.67	Formic acid	6.5
Butadiene	47	Furan	31
Butane	48	Heat, waste	0.22[3]
Butene	47	Helium	7.6

[1] biogenic

[2] land transformation

[3] MJ/MJ

Table A.9: Standard chemical exergy values of emissions and final waste flows. The data originate from and/or are calculated from thermodynamic data reported by Szargut (2007); Rivero and Garfias (2006); Stretton (2004b,a) - Continued.

Name	Exergy value [MJ/kg]	Name	Exergy value [MJ/kg]
Emissions to air			
Heptane	48	Methyl formate	17
Hexane	48	Monoethanolamine	30
Hydrogen	117	m-Xylene	44
Hydrogen bromide	1.4	Nickel	11
Hydrogen chloride	2.3	Nitric oxide	3.0
Hydrogen cyanide	24	Nitrobenzene	27
Hydrogen fluoride	4	Nitrogen	0.026
Hydrogen iodide	1.6	Nitrogen oxides	1.9
Hydrogen peroxide	4	Octane	47
Hydrogen sulfide	24	Oxygen	0.12
Iodine	1.5	Ozone	3.5
Isocyanic acid	13	Palladium	4.5
Isopropylamine	39	Pentane	48
Magnesium	31	Phenanthrene	41
Mercury	0.70	Phenol	34
Methane	52	Phosphorus	37
biogenic	52	Platinum	3.4
bromo-, Halon 1001	8.3	Propanal	31
bromochlorodifluoro-[1]	6.1	Propane	49
bromotrifluoro-, Halon 1301	4.2	Propene	49
chlorodifluoro-, HCFC-22	7.0	Propylamine	39
chlorotrifluoro-, CFC-13	5.7	Rhodium	6.7
dichloro-, HCC-30	8.3	Scandium	28
dichlorodifluoro-, CFC-12	4.6	Silicon	45
dichlorofluoro-, HCFC-21	10	Silver	3.2
fossil	52	Sodium	18
monochloro-, R-40	15	Sodium chlorate	1.3
tetrachloro-, CFC-10	4.5	Sodium formate	14
tetrafluoro-, CFC-14	5.2	Sodium hydroxide	1.9
trichlorofluoro-, CFC-11	4.3	Strontium	10
trifluoro-, HFC-23	8.1	Styrene	44
Methanol	23	Sulfur dioxide	4.9
Methyl acetate	22	Sulfur hexafluoride	8.8
Methyl acrylate	26	Sulfur oxides	3.9
Methyl amine	33	Sulfur trioxide	3.1

[1] Halon 1211

Table A.10: Standard chemical exergy values of emissions and final waste flows. The data originate from and/or are calculated from thermodynamic data reported by Szargut (2007); Rivero and Garfias (2006); Stretton (2004b,a) - Continued.

Name	Exergy value [MJ/kg]	Name	Exergy value [MJ/kg]
Emissions to air			
Sulfuric acid	10	Trimethylamine	40
t-Butyl methyl ether	39	Uranium	7.1
t-Butylamine	42	Used air	0
Tellurium	3.8	Water	1.9
Thallium	1.7	Xylene	43
Thorium	7.6	Zinc	6.7
Tin oxide	2.2	Zinc oxide	0.28
Toluene	43	Zirconium	18
Toluene, 2-chloro-	31		
Emissions to water			
1,4-Butanediol	28	Butene	47
1-Butanol	36	Butyl acetate	31
1-Pentanol	38	Butyrolactone	25
1-Pentene	47	Calcium, ion	0.84
2-Methyl-1-propanol	36	Carbon disulfide	22
2-Methyl-2-butene	47	Cesium	3.0
2-Propanol	33	Chloride	0.067
Acenaphthene	42	Chlorine	1.8
Acenaphthylene	39	Chloroacetyl chloride	9.2
Acetaldehyde	26	Chromium	11
Acetic acid	15	Chromium VI	11
Acetone	31	Chrysene	40
Acetonitrile	29	COD[1]	0
Acetyl chloride	13	Copper	2.1
Aluminium	29	Copper, ion	1.4
Ammonia	22	Cresol	35
Aniline	37	Cumene	44
Anthracene	40	Cyanide	24
Antimony	3,6	Decane	47
Barium	5,6	Diethylamine	42
Benzene	42	Dimethylamine	38
Benzene, ethyl-	43	Ethanol	29
Beryllium	67	Ethene, chloro-	22
Bromate	1	Ethyl acetate	26
Bromine	0.63	Ethylamine	37

[1] Chemical Oxygen Demand

Table A.11: Standard chemical exergy values of emissions and final waste flows. The data originate from and/or are calculated from thermodynamic data reported by Szargut (2007); Rivero and Garfias (2006); Stretton (2004b,a) - Continued.

Name	Exergy value [MJ/kg]	Name	Exergy value [MJ/kg]
Emissions to water			
Ethylene oxide	29	Phosphate	1.5
Fluoride	0.56	Phosphorus	28
Formate	4.0	Potassium, ion	0.32
Formic acid	6.3	Propanal	32
Heat, waste	0.016[1]	Propane, 1,2-dichloro-	18
Hexane	48	Propanol	33
Hydrogen chloride	6.4	Propene	49
Hydrogen fluoride	2.5	Propylamine	40
Hydrogen peroxide	3.5	Rubidium	4.5
Iodide	0.92	Scandium	21
Iron, ion	8.4	Selenium	4.4
Isopropylamine	39	Silicon	30
Magnesium	26	Sodium formate	4.0
Manganese	8.8	Sodium, ion	0.16
Mercury	0.54	Strontium	8.6
Methane, dibromo-	4.3	Sulfate	0.17
Methane, dichloro-[2]	8.2	Sulfide	22
Methane, monochloro-[3]	18	Sulfur	19
Methanol	22	t-Butyl methyl ether	38
Methyl acetate	23	t-Butylamine	42
Methyl acrylate	24	Toluene	43
Methyl amine	33	Toluene, 2-chloro-	31
Methyl formate	18	Triethylene glycol	25
m-Xylene	43	Trimethylamine	41
Naphthalene	41	Tungsten	4.5
Nickel	4.0	Urea	11
Nitrobenzene	26	Xylene	43
o-Xylene	43	Zinc	5.2
Phenol	33		
Emissions to soil			
Aluminium	33	Boron	58
Ammonia	20	Bromide	0.37
Antimony	3.6	Cadmium	2.6
Arsenic	6.6	Calcium	18
Barium	5.4	Carbon	34

[1] MJ/MJ

[2] HCC-30

[3] R-40

Table A.12: Standard chemical exergy values of emissions and final waste flows. The data originate from and/or are calculated from thermodynamic data reported by Szargut (2007); Rivero and Garfias (2006); Stretton (2004b,a) - Continued.

Name	Exergy value [MJ/kg]	Name	Exergy value [MJ/kg]
Emissions to soil			
Chromium	10	Phosphorus	28
Chromium VI	11	Potassium	9.4
Cobalt	4.5	Silicon	30
Copper	2.1	Sodium	15
Fluoride	0.56	Strontium	8.6
Heat, waste	0.016[1]	Sulfate	0.058
Iron	6.7	Sulfide	12
Lead	1.1	Sulfur	19
Magnesium	26	Sulfuric acid	1.7
Manganese	8.8	Tin	4.6
Mercury	0.54	Titanium	19
Molybdenum	7.6	Vanadium	14
Nickel	4.0	Zinc	5.2
Final waste flows			
Calcium fluoride waste	0.15		
Mineral waste, from mining	0		
Slags and ashes	0		

[1] MJ/MJ

Appendix B

Literature research

Approach

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 (www.scopus.com) 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 (www.sciencedirect.com) and Inderscience (www.inderscience.com) 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 (scholar.google.com) 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 research was carried out in September 2010 and resulted in the 116 publications listed in Tables B.1 and B.2. 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 on the abstracts, a number of publications was selected for further reading, again as far as freely accessible.

Table B.1: An overview of the 116 publications found during the literature research of September 2010.

Akiyama and Uesugi (2004)
Apaiah et al. (2006)
Arnas (2010)
Ayres and Kneese (1989)
Ayres et al. (2006)
Azzarone and Sciubba (1995)
Balocco and Grazzini (2000)
Balocco et al. (2004)
Bastianoni et al. (2005)
Bilgen et al. (2008)
Boelman and Asada (2003)
Campanella (2008)
Casarelli (1998)
Ciegis and Ciegis (2008)
Coatanea et al. (2006)
Cornelissen (1997)
Cummings and Seager (2008)
Del Rio and Rivero (1998)
Dewulf et al. (2000)
Dewulf et al. (2001)
Dewulf and Van Langenhove (2001)
Dewulf and Van Langenhove (2002a)
Dewulf and Van Langenhove (2002b)
Dewulf and Van Langenhove (2002c)
Dewulf (2009)
Dincer[1]
Dincer (2002a)
Dincer and Rosen (2004)
Dincer and Rosen (2005)
Dincer (2006)
Dincer and Rosen (2007)
Dincer (2007)
Dincer and Rosen (2008)
Dincer and Naterer (2010)
Teles dos Santos and Park (2009)
Dovjak et al. (2010)
Economou and Makrodimitri (2010)
Feng (2008)
Ferrari et al. (2001)
Ferrari (2003)
Gasparatos et al. (2009a)
Gasparatos et al. (2009b)
Gaveau et al. (2010)
Golden et al. (2005)
Golden (2006)
Gong and Wall (2001)
Gong (2004)
Gutowski et al. (2009)
Hammond (2004b)
Hammond (2004a)
Hammond (2007)
Hannemann et al. (2008)
Haseli et al. (2008)
Hau (2005)
Hepbasli (2008)
Hoang and Rao (2010)
Hoang and Alauddin (2011)
Jørgensen (2010)
Jørgensen (2006)
Kanoglu et al. (2009)
Kaygusuz and Bilgen (2009)
Khaliq and Ahmed (2006)
Khan et al. (2005)
Kilkis (2004)
Lems et al. (2004)
Lettieri et al. (2009)

[1] unpublished version, later published as Dincer (2011)

Table B.2: An overview of the 116 publications found during the literature research of September 2010 - Continued.

Li and Mo (2001)
Liu and Yao (2009)
Martinás (1998)
Midilli and Dincer (2009)
Midilli and Dincer (2010)
Morrison (2000)
Muys et al. (2001)
Ogushi (2006)
Pati et al. (2009)
Patzek (2008)
Peacock (1999)
Ptasinski et al. (2008)
Pulselli et al. (n.d.)
Reuter and Van Schaik (2008)
Robinett III et al. (2006a)
Robinett III et al. (2006b)
Rosen and Dincer (2001)
Rosen et al. (2008)
Rosen (2008b)
Rosen (2008a)
Sager (2008)
Sankara (2005)
Van Schijndel et al. (1998)
Schmidt (2004)
Schmidt and Shukuya (2005)
Sciubba (1995)
Seager et al. (2005)
Sekulić and Sankara (2006)
Sewalt et al. (2001)
Shah and Meckler (2009)
Shah et al. (2009)
Shah and Patel (2009)
Shah and Patel (2010)
Su et al. (2009)
Suganthi and Samuel (2000)
Torío and Schmidt (2007)
Torío and Schmidt (2009)
Ukidwe et al. (2005)
Wall and Gong (2001)
Wall (2005)
Wall (2010)
Wang and Hua (2005)
Winkler (2006)
Xu et al. (2003)
Yi et al. (2004)
Zhang (2006)
Zhang and Fan (2008)
Zhang and Fan (2009)
Zhang and Chen (2010)
Zvolinschi et al. (2007)

Appendix C

Exergy analysis methods

This appendix provides more information about the exergy analysis methods of Section 3.4. The exergy analysis methods are listed in alphabetical order.

CEENE
The method called 'Cumulative Exergy Extraction from the Natural Environment' (CEENE) can be considered as an extension to calculating the Cumulative Exergy Consumption (CExC). The CEENE method 'quantifies the exergy "taken away" from natural ecosystems' (Dewulf et al., 2007, p.8477) and covers the withdrawal of natural resources including land use. Dewulf et al. (2007) have taken into account land use to correct for the inconsistency between the assessment of direct and indirect exergy use, e.g. directly via solar cells and indirectly via biomass. This inconsistency relates to the fact that usually only the exergy value of the biomass is considered, neglecting the much larger amount of solar energy needed for the growth of that biomass. Another, but related, reason for taking into account land use was that land used for industrial or other human activities is not available anymore for natural processes like growing trees or flowers.

The CEENE method as introduced by Dewulf et al. (2007) distinguishes between the following eight categories of resources withdrawn from the natural environment: renewable resources, fossil fuels, nuclear energy, metal ores, minerals, water resources, land resources, and atmospheric resources (Dewulf et al., 2007; Van der Vorst et al., 2009). 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 (www.ecoinvent.org) version 1.2 have been calculated by Dewulf et al. (2007). In this way the CEENE value of a product or service can be calculated by multiplying the amounts of reference flows necessary to obtain the product or service by the corresponding CEENE factors and summing them. The unit of the resulting CEENE value is megajoules of exergy. The CEENE factors have been subdivided into the eight categories mentioned above to make it possible to calculate the contributions of each category to the overall CEENE value.

Cumulative Exergy Consumption

The method of calculating the Cumulative Exergy Consumption (CExC) is introduced by Szargut et al. (1988). It expresses 'the sum of the exergy of natural resources consumed in all the steps of a production process' (Szargut et al., 1988, p.171), or, stated differently, is equal to the 'total consumption of the exergy and natural resources connected with the fabrication of the considered product and appearing in all the links of the network of production processes' (Szargut, 2005). According to Cornelissen (1997, p.61), the CExC method is 'the first step of analysing the life cycle on the basis of exergy'. In calculating the CExC index, the network of production processes is divided into four levels (Szargut et al., 1988; Szargut, 2005). The first level to be analysed is the process under consideration, also known as the 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. According to Szargut et al. (1988) 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.

In contrast with regular life cycle analyses, the CExC method does not take into account the exergy loss caused by disposal and/or recycling of the products and clean-up of the plant. The CExC can be used to calculate the cumulative exergy loss, which is defined as the difference between the CExC and the specific exergy of the product (Szargut and Morris, 1990). The CExC over the specific exergy of the product is named the cumulative exergy efficiency or cumulative degree of perfection (CDP) (Szargut, 2005).

Cumulative Exergy Consumption for Construction and Abatement

The method of calculating the Cumulative Exergy Consumption for Construction and Abatement (CExCA) is introduced by Dewulf et al. (2001) as the sum of the Cumulative Exergy Consumption (CExC) needed for the construction and operation of the system and the cumulative exergy consumption for abatement of emissions and the system after utilization (CExA). The abatement exergy of emissions is equal to the exergy consumption caused by treating the emissions with a technological process to make the impact of the emission on the environment and man negligible.

Cumulative Exergy Demand

Analogous to the Cumulative Exergy Consumption (CExC), the Cumulative Exergy Demand (CExD) is defined as 'the sum of exergy of all resources required to provide a process or product' (Bösch et al., 2007). The CExD has been developed to facilitate the calculation of the total exergy requirement of products of which the resource demand is available in the Ecoinvent database. CExD indicators have been calculated of the resources mentioned in the Ecoinvent database version 1.2. The total exergy requirement of a product can be calculated by multiplying the required amounts of resources with the appropriate CExD indicator.

Eco-Exergy
The Eco-Exergy method has been introduced by Jørgensen (2010) to calculate the value of ecosystem services. The annual increase of Eco-Exergy is said to be a measure of the value of ecosystem services. This Eco-Exergy is calculated by multiplying the biomass increase by the 'average content of information as Kullbach's measure of information, in the various ecosystems' (Jørgensen, 2010, p.311). The reference system that is used in Eco-Exergy differs from the reference environment used in exergy analysis, i.e. in Eco-Exergy the reference system has the same temperature and pressure as the system under consideration, so only the chemical work energy determines the Eco-Exergy value of ecosystems. According to Zhang et al. (2010, p.693) 'eco-exergy has been widely used in the assessment of ecosystem health, parameter estimations, calibrations, validations and prognoses'. Beta-factors of some ecosystems are presented by Jørgensen (2010) to facilitate the calculation of Eco-Exergy values.

Ecological Cost
The concept of Ecological Cost is related to the concept of Cumulative Exergy Consumption (CExC) and has been introduced to express 'the cumulative consumption of non-renewable primary exergy, appearing in all links of an energo-technological system as a result of the fabrication of the considered final product.' (Szargut, 2002, p.381)

Ecological Cumulative Exergy Consumption
The concept of Ecological Cumulative Exergy Consumption (ECEC) has been developed by Hau and Bakshi (2004a) as an expansion of traditional or industrial Cumulative Exergy Consumption (CExC) to include the contribution of ecosystem services. This is done by expanding the system boundaries used in CExC to include the ecological processes that produce the natural resources consumed by the industrial processes. The ecological cumulative exergy values of natural resources are calculated analogous to the emergy values in Emergy analysis and are expressed in solar-equivalent joules (sej) as well. ECEC and Emergy are equivalent if the analysis boundary, the allocation approach and the method for combining global energy inputs are identical, but a remaining difference is that ECEC has no relationship with economic value (Hau and Bakshi, 2004a). A systematic algorithm for ECEC computation is provided by Hau and Bakshi (2004a).

Ecologically Based LCA
The Ecologically Based LCA method (Eco-LCA) has been developed by Zhang et al. (2010b) to include the direct and indirect role of ecosystems in LCA. The provisioning, regulating and supporting services of ecosystem goods and services are more or less included, the aspects of cultural services are not included. The missing ecosystem services have not yet been included because of lack of data. The developers kept the methodological framework of Eco-LCA similar to that of a regular LCA, because 'Eco-LCA is meant to complement and extend conventional LCA' (Zhang et al., 2010b, p.2625). The main difference between both methods is the analysis boundaries: in Eco-LCA these boundaries are extended to include ecosystems. The Eco-LCA model can be used to define many types of metrics, e.g. 'resource intensity', 'efficiency', 'renewability index' and 'physical return on investment' (Zhang et al.,

2010b, p.2628). Examples of the 'resource intensity' metrics are CExC and ECEC.

Emergy analysis

Emergy analysis is a method that has been developed by H.T. Odum (Ulgiati et al., 1994) to take into account ecosystem goods and services on an energetic basis. The method 'characterizes all products and services in equivalents of solar energy' Hau and Bakshi (2004b, p.216). Its unit of measurement is 'solar embodied joules' (sej). Apart from calculating the emergy values of all energy flows, emergy analysis can be used to assign emergy values to economic inputs. The method has encountered a lot of criticism which according to Hau and Bakshi (2004b, 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'.

Sciubba (2009); Bastianoni et al. (2007) have compared the concepts of exergy and emergy. According to Sciubba (2009) emergy analysis is an energy-based method, not an exergy-based method. He also concludes that emergy analysis is not equivalent to CExC and that 'with the modifications proposed by Bastianoni et al. (2007), emergy analysis would become equivalent to Extended Exergy Accounting' (Sciubba, 2009, p.544).

Environomics

The method called Environomics (Frangopoulos, 1992; Curti et al., 2000) 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' (Curti et al., 2000, p.723). The objective of the model can be expressed in monetary units or in physical units, e.g. exergy. According to (Curti et al., 2000, 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'. Curti et al. (2000) take into account the exergy losses caused by equipment manufacturing, the operation phase and equipment removal. The operation phase includes the external exergy loss caused by emissions or the exergy loss caused by reducing the emissions into harmless compounds, i.e. abatement of the emissions.

Exergetic Cost

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' (Valero et al., 1986, p.2). The exergetic cost values of natural fuels are much higher than their exergy values because of the inefficiencies of the processes used for the production of these natural fuels. Valero's Exergetic Cost method is also called 'Exergy Cost' (Sciubba and Wall, 2007; Dewulf et al., 2008) and 'Exergoecological analysis' (Meyer et al., 2009, p.76). The Exergetic Cost and the CExC values are said to be equivalent (Sciubba and Wall, 2007; Dewulf et al., 2008). In the Exergetic Cost method, an incidence matrix, also called structural matrix, represents the connections between the ingoing and outgoing flows of the system. This matrix is derived from the exergy balances of the components comprising the system under consideration (Valero et al., 1986; Dewulf et al., 2008). This exergetic cost method can be extended with economic indicators, like the prices of fuels entering the system and the amortization, maintenance and overhead costs of the subsystems, to obtain a method for the calculation of the thermoeconomic costs of products Valero et al. (1986).

Exergetic Life Cycle Analysis
The method of Exergetic Life Cycle Analysis (ELCA) has been developed by Cornelissen (1997) and can be considered as an extension to the regular Life Cycle Analyses. According to Cornelissen (1997) 'life cycle irreversibility is the most appropriate parameter for the depletion of natural resources'. He argues that minerals are not depleted because the atoms of the minerals cannot be lost. What can be lost are the high-grade ores, but as Cornelissen (1997) puts it, the minerals can then be obtained from low-grade ores or others sources. The lower the quality of the ore or source, the more effort, i.e. natural resources, will be needed to obtain these minerals. Cornelissen and Hirs (2002) illustrate the aforementioned with copper ore as an example; they state 'the measure for depletion of copper ore becomes the loss of natural resources to perform the required transformations. To measure this "loss" the concept of exergy is introduced' (Cornelissen and Hirs, 2002, p.1418).

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 total exergy destruction in the life cycle is called the irreversibility of the product (Cornelissen, 1997). 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 (Boudri et al., 2000).

Originally, in ELCA no distinction was made between renewable and non-renewable resources. Cornelissen and Hirs (2002) have extended the ELCA method by stating that the exergy content of renewable resources should be subtracted from the exergy loss caused by irreversibilities of the process units. The resulting exergy loss is called the non-renewable life cycle irreversibility. They regard the exergy input of the sun as 'free' and don't take into account this exergy or the irreversibilities caused by transforming solar exergy into renewable fuels. A problem with subtracting the exergy content of renewables from the exergy loss of the process units is that the exergy content of renewables is no measure of the 'renewable part' of these exergy losses. In Section 5.1.1 this problem is addressed in more detail.

An extension to the method of ELCA is called Zero-ELCA. In Zero-ELCA the processes under consideration are (virtually) extended with processes for the abatement of the emissions. The exergy loss accompanied with these processes is called abatement exergy. Cornelissen (1997) provides abatement exergy values for the emission of CO_2, SO_2, NO_x and phosphates.

Exergoeconomic analysis
In 1984 Tsatsaronis introduced the method 'Exergoeconomic analysis' for the combined exergetic and economic analysis of energy conversion processes (Tsatsaronis and Winhold, 1985). The method includes the determination of the exergy losses and costs related to the individual plant components (units). These costs consist of the investment costs as well as the operation and maintenance costs plus sometimes

also a part of the overhead expenses. The costs per unit exergy of each process flow stream is calculated via cost balances that are formulated for all plant components. Subsequently the average exergy unit costs for the fuels and products of each plant component are calculated from the costs per unit of exergy of each process flow stream, followed by the calculation of the costs of the exergy losses in each plant component.

An extension to this method is the Advanced Exergoeconomic analysis (Tsatsaronis, 2008; Tsatsaronis and Morosuk, 2010) in which the total exergy destruction, also known as internal exergy loss, within a component is split into endogenous avoidable, exogenous avoidable, endogonous unavoidable and exogenous unavoidable parts. The endogenous exergy destruction caused by a component is the exergy destruction that takes place when this component operates with its current efficiency while all other components of the system operate in an ideal way. The exogenous exergy destruction of a component is the exergy destruction caused by that component because of irreversibilities occurring in the other components of the system. the exergy destruction can also be split into unavoidable and avoidable exergy destruction. The unavoidable exergy destruction is the exergy destruction that cannot be reduced because of technological limitations, e.g. availability and costs of materials and/or manufacturing methods. Combining the concepts of endogenous/exogenous exergy destruction and avoidable/unavoidable exergy destruction leads to the aforementioned four components of exergy destruction. The advanced exergoeconomic analysis method determines the costs of the avoidable parts of exergy destruction and the investment costs associated with the endogenous avoidable exergy destruction.

Exergoenvironmental analysis
In Exergoenvironmental analysis (Meyer et al., 2009) the concept of exergoeconomic analysis is used to allocate the environmental impact of a process to the individual components of the process. The environmental impact of the process is determined with the LCA methodology in combination with the Eco-indicator 99 method. To calculate all internal and output streams of the components, environmental impact balances are defined and auxiliary equations are formulated. According to the environmental impact balance of a component the total environmental impact of the input streams to that component plus the environmental impact of the component itself is equal to the total environmental impact of the output streams. The environmental impact of the component is the sum of the environmental impacts due to construction, operation and maintenance, and disposal of that component. The auxiliary equations are obtained in the same way as in exergoeconomic analysis.

Besides the environmental impact determined with the LCA methodology, also the exergy destruction caused by the components is been taken into account. For this purpose the exergy destruction of the component is multiplied by the average specific environmental impact of the fuel for this component.

During the exergoenvironmental analysis several exergoenvironmental parameters are evaluated. First, all components are compared with respect to their total environmental impact. Of these components, the components with the highest improvement potential are selected. In accordance with the cause of the environmental impact, i.e. component-related impact or thermodynamic efficiency (relatively large exergy destruction), it is determined whether LCA or exergy analysis should be applied in improving the environmental performance of the component under consideration.

Expanded Cumulative Exergy Consumption
The method called Expanded Cumulative Exergy Consumption is introduced by Wang et al. (2005). It is an extension of the cumulative exergy consumption (CExC) with abatement exergy, like the CExCA method of Dewulf et al. (2001).

Extended Exergy Accounting
The concept of Extended Exergy Accounting (EEA) has been introduced by Sciubba (2001). EEA integrates cumulative exergy consumption (CExC) and thermo-economic methods into an approach in which also labour and environmental impact are taken into account. An EEA covers the whole life cycle of a product or plant, i.e. the construction, production, decommissioning and clean-up phases.

To be able to include capital costs, the conversion factor K_{ex} is introduced. K_{ex} is defined as 'the ratio of some measure of the monetary circulation to the global exergetic input' (Sciubba, 2001, p.78), e.g. the global monetary circulation in a country as reported by the Central Bank. The exergetic value of labour in a portion of a society is computed as 'the total (yearly averaged) exergetic resource into that portion input divided by the number of working hours sustained by it' (Sciubba, 2001, p.75). The environmental impact of emissions is taken into account by extending the process under consideration with processes for treating these emissions until they have zero-impact (Sciubba, 2001, 2003).

Life Cycle Exergy Analysis
The method of Life Cycle Exergy Analysis has been introduced by Gong and Wall (1997). An important aspect of this method is the calculation of the exergetic payback time of a system, especially of systems in which renewable energy is used as a resource. In LCEA the resources are classified into natural flows (like sunlight, winds and ocean currents) and stocks, like described by Wall and Gong (2001). The stocks are divided into deposits (dead stocks) and funds (living stocks). Deposits are non-renewable resources like oils, minerals and metals and can only give a flow while diminishing. Funds, e.g. forests and fields, are renewable resources that result in yields (flows) like forest crops and agricultural crops. Renewable resources are regarded as free assets that not need be accounted for (Gong, 2004, 2005). The LCEA method compares the indirect exergy used for construction, maintenance and clean-up of the plant with the amount of exergy delivered during operation of the plant. The indirect exergy can originate from renewable or non-renewable resources (Gong and Wall, 2001). When, during operation, the exergy output is produced by converting a non-renewable kind of direct exergy input, the system will never pay back for the used direct and indirect exergy inputs. In case of using a renewable kind of direct exergy input, this direct exergy input can be disregarded, and at some time t the amount of exergy output will equal the amount of indirect exergy input. This time t is called $t_{\text{pay back}}$. All exergy output produced between $t = t_{\text{pay back}}$ and $t = t_{\text{closure}}$ can be regarded as the net exergy output of the plant. According to Gong and Wall (2001, p.226) 'Sustainable engineering should 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'. They illustrate this 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.

Net Exergy Consumption

The Net Exergy Consumption (CNEx) method is an extension to the Cumulative Exergy Consumption (CExC) method in the sense that exergy content of products is accounted for. (Berthiaume et al., 2001) defined the CNEx as the CExC minus the exergy of the products.

Multi-criteria approach of Frangopoulos and Keramioti

Frangopoulos and Keramioti (2010) present a multi-criteria approach in which they designate four groups of sustainability indicators: technical indicators, environmental indicators, economic indicators and social indicators. The exergetic efficiency is one of the technical indicators. 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 normalisation and subsequently averaging of the indicators within each group. The overall sustainability indicator is defined as the average of the group indicators. Frangopoulos and Keramioti (2010) also present 'amoeba' and sectorial plots of the indicators. Tonon et al. (2006) as well present amoeba plots of normalised thermodynamic, economic and environmental indicators.

Multi-criteria approach of Mirandola and Stoppato

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' (Mirandola and Stoppato, 2003, p.166), see also Giannantoni et al. (2005).

Sustainability indicators based on exergy

Several researchers have developed sustainability indicators in an attempt to quantify the sustainability of technological processes. e.g. Dewulf et al. (2000) present three sustainability indicators 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', an environmental parameter related to the condition that 'no harmful products are to be emitted by the technosphere' and a production efficiency parameter to take into account the efficiency of the production process itself (Dewulf et al., 2000, p.109). Also other sustainability indicators have been developed, either elaborating on the work of others or newly developed, e.g. by Sewalt et al. (2001); Lems et al. (2002, 2003); Bastianoni et al. (2005); Cummings and Seager (2008); Rosen et al. (2008); Hoang and Rao (2010); Coskun et al. (2011). An chronological overview is presented below.

Sustainability coefficient of Dewulf et al. (2000)

In an attempt to quantify the sustainability of technological processes Dewulf et al. (2000) have developed an overall sustainability coefficient that is a combination of three sustainability parameters based on exergy. The first parameter relates to the origin of the resources by distinguishing between renewable and non-renewable resources. Dewulf et al. (2000, p.109) define the renewability parameter α as 'the fraction of renewable exergy consumption with respect to the total exergy consumption' (Equation C.1).

$$\alpha = \frac{R_{\mathrm{cons,renewable}}}{R_{\mathrm{cons}}} \tag{C.1}$$

with:
α = renewability parameter
$R_{\mathrm{cons,renewable}}$ = renewable exergy consumption
R_{cons} = total exergy consumption

As a second condition for sustainable technology, Dewulf et al. (2000, p.110) state that 'no harmful products are to be emitted by the technosphere.' This results in the environmental parameter η_1 (Equation C.2).

$$\eta_1 = \frac{R2}{R1 + R2 + R3} \tag{C.2}$$

with:
η_1 = environmental parameter
R1 = exergy required for the abatement of emissions during production
R2 = exergy required for running the production process
R3 = exergy required for transforming the product, after its use and if possible recycling, into harmless products

Thirdly, they defined the production efficiency parameter η_2 (Equation C.3) because the sustainability of a process also depends on the efficiency of the production process itself.

$$\eta_2 = \frac{P}{R2} \tag{C.3}$$

with:
η_2 = production efficiency parameter
P = exergetic production rate of useful products
R2 = exergy required for running the production process

The product of η_1 and η_2 is called η and is regarded as a measure of the overall exergetic efficiency of the technosphere (Equation C.4).

$$\eta = \eta_1 \cdot \eta_2 \tag{C.4}$$

The overall sustainability coefficient S is based on the aforementioned parameters as shown in Equation C.5. S varies between 0 and 1, the higher S, the more sustainable the technosphere is.

$$S = \frac{\alpha + \eta}{2} \tag{C.5}$$

Zvolinschi et al. (2007) have applied the above mentioned indicators α, η_1 and η_2 to options for power production and recommend using these indicators within the industrial ecology framework.

Eco-efficiency indicator of Sewalt et al. (2001)
The eco-efficiency indicator of Sewalt et al. (2001) is to be used in combination with a regular Life Cycle Assessment. The eco-efficiency indicator distinguishes between renewable and non-renewable energy (Equation C.6).

$$\eta_{eco} = \frac{\eta \cdot (F_{\text{n-r}} + F_{\text{r}})}{F_{\text{n-r}} + \eta \cdot F_{\text{r}}} \tag{C.6}$$

with:
η_{eco} = eco-efficiency indicator
η = exergetic efficiency = total useful output over the total exergy feed (non-renewable plus renewable)
$F_{\text{n-r}}$ = non-renewable exergy feed
F_{r} = renewable exergy feed

Sewalt et al. (2001, p.41) also describe how the calculation of the eco-efficiency can be made compatible with the exergetic cost method of Valero et al. (1986). According to the authors this 'expanded Valero method [...] can be used for calculating the eco-efficiencies of more complex energetic systems'.

Sustainability parameters of Lems et al. (2002, 2003)
Lems et al. (2002, 2003) introduce a new parameter for sustainable resource utilization and revise the efficiency parameters of Dewulf et al. (2000). According to them, the three sustainability indicators should not be merged into one single sustainability indicator because of loss of information, the multi-dimensional nature of the concept of sustainability and the subjectivity of combining these three indicators into one sustainability indicator.

Lems et al. (2002) calculate their new sustainable resource utilization parameter (α) from the average and minimum resource abundance factors according to Equations C.7 to C.10.

$$\tau = \frac{M_{\text{reserves}}}{\phi_{\text{m,consumption}} - \phi_{\text{m,production}}} \tag{C.7}$$

with:
τ = resource depletion time
M_{reserves} = extent of natural reserves
$\phi_{\text{m,consumption}}$ = consumption rate
$\phi_{\text{m,production}}$ = production rate

$$a_{\text{i}} = \frac{\tau_{\text{i}}}{\tau_{\text{i}} + \tau_0} \tag{C.8}$$

with:
a_{i} = abundance factor of resource i
τ_{i} = depletion time of resource i
$\tau_0 = \tau$ at which a_{i} is 50%

$$a^{\mathrm{average}} = \frac{\sum_{\mathrm{i}} a_{\mathrm{i}} \cdot Ex_{\mathrm{in,i}}}{\sum_{\mathrm{i}} Ex_{\mathrm{in,i}}} \tag{C.9}$$

with:
a^{average} = average abundance
a_{i} = average abundance factors of the individual resources
$Ex_{\mathrm{in,i}}$ = exergy flows of the individual resources to the process

$$\alpha = a^{\mathrm{average}} \cdot a^{\mathrm{min}} \tag{C.10}$$

with:
α = sustainable resource utilization parameter
a^{average} = average resource availability
a^{min} = smallest of resource abundance factors $\mathrm{a_i}$ relevant in the process

The second parameter of Lems et al. (2002, 2003) is the exergy efficiency (η) and is defined in Equation C.11.

$$\eta = \frac{\sum Ex_{\ \mathrm{out,useful}}}{\sum Ex_{\ \mathrm{in,process}}} \tag{C.11}$$

with:
η = exergy efficiency
$Ex_{\mathrm{out,useful}}$ = useful outgoing exergy flows, i.e. products and by-products
$Ex_{\mathrm{in,process}}$ = resource flows

The environmental compatibility parameter (ξ) is the third parameter and is defined in Equation C.12.

$$\xi = \frac{Ex^{\mathrm{total}}_{\mathrm{in,process}}}{Ex^{\mathrm{total}}_{\mathrm{in,process}} + Ex^{\mathrm{total}}_{\mathrm{in,abatement}}} \tag{C.12}$$

with:
ξ = environmental compatibility parameter
$Ex^{\mathrm{total}}{}_{\mathrm{in,process}}$ = exergy required to run the process
$\mathrm{Ex}^{\mathrm{total}}{}_{\mathrm{in,abatement}}$ = exergy required for abating the harmful effects on the environment

Efficiency indices applied by Bastianoni et al. (2005)
Bastianoni et al. (2005) propose to use the following four indices to understand the sustainability of a process or system because of their focus on different aspects of sustainability.

- $Ex_{\mathrm{out}}/Ex'_{\mathrm{in}}$: This index is defined as the exergy of the useful products divided by the feeding exergy, i.e. the chemical exergy of the energy and matter input of a process or system plus the exergy needed to provide this energy and matter. Another name of this index is the degree of perfection (Szargut et al., 1988).

- Ex_{out}/Em: The exergy of the useful products divided by the emergy input to the process or system.

- $Ex_{\mathrm{s}}/Ex'_{\mathrm{in}}$: The exergy stored in the system or cumulative exergy content divided by the feeding exergy. This index is not dimensionless but is measured in time.
- Ex_{s}/Em: This index is measured in time as well.

Resource exergy renewal time indicator of Cummings and Seager (2008)
According to Norgate et al. (2009, p.5), Cummings and Seager (2008) have suggested an alternative for the indicator α introduced by Dewulf2000, namely 'the resource exergy renewal time, which they defined as the exergy input of the process divided by the exergetic renewal rate both over the time frame of interest'.

Sustainability index of Rosen et al. (2008)
To express the sustainability of a fuel resource, Rosen et al. (2008) define their sustainability index (SI) as the inverse of the depletion number described by Connelly and Koshland (2001) as follows (Equation C.13).

$$SI = \frac{1}{D_{\mathrm{p}}} = \frac{Ex_{\mathrm{in}}}{Ex_{\mathrm{D}}} \tag{C.13}$$

with:
SI = sustainability index
D_{p} = depletion number
Ex_{in} = exergy input
Ex_{D} = exergy destruction caused by internal irreversibilities

Sustainable efficiency measure of Hoang and Rao (2010)
Their measure is based on the total cumulative exergy content of the inputs (TCExC). The sustainable efficiency measure (SE) is then defined as the ratio of the minimum TCExC to an observed TCExC given a certain output.

Exergy parameters of Coskun et al. (2011)
Coskun et al. (2011) introduce three new exergy parameters to be used in addition to existing exergy parameters. The three new parameters are the total exergy destruction ratio (TExDR), the component exergy destruction ratio (CExDR) and the dimensionless exergy destruction (DExD). The TExDR is the total exergy destruction of the system divided by the total exergy input to the system, the CExDR is defined as the exergy destruction of any component of the system over the total exergy input to the system and the DExD is the ratio of the exergy destruction of any component of the system to the total exergy destruction of the system.

Appendix D

LNG case study: data and results

This appendix gives more detailed information about the data used for and the results of the assessments of the three systems of the LNG case study.

Adaptations to the standard LNG supply chain modelled in the Ecoinvent database

It appeared from studying the LNG supply chain in SimaPro/Ecoinvent in more detail that the preceding unit process called 'Natural gas, at production onshore/DZ U' applies a natural gas drying process that is based on the situation in Norway. Because this led to an unexpected use of hydropower installations, these processes have been modified as follows. The unit processes 'Natural gas, liquefied, at freight ship/DZ U' is connected to the unit process 'Drying, natural gas/NO U' via the successive unit processes 'Natural gas, liquefied, at liquefaction plant/DZ U', 'Natural gas, burned in gas motor, for storage/DZ U' and 'Natural gas, at production onshore/DZ U'. All these unit processes have been copied and renamed so that the new unit process 'Natural gas, liquefied, at freight ship/DZ U (adapted)' is linked to the new unit process 'Natural gas, at production onshore/DZ U (adapted)'. The 'Natural gas, at production onshore/DZ U (adapted)' differs from the original unit process 'Natural gas, at production onshore/DZ U' in the sense that the input called 'Drying, natural gas/NO U' is replaced with a new input, and thus new unit process, called 'Drying, natural gas/DZ U'. This new unit process 'Drying, natural gas/DZ U' uses 'Natural gas, at production onshore/DZ U' and 'Electricity, medium voltage, at grid/NL U' as inputs instead of the 'Natural gas, at production offshore/NO U' and 'Electricity, medium voltage, at grid/NO U' inputs of the original drying process called 'Drying, natural gas/NO U'.

Table D.1: Overview of the inputs and outputs of the three systems modelled in SimaPro.

	Waste heat	Oxyfuel	ORC
Inputs			
Hard coal supply mix/NL U [Mton]	2.87	2.56	2.70
LNG, at freight ship [10^{10} m3][1]	1.42	1.42	1.42
Nitrogen [Mton][2]	16.4	-	16.4
Hard coal power plant/RER/I U [p]	0.116	0.104	0.110
Liquid storage tank [p][3]	0.885	0.885	0.885
Products			
Electricty [PJ]	27	27	27
H-gas [Mton]	12	12	12
Nitrogen [Mton]	15.3	15.3	15.3
Captured CO_2 [Mton]	5.5	5.6	5.6
Emissions to air			
CO_2 [Mton]	0.964	0.295	0.907
NO_x [kton]	1.37	0.0216	1.29
SO_x [ton]	11.1	0	10.4
N_2 [Mton]	25.9	0	24.4
O_2 [Mton]	2.47	0.716	2.32
H_2O [Mton]	1.35	0.983	1.27
Final waste flows			
Waste heat to river [PJ]	22	20.9	28.6
Slags and ashes [Mton]	0.345	0.295	0.324

[1] Ecoinvent process ‘Natural gas, liquefied, at freight ship/DZ U’ (adapted)

[2] Ecoinvent process ‘Nitrogen, via cryogenic air separation, production mix, at plant, gaseous EU-27 S’

[3] Ecoinvent process ‘Liquid storage tank, chemicals, organics/CH/I U’

Table D.2: Capacity and investment costs of the installations.

	Capacity [MWe]	Investment costs [10^6 €]
USK Coal power plant	1070	1784[1]
Oxyfuel power plant	1000	1483[2]
LNG terminal Waste heat and Oxyfuel systems	12 BCM[3]	800
LNG terminal ORC system	12 BCM[3]	762

[1] including MEA unit for carbon dioxide capture

[2] including ASU (air separation unit)

[3] Billion Cubic Metre evaporated LNG

Table D.3: Process contributions to the ReCiPe scores of the three systems.

[%]	Waste heat	Oxyfuel	ORC
Natural gas production[1]	65	70	66
Natural gas for storage[2]	8.7	9.4	8.8
Nitrogen production[3]	4.8		4.8
Hard coal mining[4]	2.1	2.0	2.0
Subtotal	81	82	81
Power plant & LNG terminal	1.9	0.59	1.8

[1] Ecoinvent process 'Natural gas, at production onshore/DZ U' (adapted)

[2] Ecoinvent process 'Natural gas, burned in gas motor, for storage/DZ U' (adapted)

[3] Ecoinvent process 'Nitrogen, via cryogenic air separation, production mix, at plant, gaseous EU-27 S'

[4] Ecoinvent process 'Hard coal, at mine/ZA U'

Table D.4: ReCiPe scores of the natural gas production process and its subprocesses.

[%]	Total[1]	Process itself[2]	Subprocesses[3]
Human Health	3.4	0.80	2.6
Ecosystems	3.0	0.52	2.5
Resources	94	91	2.8
Total	100	92	7.9

[1] Natural gas production process including its subprocesses.

[2] Ecoinvent process 'Natural gas, at production onshore/DZ U' (adapted)

[3] Subprocesses of the Natural gas production process.

Table D.5: Contributions of the investment costs and yearly costs and revenues to the PWR.

	Waste heat		Oxyfuel		ORC	
	[10^8 €]	[%]	[10^8 €]	[%]	[10^8 €]	[%]
Investment costs						
Power plant	0.71	4.4	0.67	4.0	0.72	4.5
LNG terminal	0.29	1.8	0.33	1.9	0.28	1.7
Yearly costs						
OpEx	0.34	2.1	0.34	2.0	0.34	2.1
Coal	0.61	3.8	0.61	3.6	0.58	3.6
LNG	14	87	15	88	14	87
MEA	0.063	0.39	-		0.064	0.40
Nitrogen	0.1	0.62	-		0.11	0.68
subtotal	16	100	17	100	16	100
Revenues						
Electricity	1.5		1.7		1.5	
H-gas	13		15		13	
Carbon credits	0.37		0.42		0.38	
Nitrogen	-		1		-	
subtotal	15		18		15	
PWR	-0.62		0.75		-0.57	

Table D.6: Overview of the origin of the employees of the three systems.

[10^4 man-hours]	Waste heat	Oxyfuel	ORC
Philippines	30	29	29
South Africa	15	13	14
Netherlands	11	11	11
Colombia	9.3	8.3	8.7
Australia	8.4	7.5	7.9
Indonesia	8.4	7.8	8.1
China	8.1	7.5	7.8
USA	7.4	6.6	6.9
Eastern Europe	7.4	6.7	7.0
Algeria	6.2	6.2	6.2
South Korea	5.9	5.8	5.9
Russia	4.7	4.5	4.6
India	4.3	4.1	4.2
Myanmar	3.2	3.1	3.1
Ukraine	3.1	2.9	3.0
Croatia	2.0	2.0	2.0
Canada	2.0	1.7	1.8
Venezuela	1.9	1.7	1.8
Romania	1.6	1.6	1.6
Bulgaria	1.6	1.6	1.6
Other	4.7	4.4	4.5

Table D.7: Contributions of the processes to the $\mathrm{IHDI}_{\mathrm{overall}}$ scores of the three systems.

[%]	Waste heat	Oxyfuel	ORC
Hard coal mining	39	37	38
Coal transport	13	12	13
Natural gas production	0.0	0.0	0.0
Liquefaction	4.9	5.2	5.1
LNG transport	33	35	34
Power plant	10	11	10

Table D.8: The contribution of the processes of Table D.3 to the total TCExL and CExD scores of the systems.

[%]	Waste heat		Oxyfuel		ORC	
	TCExL	CExD	TCExL	CExD	TCExL	CExD
Natural gas production[1]	0.19	69	0.23	73	0.20	70
Natural gas for storage[2]	34	-	41	-	36	-
Nitrogen production[3]	3.4	4.1	n/a	n/a	3.5	4.2
Hard coal mining[4]	1.9	2.3	2.0	2.2	1.8	2.2
Power plant/LNG terminal	18	-	19	-	17	-
Total	57	75	63	75	58	76

[1] Ecoinvent process ‘Natural gas, at production onshore/DZ U’ (adapted)

[2] Ecoinvent process ‘Natural gas, burned in gas motor, for storage/DZ U’ (adapted)

[3] Ecoinvent process ‘Nitrogen, via cryogenic air separation, production mix, at plant, gaseous EU-27 S’

[4] Ecoinvent process ‘Hard coal, at mine/ZA U’

Table D.9: Contributions of supply chains and processes to the total scores of the Waste heat system.

[%]	ReCiPe	PWR	$\mathrm{IHDI}_{\mathrm{overall}}$	TCExL
Coal supply chain				
Hard coal mining[1]	2.1		39	1.9
Coal transport			13	
Purchase of coal		3.9		
subtotal	*(2.1)*	*(3.9)*	*(52)*	*(1.9)*
LNG supply chain				
Natural gas production[2]	65		0.0	0.19
Liquefaction			4.9	
Natural gas for storage[3]	8.7			34
LNG transport			33	
Purchase of LNG		86		
subtotal	*(74)*	*(86)*	*(38)*	*(35)*
Nitrogen supply chain				
Nitrogen production[4]	4.8			3.4
Purchase of nitrogen		0.40		
subtotal	*(4.8)*	*(0.40)*	(-)	*(3.4)*
Power plant and LNG terminal				
Power plant and LNG terminal	1.9		10	18
Investment costs power plant		4.5		
Investment costs LNG terminal		1.9		
OpEx		2.2		
MEA costs		0.66		
subtotal	*(1.9)*	*(9.2)*	*(10)*	*(18)*
Total	82	100[5]	100	58

[1] Ecoinvent process ‘Hard coal, at mine/ZA U’. The fact that about 2% of the ReCiPe and TCExL numbers contributes to the LNG supply chain is neglected.

[2] Ecoinvent process ‘Natural gas, at production onshore/DZ U’ (adapted)’

[3] Ecoinvent process ‘Natural gas, burned in gas motor, for storage/DZ U’ (adapted)

[4] Ecoinvent process ‘Nitrogen, via cryogenic air separation, production mix, at plant, gaseous EU-27 S’

[5] Costs only, because of the opposite signs of costs and revenues.

Table D.10: Contributions of supply chains and processes to the total scores of the ORC system.

[%]	ReCiPe	PWR	$\text{IHDI}_{\text{overall}}$	TCExL
Coal supply chain				
Hard coal mining[1]	2.0		38	1.8
Coal transport			13	
Purchase of coal		3.7		
subtotal	*(2.0)*	*(3.7)*	*(51)*	*(1.8)*
LNG supply chain				
Natural gas production[2]	66		0.0	0.2
Liquefaction			5.1	
Natural gas for storage[3]	8.8			36
LNG transport			34	
Purchase of LNG		87		
subtotal	*(74)*	*(87)*	*(39)*	*(36)*
Nitrogen supply chain				
Nitrogen production[4]	4.8			3.5
Purchase of nitrogen		0.4		
subtotal	*(4.8)*	*(0.4)*		*(3.5)*
Power plant and LNG terminal				
Power plant and LNG terminal	1.8		10	17
Investment costs power plant		4.5		
Investment costs LNG terminal		1.8		
OpEx		2.2		
MEA costs		0.7		
subtotal	*(1.8)*	*(9.2)*	*(10)*	*(17)*
Total	83	100[5]	100	58

[1] Ecoinvent process ‘Hard coal, at mine/ZA U’. The fact that about 2% of the ReCiPe and TCExL numbers contributes to the LNG supply chain is neglected.

[2] Ecoinvent process ‘Natural gas, at production onshore/DZ U’ (adapted)’

[3] Ecoinvent process ‘Natural gas, burned in gas motor, for storage/DZ U’ (adapted)

[4] Ecoinvent process ‘Nitrogen, via cryogenic air separation, production mix, at plant, gaseous EU-27 S’

[5] Costs only, because of the opposite signs of costs and revenues.

Appendix E

Fossil versus renewable case study: data and results

This appendix gives more detailed information about the data used for and the results of the assessments of the three systems of the Fossil versus renewable case study.

Wood pellets supply chain of the Co-firing system
The Wood pellets supply chain consists of the following unit processes and connected Ecoinvent unit processes. Table E.1 presents an overview of the inputs and outputs of the power plant of the Co-firing system.

- Wood pellets at Savannah harbor. This product/process is based on the Ecoinvent unit process 'Wood pellets, u=10%, at storehouse/RER U' with the following adaptations: 1.285 m^3 of 'Georgia wood from planing, kiln dried' is used as feedstock and the total transport amounts to 104.65 tkm of 'Transport, freight train, diesel/RER U'.
- Georgia wood from planing, kiln dried. This product/process is based on the Ecoinvent unit process 'Industrial residue wood, from planing, softwood, kiln dried, u=10%, at plant/RER U' with the following adaptation: 1 m^3 of 'Georgia sawn timber, kiln dried' is needed as feedstock.
- Georgia sawn timber, kiln dried. This product/process is based on the Ecoinvent unit process 'Sawn timber, softwood, raw, kiln dried, u=10%, at plant/RER U' with the following adaptations: 1.001 m^3 of 'Georgia sawn timber, forest-debarked' is used as feedstock and 958 MJ of 'Georgia wood chips, burned in furnace' as the heat source.
- Georgia sawn timber, forest-debarked. This product/process is based on the Ecoinvent unit process 'Sawn timber, softwood, raw, forest-debarked, u=70%, at plant/RER U' with the following modifications: 0.9996 m^3 of 'Georgia wood, debarked, at forest road' is used as feedstock and the total transport amounts to 11.9 tkm of 'Transport, lorry larger than 16t, fleet average/RER U'.

- Georgia wood, debarked, at forest road. This product/process is based on the Ecoinvent unit process ‘Round wood, softwood, debarked, u=70% at forest road/RER U’ with the following modifications: 1 m^3 of ‘Georgia wood, under bark’ is needed and 0.1 m^3 of ‘Georgia bark’ is produced as a by-product.

- Georgia wood, under bark. One m^3 of this wood is assumed to consist of 0.65 m^3 of ‘Round wood, softwood, under bark, u=70% at forest road/RER U’, 0.235 m^3 of ‘Industrial wood, softwood, under bark, u=140%, at forest road/RER U’ and 0.115 m^3 ‘Residual wood, softwood, under bark, u=140%, at forest road/RER U’.

- Georgia wood chips, burned in furnace. This product/process is based on the Ecoinvent unit process ‘Wood chips, from industry, softwood, burned in furnace 300kW/CH U’ with the following modifications: 0.000328 m^3 of ‘Georgia bark’ is used as a fuel and no transport is included.

Wind power plants of the Wind farm system
The Wind farm system consists of onshore and offshore wind power plants (Table E.1). As described in Section 8.2.1, the wind power plants are modifications of the largest onshore and offshore wind power plants modelled in the Ecoinvent database. The capacity and size of the turbines was adapted on the basis of several information sources (Enercon, 2010; Siemens, 2011; EEN, 2010; Pondera, 2009; Van Grinsven, 2009). It is assumed that the material composition of the moving and fixed parts of the wind turbines is the same as in the Ecoinvent unit processes. The capacity factor of the wind turbines was assumed to be 0.45 on average, based on an average wind speed of 8.3 to 8.7 m/s (Enercon, 2010; Siemens, 2011; Van Grinsven, 2009).

- Electricity from the onshore wind power plants. This electricity is based on the Ecoinvent process ‘Electricity, at wind power plant 800 kW/kWh/RER’ with the following modifications: the use of materials/fuels equals 0.0000575 kg of ‘Lubricating oil, at plant/RER U’, $1.27 \cdot 10^{-8}$ personkm of ‘Transport, passenger car/RER U’, $2.41796 \cdot 10^{-9}$ p of a ‘Wind power plant 7.5 MW, onshore, moving parts’ and the same amount of a ‘Wind power plant 7.5 MW, onshore, fixed parts’, plus 0.0000575 kg of ‘Disposal, used mineral oil, 10% water, to hazardous waste incineration/CH U’. The ‘Wind power plant 7.5 MW, onshore, moving parts’ and the ‘Wind power plant 7.5 MW, onshore, fixed parts’ are modifications of the Ecoinvent unit processes ‘Wind power plant 800 kW, moving parts RER I U ’ and ‘Wind power plant 800 kW, fixed parts/RER/I U’, respectively (Tables E.2 and E.3)

- Electricity from the offshore wind power plants. This electricity is based on the Ecoinvent process ‘Electricity, at wind power plant 2 MW, offshore/kWh/OCE’ with the following modifications: $3.50214 \cdot 10^{-9}$ p of a ‘Wind power plant 3.6 MW, offshore, moving parts’ and the same amount of a ‘Wind power plant 3.6 MW, offshore, fixed parts’ are needed. The ‘Wind power plant, offshore, moving parts’ and ‘Wind power plant, offshore, fixed parts’ are modifications of the Ecoinvent unit processes ‘Wind power plant 2 MW, offshore, moving parts/OCE/I U' and 'Wind power plant 2 MW, offshore, fixed parts/OCE/I U', respectively (Tables E.2 and E.3).

Fermentation of verge grass in the Bioethanol system

The Bioethanol system consists of the following unit processes and connected Ecoinvent unit processes.

- Grass from verge grass. This product/process is based on the Ecoinvent unit process 'Grass from natural meadow extensive IP, at field/CH U' with the following adaptations: the ' Energy, gross calorific value, in biomass' is set at 18 MJ/kg, the land transformations and land occupation are set at zero, the 'Mowing, by rotary mower CH U' is calculated at 0.000877 ha and the use of 'Glyphosate, at regional storehouse/CH U' and all emissions are set at zero.
- Fermentation of verge grass to bioethanol. This process is an adaptation of a reconstruction of the 'Multioutput-process "grass, to fermentation"' on the basis of Jungbluth et al. (2007) and the Ecoinvent unit processes 'Ethanol, 95% in H_2O, from grass, at fermentation plant/CH U', 'Grass fibres, at fermentation/CH U' and 'Proteins, from grass, at fermentation/CH U'. The products of this multi-output process are 1 kg of 'Ethanol, 95% in H2O, from fermentation of verge grass', 1.62 kg of 'Grass fibres, from fermentation of verge grass' and 2.01 kg of 'Proteins, from fermentation of verge grass'. The applied exergy based allocation factors between these products are 28, 31 and 41, respectively. The amount of verge grass used as a feedstock is 8.07 kg, based on dry matter. The transport is calculated at 4.04 tkm of 'Transport, lorry 3.5-16t, fleet average/RER U'.
- Electricity from bioethanol. This unit process is based on research conducted by De Vries (1999). Table E.1 presents an overview of the inputs and outputs.

Table E.1: Overview of the inputs and outputs of the main processes of the three systems modelled in SimaPro. The allocation factors are placed in brackets after the amounts of products.

Per year	Co-firing	Wind	Bioethanol
Inputs			
Hard coal supply mix/NL U [Mton]	2.4		
Wood pellets, at Savannah harbor [10^6 m^3][1]	1.58		
Wood pellets, transoceanic transport [10^9 tkm][2]	7.37		
Wood pellets, inland transport [10^6 tkm][3]	51.5		
Hard coal power plant/RER/I U [p]	0.121		
Electricity, onshore [GWh][4]		748	
Electricity, offshore [GWh][5]		652	
Ethanol, 95% in H2O, from grass [kton][6]			75.7
Gas power plant, 100 MWe/RER/I U [p]			0.038
Products			
Electricity [PJ]	26.6 (96)	5.04	0.876
Heat [PJ]	4.6 (4)		
Resources			
Air [Mton]			0.673
Emissions to air			
CO_2 fossil [Mton]	4.06		
CO_2 biogenic [Mton]	1.16		0.145
CO fossil [kton]			
NO_x [kton]	3.39		$1.55\cdot10^{-9}$
Nitrogen [Mton]			0.515
SO_2 [kton]	1.04		
PM10 [ton]	98		
Water [kton]			88.9
Emissions to water			
Heat, waste (river) [GJ]	142		
Final waste flows			
Slags and ashes [Mton]	0.412		

[1] Ecoinvent process 'Wood pellets, u=10%, at storehouse/RER U' (adapted)

[2] Ecoinvent process 'Transport, transoceanic freight ship/OCE U'

[3] Ecoinvent process 'Transport, barge/RER U'

[4] Ecoinvent process 'Electricity, at wind power plant 800 kW/kWh/RER' (adapted)

[5] Ecoinvent process 'Electricity, at wind power plant 2 MW, offshore/kWh/OCE' (adapted)

[6] Ecoinvent process 'Ethanol, 95% in H_2O, from grass, at fermentation plant/kg/CH' (adapted)

Table E.2: Overview of the materials, fuels and wastes related to the construction of the moving parts of the 7.5 MW onshore and 3.6 MW offshore wind power plants.

	Onshore[1]	Offshore[2]
Materials/fuels		
Electricity, medium voltage[kWh][3]	330000	112500
Aluminium, primary, at plant/RER U [kg]	3908	1278
Cast iron, at plant/RER U [kg]	122319	43757
Chromium steel 18/8, at plant/RER U [kg]	274242	82610
Copper, at regional storage/RER U [kg]	5786	2091
Glass fibre reinforced plastic [kg][4]	182394	74224
Lead, at regional storage/RER U [kg]	9	1
Lubricating oil, at plant/RER U [kg]	1110	1227
Polyethylene, HDPE, granulate [kg][5]	594	45
Polypropylene, granulate, at plant/RER U [kg]	20	10
Polyvinylchloride, bulk polymerised [kg][5]	428	
Steel, low-alloyed, at plant/RER U [kg]	69570	23562
Synthetic rubber, at plant/RER U [kg]	1888	151
Tin, at regional storage/RER U [kg]	9	1
Section bar rolling, steel/RER U [kg]	191890	67530
Sheet rolling, aluminium/RER U [kg]	3908	1278
Sheet rolling, chromium steel/RER U [kg]	274242	82610
Wire drawing, copper/RER U [kg]	5786	2091
Transport, lorry larger than 16t, fleet average/RER U [tkm]	82414	46590
Transport, freight, rail/RER U [tkm]	203586	46590
Transport, barge/RER U [tkm]		539
Waste to treatment		
Disposal, plastics, mixture, 15.3% water [kg][6]	65719	25042
Disposal, glass, 0% water [kg][6]	118562	49317
Disposal, used mineral oil, 10% water [kg][7]	1110	1227
Disposal, polyethylene, 0.4% water [kg][6]	594	45
Disposal, polypropylene, 15.9% water [kg][6]	20	
Disposal, polyvinylchloride, 0.2% water [kg][6]	428	10

[1] Ecoinvent process ‘Wind power plant 800 kW, moving parts/RER/I U’ (adapted)

[2] Ecoinvent process ‘Wind power plant 2 MW, offshore, moving parts/OCE/I U’ (adapted)

[3] Ecoinvent process ‘Electricity, medium voltage, production UCTE, at grid/UCTE U’

[4] Ecoinvent process ‘Glass fibre reinforced plastic, polyamide, injection moulding, at plant/RER U’

[5] at plant/RER U

[6] to municipal incineration/CH U

[7] to hazardous waste incineration/CH U

Table E.3: Overview of the resources, materials, fuels and wastes related to the construction of the fixed parts of the 7.5 MW onshore and 3.6 MW offshore wind power plants.

	Onshore[1]	Offshore[2]
Resources		
Transformation, from pasture and meadow [m^2]	221	
Transformation, to industrial area, built up [m^2]	221	
Transformation, from sea and ocean [m^2]		81
Transformation, to industrial area, benthos [m^2]		81
Occupation, industrial area, built up [m^2a]	4426	
Occupation, industrial area, benthos [m^2a]		1625
Materials/fuels		
Electricity, medium voltage, at grid/NL U [kWh]	26	
Concrete, normal, at plant/CH U [m^3]	1497	872
Copper, at regional storage/RER U [kg]		3900
Diesel, burned in building machine/GLO U [MJ]	24638	3355
Epoxy resin, liquid, at plant/RER U [kg]	936	866
Excavation, hydraulic digger/RER U [m^3]		52500
Gravel, unspecified, at mine/CH U [kg]		300000
Lead, at regional storage/RER U [kg]		7580
Polyvinylchloride, bulk polymerised, at plant/RER U [kg]		3500
Reinforcing steel, at plant/RER U [kg]	205537	80000
Steel, low-alloyed, at plant/RER U [kg]	3220000	188015
Sheet rolling, steel/RER U [kg]	3220000	188015
Welding, arc, steel/RER U [m]	494	361
Wire drawing, copper/RER U [kg]		3900
Transport, lorry larger than 16t, fleet average/RER U [tkm]	636060	166433
Transport, freight, rail/RER U [tkm]	786606	44896
Transport, barge/RER U [tkm]		6327
Waste to treatment		
Disposal, polyvinylchloride, 0.2% water [kg][3]		3500

[1] Ecoinvent process 'Wind power plant 800 kW, moving parts/RER/I U' (adapted)
[2] Ecoinvent process 'Wind power plant 2 MW, offshore, moving parts/OCE/I U' (adapted)
[3] to municipal incineration/CH U

Table E.4: Processes that contribute most to the ReCiPe scores of the three options.

Compared to total ReCiPe score [%]	Co-firing[1]	Wind farm[2]	Bioethanol[3]
Main process	36.30		
Hard coal, at mine	26.96	14.39	5.55
Softwood, standing, in forest	9.67		
Disposal, spoil from mining	5.79	2.80	1.99
Operation, transoceanic freight ship	4.60[4]	1.24	
Nylon 66, glass-filled		11.85	
Pig iron		7.80	
Hard coal, burned		5.79	8.20
Natural gas, at production		5.19	11.71
Iron ore, 46% Fe, at mine		4.26	
Crude oil, at production		4.05	15.13
Natural gas, burned		3.34	12.11
Sinter, iron		2.84	
Ferrochromium, high-carbon		2.35	
Clinker		2.30	
Operation, lorry		0.68	12.73
Fodder loading			3.16
Biogas, from biowaste			2.53
Mowing			2.00
Disposal, sulfidic tailings		1.96	
Lignite, at mine		1.86	1.28
Steel, electric		1.83	
Ferronickel		1.69	
Lignite, burned		1.32	1.90
Quicklime		1.14	
Hard coal coke		0.73	
Disposal, plastics		0.73	
Blast furnace gas			1.81
Total	83.32	80.13	80.09

[1] More detailed information can be found in Table E.5.

[2] More detailed information can be found in Table E.6.

[3] More detailed information can be found in Table E.7.

[4] 3.6% coal transport and 0.95% wood pellets transport

Table E.5: Processes that contribute most to the ReCiPe score of the Co-firing option.

Compared to total ReCiPe score	%
Main process	36.30
Softwood, standing, under bark, in forest/RER U	9.67
Hard coal, at mine/ZA U	7.97
Disposal, spoil from coal mining, in surface landfill/GLO U	5.79
Hard coal, at mine/RLA U	5.54
Hard coal, at mine/RNA U	5.27
Hard coal, at mine/AU U	4.85
Operation, transoceanic freight ship/OCE U	4.60[1]
Hard coal, at mine/EEU U	3.34
Total	83.32

[1] 3.6% coal transport and 0.95% wood pellets transport

Table E.6: Processes that contribute most to the ReCiPe score of the Wind farm option.

Compared to total ReCiPe score	%
Nylon 66, glass-filled, at plant/RER U	11.85
Pig iron, at plant/GLO U	7.80
Hard coal, at mine/EEU U	6.15
Iron ore, 46% Fe, at mine/GLO U	4.26
Hard coal, at mine/WEU U	4.13
Hard coal, burned in industrial furnace 1-10MW/RER U	4.11
Natural gas, burned in industrial furnace larger than 100kW/RER U	3.34
Sinter, iron, at plant/GLO U	2.84
Ferrochromium, high-carbon, 68% Cr, at plant/GLO U	2.35
Clinker, at plant/CH U	2.30
Natural gas, at production onshore/RU U	2.18
Disposal, sulfidic tailings, off-site/GLO U	1.96
Lignite, at mine/RER U	1.86
Steel, electric, un- and low-alloyed, at plant/RER U	1.83
Ferronickel, 25% Ni, at plant/GLO U	1.69
Hard coal, at mine/ZA U	1.56
Disposal, spoil from coal mining, in surface landfill/GLO U	1.45
Disposal, spoil from lignite mining, in surface landfill/GLO U	1.35
Lignite, burned in power plant/DE U	1.32
Operation, transoceanic freight ship/OCE U	1.24
Quicklime, in pieces, loose, at plant/CH U	1.14
Natural gas, at production onshore/DZ U	1.11
Crude oil, at production onshore/RME U	1.04
Hard coal, burned in power plant/DE U	0.97
Natural gas, at production offshore/NO U	0.95
Natural gas, at production onshore/NL U	0.94
Hard coal, at mine/AU U	0.94
Hard coal, at mine/RNA U	0.93
Crude oil, at production onshore/RAF U	0.86
Crude oil, at production offshore/NO U	0.81
Hard coal coke, at plant/RER U	0.73
Disposal, plastics, mixture, 15.3% water, to municipal incineration/CH U	0.73
Hard coal, burned in power plant/PL U	0.72
Operation, lorry larger than 16t, fleet average/RER U	0.68
Hard coal, at mine/RLA U	0.68
Crude oil, at production onshore/RU U	0.67
Crude oil, at production offshore/GB U	0.67
Total	80.13

Table E.7: Processes that contribute most to the ReCiPe score of the Bioethanol option plus the ReCiPe scores of the final power plant and the fermentation process.

Compared to total ReCiPe score	%
Operation, lorry 3.5-16t, fleet average/RER U	12.7
Natural gas, burned in power plant/NL U	10.1
Hard coal, burned in power plant/NL U	6.82
Natural gas, at production onshore/NL U	6.61
Crude oil, at production onshore/RAF U	3.95
Fodder loading, by self-loading trailer/CH U	3.16
Crude oil, at production onshore/RME U	3.13
Natural gas, at production offshore/NL U	2.78
Biogas, from biowaste, at storage/CH U	2.53
Natural gas, at production offshore/NO U	2.31
Crude oil, at production/NG U	2.30
Crude oil, at production offshore/NO U	2.16
Mowing, by rotary mower/CH U	2.00
Lignite, burned in power plant/DE U	1.90
Blast furnace gas, burned in power plant/RER U	1.81
Crude oil, at production onshore/RU U	1.80
Crude oil, at production offshore/GB U	1.79
Hard coal, at mine/ZA U	1.40
Hard coal, burned in power plant/DE U	1.37
Lignite, at mine/RER U	1.28
Hard coal, at mine/EEU U	1.18
Hard coal, at mine/WEU U	1.17
Natural gas, sweet, burned in production flare/MJ/GLO U	1.13
Disposal, spoil from coal mining, in surface landfill/GLO U	1.06
Disposal, spoil from lignite mining, in surface landfill/GLO U	0.93
Hard coal, at mine/RLA U	0.90
Hard coal, at mine/RNA U	0.90
Natural gas, burned in boiler[1]	0.87
Power plant[2]	0.00
Ethanol, 95% in H_2O from fermentation of verge grass/CH U[3]	-
Total	80.09

[1] Ecoinvent process 'Natural gas, burned in boiler condensing modulating larger than 100kW/RER U'

[2] Based on research conducted by De Vries (1999).

[3] adapted

Table E.8: Contributions of the investment costs and yearly costs and revenues to the PWR.

	Co-firing		Wind farm		Bioethanol	
	[10^6 €]	[%]	[10^6 €]	[%]	[10^6 €]	[%]
Investment costs	1	39	1	73	1	73
Yearly costs						
OpEx	0.34	13	0.36	27	0.36	27
Coal	0.94	37	-	-	-	-
Trees	0.27	11	-	-	-	-
subtotal	2.6	100	1.4	100	1.4	100
Revenues						
Electricity	3.0		0.76		0.78	
Subsidy			0.48			
Verge grass processing					1.8	
subtotal	3.0		1.2		2.5	
PWR	0.42		-0.12		1.17	

Table E.9: Contributions of the processes to the $\mathrm{IHDI}_{\mathrm{overall}}$ score of the Co-firing option.

%	Co-firing
Hard coal mining	37
Coal transport	12
Wood pellet production	22
Wood pellet transport	24
Power plant	4.9

Table E.10: The contribution of the processes of Table E.5 to the CExD and TCExL scores of the Co-firing option.

Compared to total score [%]	CExD	TCExL
Main process	-	32
Softwood, standing, under bark, in forest/RER U	8.8	0.82
Hard coal, at mine/ZA U	6.6	1.6
Disposal, spoil from coal mining, in surface landfill/GLO U	-	0.0
Hard coal, at mine/RLA U	4.8	1.1
Hard coal, at mine/RNA U	4.3	1.2
Hard coal, at mine/AU U	4.1	1.2
Operation, transoceanic freight ship/OCE U	-	2.0
Hard coal, at mine/EEU U	2.6	0.73
Total	31	40

Table E.11: The contribution of the processes of Table E.6 to the CExD and TCExL scores of the Wind farm option.

Compared to total score [%]	CExD	TCExL
Nylon 66, glass-filled, at plant RER U	0.46	0.56
Pig iron, at plant GLO U	0.010	1.10
Hard coal, at mine EEU U	0.38	0.16
Iron ore, 46% Fe, at mine GLO U	0.11	0.00
Hard coal, at mine WEU U	0.24	0.13
Hard coal, burned in industrial furnace 1-10 MW/RER U	-	0.23
Natural gas, burned in industrial furnace[1]	-	0.36
Sinter, iron, at plant/GLO U	0.00	0.08
Ferrochromium, high-carbon, 68% Cr, at plant/GLO U	0.00	0.01
Clinker, at plant/CH U	0.00	0.09
Natural gas, at production onshore/RU U	0.14	0.00
Disposal, sulfidic tailings, off-site/GLO U	-	0.00
Lignite, at mine/RER U	0.13	0.02
Steel, electric, un- and low-alloyed, at plant/RER U	-	0.08
Ferronickel, 25% Ni, at plant/GLO U	0.29	0.43
Hard coal, at mine/ZA U	0.10	0.04
Disposal, spoil from coal mining,[2]	-	0
Disposal, spoil from lignite mining,[2]	-	0
Lignite, burned in power plant/DE U	0.01	0.11
Operation, transoceanic freight ship/OCE U	-	0.06
Quicklime, in pieces, loose, at plant/CH U	-	0.05
Natural gas, at production onshore/DZ U	0.07	0.00
Crude oil, at production onshore/RME U	0.07	0.00
Hard coal, burned in power plant/DE U	0.01	0.09
Natural gas, at production offshore/NO U	0.06	0.00
Natural gas, at production onshore/NL U	0.06	0.00
Hard coal, at mine/AU U	0.06	0.03
Hard coal, at mine/RNA U	0.06	0.02
Crude oil, at production onshore/RAF U	0.06	0.00
Crude oil, at production offshore/NO U	0.06	0.00
Hard coal coke, at plant/RER U	-	0.07
Disposal, plastics, mixture, 15.3% water, [3]	-	0.06
Hard coal, burned in power plant/PL U	0.00	0.04
Operation, lorry more than 16t, fleet average/RER U	-	0.05
Hard coal, at mine/RLA U	0.05	0.02
Crude oil, at production onshore/RU U	0.05	0
Crude oil, at production offshore/GB U	0.05	0
Electricity, at wind power plant 7.5 MW onshore/RER U[4]	-	1.94
Electricity, at wind power plant 3.6 MW, offshore U[4]	-	1.69
Total	2.55	7.53

[1] Ecoinvent process 'Natural gas, burned in industrial furnace larger than 100kW/RER U'

[2] in surface landfill/GLO U

[3] to municipal incineration/CH U

[4] adapted

Table E.12: The contribution of the processes of Table E.7 to the CExD and TCExL scores of the Bioethanol option.

Compared to total score [%]	CExD	TCExL
Operation, lorry 3.5-16t, fleet average/RER U	-	2.78
Natural gas, burned in power plant/NL U	-	3.70
Hard coal, burned in power plant/NL U	0.19	2.04
Natural gas, at production onshore/NL U	1.79	0.39
Crude oil, at production onshore/RAF U	1.17	0.01
Fodder loading, by self-loading trailer/CH U	-	0.62
Crude oil, at production onshore/RME U	0.93	0.00
Natural gas, at production offshore/NL U	0.75	0.16
Biogas, from biowaste, at storage/CH U	-	0.05
Natural gas, at production offshore/NO U	0.63	0.13
Crude oil, at production/NG U	0.68	0.00
Crude oil, at production offshore/NO U	0.64	0.00
Mowing, by rotary mower/CH U	-	0.40
Lignite, burned in power plant/DE U	0.05	0.51
Blast furnace gas, burned in power plant/RER U	-	0.30
Crude oil, at production onshore/RU U	0.53	0.01
Crude oil, at production offshore/GB U	0.53	0.02
Hard coal, at mine/ZA U	0.39	0.11
Hard coal, burned in power plant/DE U	0.04	0.40
Lignite, at mine/RER U	0.39	0.01
Hard coal, at mine/EEU U	0.31	0.10
Hard coal, at mine/WEU U	0.29	0.12
Natural gas, sweet, burned in production flare/MJ/GLO U	0.13	0.11
Disposal, spoil from coal mining, in surface landfill/GLO U	-	0.00
Disposal, spoil from lignite mining, in surface landfill/GLO U	-	0.00
Hard coal, at mine/RLA U	0.27	0.06
Hard coal, at mine/RNA U	0.25	0.08
Natural gas, burned in boiler[1]	-	1.98
Power plant[2]	-	14.66
Ethanol, 95% in H_2O from fermentation of verge grass/CH U[3]	-	13.95
Total	9.95	42.71

[1] Ecoinvent process ‘Natural gas, burned in boiler condensing modulating larger than 100kW/RER U’

[2] Based on research conducted by De Vries (1999).

[3] adapted

Propositions belonging to the dissertation

Exergy and Sustainability

Insights into the Value of Exergy Analysis
in Sustainability Assessment of Technological Systems

by Lydia Stougie

1. The use of the TCExL method in technological design processes contributes to a sustainable society.
2. Understanding exergy is indispensable to sustainable environmental and energy policy.
3. A sustainable technological installation does not necessarily contribute to sustainability.
4. A life cycle is not a cycle until it is closed.
5. Money makes life more comfortable, but not more sustainable.
6. The amount of meat indicated in recipes with meat is too large.
7. The biggest challenge for B flat clarinettists is letting the B4 flat not be incongruous.
8. A major 7th interval is not an attractive beginning for a children's song.
9. Genealogical research is easier to start than to stop.
10. The public awareness of the number π benefits from the fact that the month of April has only 30 days.

These propositions are considered opposable and defendable and as such have been approved by the supervisor, prof.dr.ir. M.P.C. Weijnen.

Stellingen behorende bij het proefschrift

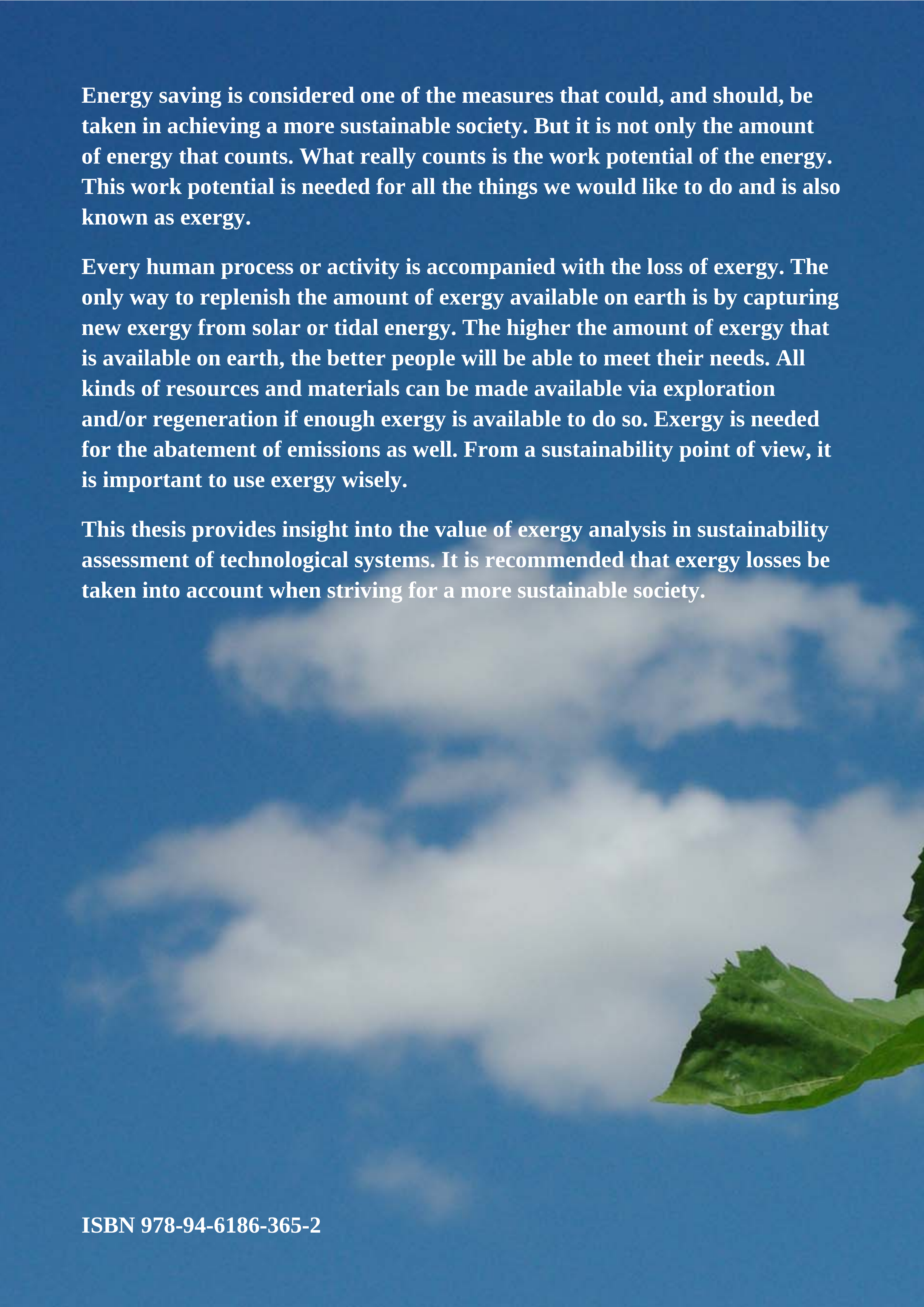
Exergy and Sustainability

Insights into the Value of Exergy Analysis in Sustainability Assessment of Technological Systems

van Lydia Stougie

1. Gebruik van de TCExL-methode in technologische ontwerpprocessen draagt bij aan een duurzame samenleving.
2. Begrip van exergie is onmisbaar voor duurzaam milieu- en energiebeleid.
3. Een duurzame technologische installatie draagt niet per definitie bij aan duurzaamheid.
4. Een levenscyclus is pas een cyclus als die gesloten is.
5. Geld maakt het leven gemakkelijker, maar niet duurzamer.
6. In recepten met vlees wordt teveel vlees voorgeschreven.
7. De grootste uitdaging voor bes-klarinettisten is om de eengestreepte bes niet uit de toon te laten vallen.
8. Een groot septieminterval is geen aantrekkelijk begin voor een kinderliedje.
9. Het is gemakkelijker om met stamboomonderzoek te beginnen dan om er mee te stoppen.
10. Voor de bekendheid van het getal π is het goed dat de maand april maar 30 dagen heeft.

Deze stellingen worden opponeerbaar en verdedigbaar geacht en zijn als zodanig goedgekeurd door de promotor, prof.dr.ir. M.P.C. Weijnen.



Energy saving is considered one of the measures that could, and should, be taken in achieving a more sustainable society. But it is not only the amount of energy that counts. What really counts is the work potential of the energy. This work potential is needed for all the things we would like to do and is also known as exergy.

Every human process or activity is accompanied with the loss of exergy. The only way to replenish the amount of exergy available on earth is by capturing new exergy from solar or tidal energy. The higher the amount of exergy that is available on earth, the better people will be able to meet their needs. All kinds of resources and materials can be made available via exploration and/or regeneration if enough exergy is available to do so. Exergy is needed for the abatement of emissions as well. From a sustainability point of view, it is important to use exergy wisely.

This thesis provides insight into the value of exergy analysis in sustainability assessment of technological systems. It is recommended that exergy losses be taken into account when striving for a more sustainable society.

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