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EXERGY ANALYSIS AND SUSTAINABILITY ASSESSMENT OF RENEWABLE ENERGY SYSTEMS BY MEANS OF THE TOTAL CUMULATIVE EXERGY LOSS METHOD

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"Progress is impossible without change,
and those who cannot change their minds
cannot change anything."
George Bernard Shaw

"People don't take trips, trips take people."
John Steinbeck

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This thesis is the result of work, people and experiences.

There are many people that had an important role in my life, especially in the past two years, and that, directly or indirectly, helped me to be where I am now.

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Abstract

Exergy analysis is meant to evaluate and localize irreversibilities that characterised every technological process and that are quantified by exergy losses, i.e. degradations of energy quality. The amount of exergy lost, is lost forever and cannot be transformed into useful work. For this reason it is important to avoid as much as possible that these losses occur, especially in trying to use energy in an efficient and sustainable way. Some researchers in this field pointed out that sustainability and exergy are somehow related, and that exergy analysis can be used in sustainability assessments of technological processes and systems. To understand better if the assessment through exergetic methods can take into account each aspect of sustainability, i.e. environmental, economic and social aspects, it is preferable to apply both exergetic and regular methods.

The case study of this thesis work was conducted at Delft University of Technology (Technische Universiteit Delft) and deals with the sustainability assessment of the electricity production from three different renewable power generation systems, located in the Netherlands: an offshore wind farm, a photovoltaic park and a biomass-fired power plant.

The environmental sustainability was assessed conducting an LCA, with the help of the software SimaPro and the Ecoinvent database. The economic sustainability was analysed calculating two economic indicators, the Net Present Value (NPV) and the Present Worth Ratio (PWR). The social sustainability was not subject of this study because of the lack of data. An exergetic method, newly developed by Stougie [1], the so-called Total Cumulative Exergy Loss method, was applied in parallel. This method allows to calculate the total exergy loss associated with a process, from a life cycle point of view.

The main goal of this research was to evaluate if the system preferred from the exergetic point of view, was also preferred from the environmental and economic point of view or, in other words, if the three methods chosen for the research would have led to an unanimous choice of the most sustainable system. Therefore, once the assessments were conducted separately, the results were compared and discussed to point out some conclusions about the relationship between exergy losses and sustainability. From the comparison it is deduced that the system preferred from the exergetic point of view is the offshore wind farm, which is also the less environmentally impactful, but also the one with the lower economic indicators, because less profitable.

Furthermore, it was pointed out that, while the relationship between exergy losses and environmental impact is predictable, the link with economic aspects is not easy to guess in advance and strongly depends from assumptions made before the assessment.

Since the TCExL method was developed recently, it is suggested to apply it in other research to confirm its applicability in sustainability assessment, evaluating also social aspects, neglected in this case study, in order to take into account all the three dimensions of sustainability.

Sommario

L'analisi exergetica ha lo scopo di valutare e localizzare le irreversibilità che caratterizzano ogni processo tecnologico e che sono quantificate da perdite exergetiche, ovvero degradazioni della qualità dell'energia. La quantità di exergia persa durante un processo è perduta per sempre e non può più essere trasformata in lavoro utile. Per questo motivo è molto importante evitare il più possibile che queste perdite si verifichino, specialmente quando si cerca di usare l'energia in modo efficiente e sostenibile. Alcuni ricercatori in questo settore hanno osservato che sostenibilità ed exergia sono in qualche modo connesse tra loro, e che quindi l'analisi exergetica può essere applicata nella valutazione della sostenibilità di processi e sistemi tecnologici. Per comprendere meglio se la valutazione attraverso metodi exergetici consente di tenere in considerazione ogni aspetto della sostenibilità, ovvero quello ambientale, economico e sociale, è preferibile usare insieme metodi exergetici e tradizionali.

Il caso studio di questo lavoro di tesi è stato condotto presso l'Università Tecnica di Delft (Technische Universiteit Delft) e riguarda la valutazione della sostenibilità della produzione di energia elettrica da tre diversi sistemi di generazione che utilizzano fonti rinnovabili e che si trovano nei Paesi Bassi: un parco eolico offshore, una parco fotovoltaico e una centrale a biomassa.

La sostenibilità ambientale è stata valutata tramite un'analisi LCA, con l'aiuto del software SimaPro e del database Ecoinvent. La sostenibilità economica è stata analizzata calcolando due indicatori economici, il Net Present Value (NPV) e il Present Worth Ratio (PWR). La sostenibilità sociale non è stata oggetto di studio a causa della mancanza di dati. Parallelamente, è stato utilizzato un metodo exergetico sviluppato recentemente da Stougie [1], chiamato Total Cumulative Exergy Loss, che consente di calcolare la perdita exergetica complessiva associata ad un processo, considerando l'intero ciclo di vita.

Lo scopo principale di questa ricerca era quello di valutare se il sistema preferito dal punto di vista exergetico fosse anche quello preferito dal punto di vista ambientale ed economico, ovvero comprendere se i tre metodi usati avrebbero portato ad una scelta unanime del sistema più sostenibile. Per questo motivo, una volta condotte le analisi separatamente, i risultati sono stati paragonati e discussi per trarre alcune conclusioni riguardo il rapporto tra perdite exergetiche e sostenibilità. Dal confronto dei risultati si evince che il sistema preferito dal punto di vista exergetico è il parco eolico, che risulta essere anche il sistema con il minor impatto ambientale, ma quello che presenta un inferiore valore degli indicatori economici, perché meno profittevole.

Inoltre si è potuto dedurre che, mentre la relazione tra perdite exergetiche e impatto ambientale è prevedibile, il rapporto con aspetti economici non è facile da supporre in anticipo e dipende fortemente dalle assunzioni fatte prima dell'analisi.

Poichè il metodo Total Cumulative Exergy Loss è stato sviluppato recentemente, si consiglia di applicarlo in altre ricerche per confermarne ulteriormente la validità, conducendo anche un'analisi della sostenibilià sociale, omessa in questa ricerca, in modo tale da poter considerare tutti e tre le dimensioni della sostenibilità.

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Introduction

I want to start with a 'not-so-scientific' definition of exergy that caught my attention: "Exergy is the elixir of life. Exergy is that portion of energy available to do work. Elixir is defined as a substance held capable of prolonging life indefinitely, which implies sustainability of life" [2]. This definition reassumes in a few words the main subjects of this thesis work: exergy and sustainability.

After centuries of economic development at the expense of the environment, our society is finally getting aware of the impact that human activities have on the planet. Global warming, extinction of species and habitats, pollution and natural resources depletion are only few of the issues to take care of, in order to improve life quality on the long term. In trying to find a solution to these problems, decision makers started promoting the so-called 'sustainable development' as the basis of an economic growth that put more attention on environment and society. One of the consequences is that now, more often than in the past, productive processes are designed to be more sustainable and less environmentally impactful, with the help of tools that make the assessment of their sustainability easier. Several methods based on a classical approach are commonly applied for the sustainability assessment of a process and are useful to understand if it is more or less sustainable from a certain point of view, i.e. environmental, economic and social.

Exergy analysis, a thermodynamic-based method, is used as well in the assessment of technological processes, usually with the goal to localize and reduce inefficiencies due to exergy losses that occur in each stage of the process itself. Exergy is strictly related to energy, since it enables to quantify the quality of energy. We know that every real process is accompanied with losses of energy quality, i.e. exergy losses, which are permanent: when exergy is lost, it is lost forever and it cannot be converted anymore into useful work. Replenishing the lost amount of exergy is only possible by capturing new exergy from solar and/or tidal energy, therefore it is important to avoid these losses as much as possible when trying to use energy in a more efficient way. Researchers have pointed out that exergy and sustainability are somehow related, even if the link is not completely clear, especially with regard to social and economic aspects.

Anyway, some important questions do not have a definite answer yet:

1. Is it is possible to use exergy analysis in sustainability assessment with the goal to obtain information about each aspect of sustainability?
2. Can we, comparing the results of the exergetic assessments of different processes, understand which one is preferred over the others, in a consistent way with the results obtained from regular sustainability assessment methods?
3. Is the process preferred from the exergetic point of view also the best choice from the environmental, economic and social point of view?

This research is conducted with the aim to help answering the aforementioned questions about the relationship between exergy and sustainability and to provide a contribution in the field of exergy analysis applied in sustainability assessment.

Among the processes that have an important environmental impact, electricity generation has a big role in the total greenhouse gas emissions, since it is at the basis of every other productive process. The first step towards a more sustainable development is the replacement of coal, oil and natural gas with alternative renewable energy sources, nowadays strongly supported by government with subsidies and tax incentives. The second step in the same direction, is to choose those technologies which have a lower impact on environment and society and that result more convenient from the economic point of view. Therefore it was decided to assess and compare the sustainability of three power generation systems that make use of renewable energy sources, with both regular and exergetic methods, with the aim to understand which system is preferred from each point of view. The systems are modeled with the help of the Ecoinvent database and their environmental impact is assessed through a LCA conducted with the software SimaPro. Two economic indicators, i.e the Net Present Value and the Present Worth Ratio, are calculated to analyse the systems from the economic point of view. A limit of this research is that it does not focus on the calculation of social indicators to evaluate the social sustainability of the systems, because of the lack of data. Furthermore, a newly developed exergetic method, the Total Cumulative Exergy Loss method, is applied to calculate exergy losses [1].

Chapter 1 introduces the concept of exergy and describes how to calculate exergy values of heat, work and flows of matter and deals with the advantages of exergy analysis over energy analysis and in which fields it can be applied to assess the performance of a system. Exergy analysis can be considered a multidisciplinary tool since its applications can be found for example in engineering, economic, environmental and societal fields.

The concept of sustainable development and sustainability assessment methods are introduced in Chapter 2. To get a complete assessment of the sustainability of a process, three aspects should always be considered, i.e. environmental, economic and social aspects. There are several methods used to assess the ‘three pillars’ of sustainability separately, and a transversal approach which integrates them is currently under development. Anyway regular methods are not always objective and present other shortcomings in assessing the sustainability of technological systems, while exergy analysis can be more helpful when applied in this field. Chapter 2 deals also with what is known about the relationship between exergy and sustainability, and describes some of the exergetic methods that can be found in literature.

Since all exergetic methods do not consider all the aspects that should be taken into account in sustainability assessment methods, a new method was developed by Stougie, i.e the Total Cumulative Exergy Loss method, which is explained in detail in Chapter 3. The TCExL includes exergy losses caused by the system and its whole supply chain, considering the abatement of emissions and land occupation as well, usually not taken into account by ecergetic methods. The TCExL method is used in this research to calculate exergy losses because considered and improvement compared to the other exergetic methods used in sustainability assessment.

Chapter 4 introduces the case study of this research, focusing on methods applied for the sustainability assessment of the systems. The three systems chosen for the case study are currently under construction in the Netherlands, and are an offshore wind farm, a photovoltaic park and a biomass power plant. Their sustainability is assessed considering the whole supply chain of electricity generation from a life cycle point of view.

Information about the offshore wind farm, the photovoltaic park and the biomass power plant and data and assumptions needed to assess their sustainability are provided in chapters 5, 6 and 7, respectively. An overview of data used in the environmental and economic assessments is given before presenting the results obtained for each system.

The results of each assessment are compared in Chapter 8, before considering each aspect of sustainability separately and then comparing the results all together to point out how the choice of the system preferred from the exergetic point of view influences the other components of sustainability.

Chapter 1

The concept of exergy and applications of exergy analysis

In this chapter, after a brief introduction to the concept of exergy in Section 1.1, followed by an explanation of the equations used to calculate exergy values for mass flows, heat and work in Section 1.2. Section 1.3 introduces exergy analysis and its applications, focusing on the calculation of exergy losses and the presentation of results.

1.1 Introduction to exergy

The term exergy was coined by Zoran Rant in 1956 [3], but the concept was put forward by Gibbs , who introduced the 'available energy', defined as *"the greatest amount of mechanical work which can be obtained from a given quantity of a certain substance in a given initial state, without increasing its total volume or allowing heat to pass to or form external bodies, except such as at the close of the processes are left in their initial condition"* [4] .

This definition does not depart much from the currently used definition of exergy: the exergy of a system is the maximum theoretical useful work obtained if the system is brought into thermodynamic equilibrium with a reference environment through processes in which it interacts only with the environment.

The concept of exergy is strictly connected to energy and thermodynamics. When talking about thermodynamics, we should always keep in mind that energy is not only characterised by its amount but also by its quality and that it can be found in several forms (e.g. kinetic, potential, thermal, electrical, etc). The same amount of different forms of energy can be characterised by a different quality. As stated by the conservation of energy principle, energy cannot be created or destroyed, but can only be transformed from one form to another. However, even if energy is conserved, not all that energy is always available to do useful work, as stated in the second law of thermodynamic: work can always be converted completely into heat, but heat cannot always be converted completely into work. The concept of exergy can be introduced in this context: exergy is the energy theoretically available to be transformed into work, also indicated as work potential or energy quality. In ideal processes exergy is preserved but every real process implies a degradation of energy quality, accompanied with entropy generation. Both the concepts of entropy and exergy are important, because entropy enables quantifying losses in quality but it is not a direct measure of energy quality [5], unlike exergy that makes possible to measure the energy quality itself.

1.2 Calculation of exergy values

Exergy values of mass flows and energy flows (heat, work, electricity) are calculated as shown in this section. As already mentioned the exergy of a system is the maximum useful work that can be obtained during an ideal process that brings the system in total equilibrium with the reference environment, therefore to be able to calculate exergy values, it is necessary to define the reference environment first. Several models of the reference environment have been developed by researchers, each one defined by its chemical composition, hence by different values of reference exergy which lead to different calculated exergy values of mass and energy flows.

One of the most used reference environment is the one developed by Szargut et al. [6], consisting of substances presented in the natural environment (atmosphere, oceans and earth) that are in perfect equilibrium with each other at T_0=298.15 K (25°C) and p_0=1 atm (1.013 bar).

1.2.1 Exergy value of work

Exergy is defined as the maximum work potential, therefore the exergy content of a work flow equals its energy content, as shown in Equation 1.1.

$$Ex_{work} = W \tag{1.1}$$

Since that electrical energy can be converted completely into work by applying a reversible process, also the exergy value of electricity is equal to its energy value.

$$Ex_{el} = E_{el} \tag{1.2}$$

1.2.2 Exergy value of heat

As stated by the second law of thermodynamics, the supplied heat in a heat engine cannot be completely converted into work. The produced work is maximum when considering a reversible process and can be calculated considering the Carnot efficiency.

The exergy value of heat flows with temperature $T > T_0$ is presented in Equation 1.3.

$$Ex_{heat} = Q \cdot \left(1 - \frac{T_0}{T}\right) \tag{1.3}$$

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 heat flows with temperature $T < T_0$ is presented in Equation 1.4 [7]; the energy value of cold is assumed to be negative because of thermodynamic sign conventions.

$$Ex_{cold} = Q_c \cdot \left(1 - \frac{T_0}{T}\right) \tag{1.4}$$

with:

Ex_{cold} = exergy value of cold [J]

Q_c = energy value of cold [J]

T_0= temperature of the reference environment [K]

T= temperature of the cold [K]

1.2.3 Exergy value of mass flows

Excluding nuclear, magnetic, electrical and surface tension effects, the exergy value of a mass flow consists of four components: kinetic, potential, physical and chemical. Kinetic and potential energy can be converted to work entirely, therefore their exergy values equal their energy values. For many thermodynamic processes the variation of kinetic and potential exergy values are usually negligible compared to physical and chemical exergy values, and for this reason they are included in the calculation of the exergy value of mass flows only in specific cases.

The specific values of kinetic and potential exergy, in J/Kg, are shown in Equation 1.5.

$$ex_{mass,kin} = \frac{v^2}{2} \qquad\qquad ex_{mass,pot} = gz \tag{1.5}$$

Neglecting these two components, the exergy value of mass flows can be calculated as presented in Equation 1.6.

$$Ex_{mass,tot} = Ex_{mass,phys} + Ex_{mass,chem} \tag{1.6}$$

Physical exergy value

The physical exergy value of a mass flow is the maximum useful work obtained passing from a generic state (T, p) to the state of the reference environment (T_0, p_0) through physical processes [8]. The physical exergy value of a mass flow can be obtained combining the first and the second law of thermodynamics. Equation 1.7 presents the physical exergy value of a mass flow.

$$Ex_{mass,phys} = m[(H - H_0) - T_0(S - S_0)] \tag{1.7}$$

with:
$Ex_{mass,phys}$ = 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 (T_0, p_0) [J/kg]
S = specific entropy of the mass flow [J/(kgK)]
S_0 = specific entropy of the mass flow at (T_0, p_0) [J/kgK]

Chemical exergy value

The chemical exergy value of a mass flow results from the deviation of chemical composition of the flow itself from the composition of the common components of the reference environment.

This means that the chemical exergy value should be taken into account in every process that involves a change of composition of the flow, such as during a combustion reaction. The chemical exergy value of a mass flow is calculated from the chemical exergy values of its components, considering also the mixing of the components to the final composition of the mass flow that is accompanied with exergy losses. Equation 1.8 shows the calculation of the chemical exergy value of component i from the standard chemical exergy values of the elements, that were tabulated by Szargut et al. [6].

$$ex^0{}_{chem,i} = g_{f,i} + \sum_e n_e ex^0{}_{chem,e} \tag{1.8}$$

with:
$ex^0{}_{chem,i}$= standard molar chemical exergy of component i [J/mole]

$g_{f,i}$= 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

$ex^0{}_{chem,e}$= standard molar chemical exergy of element e [J/mole]

The exergy loss caused by the mixing of different components is shown, for homogeneous mixture, in Eq. 1.9. For ideal mixing the activity coefficient equals one.

$$ex_{mix} = RT_0 \sum_i x_i ln(\gamma_i x_i) \tag{1.9}$$

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_i =mole fraction of component i

γ_i= activity coefficient of component i

Equation 1.10 presents the chemical exergy value of a mass flow.

$$Ex_{mass,chem} = \sum_{i=1}^{i=n} n_i ex^0{}_{chem,i} + n_{tot} ex_{mix} \tag{1.10}$$

with:

$Ex_{mass,chem}$ = chemical exergy of a mass flow [J/s]

n_i = mole flow of component i [mole/s]

$ex^0{}_{chem,i}$= 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]

1.3 Exergy analysis and fields of application

As mentioned before, energy is usually characterised only by its amount but it has also a quality and every real process is accompanied with a degradation of energy quality, i.e. an exergy loss. When exergy is lost, it cannot be used anymore and the only way to replenish this amount is to capture new exergy from solar energy. Since every exergy loss represents a waste of energy that cannot be used in useful processes, it is is very important to take into account this loss of quality, but this is not possible when conducting an energy analysis, because it does not consider the quality of different types of energy. Even though energy analysis is conventionally used to assess energetic systems, when evaluating the rational use of energy it is always preferable to conduct an exergy analysis, because it presents several advantages compared to energy analysis and it allows to improve efficiency, environmental and economic performance of a system [9].

First of all, exergy analysis is used to identify type, location and magnitude of thermodynamic inefficiencies in a system and for this reason it can be used in optimization procedures with the aim to reduce exergy losses and make the system more efficient. Furthermore exergetic efficiencies can also be used to compare different energetic systems (e.g. direct and inverse thermodynamic cycles), unlike energetic parameters that must be related to the same type of technology to make a comparison. Another important aspect is that exergy analysis can be combined with economic principles, in the same way as energy analysis, obtaining the so called exergoeconomic analysis, used for the best allocation of economic resources in order to optimize systems, and also to analyse the economic feasibility of a system to be built.

Section 1.3.1 deals with the presentation of the results of an exergy analysis, focusing on the calculation of exergy efficiencies. After that, internal and external exergy loss are presented, in sections 1.3.2 and 1.3.3, resepctively, and a brief description of fields of application of exergy analysis is illustrated in Section 1.3.4.

1.3.1 Exergy efficiencies

When conducting an exergy analysis, calculation of exergy values, balances and efficiencies are applied, similarly to what is done during an energy analysis. This implies the calculation of the total loss of energy quality, or total exergy loss, given by the sum of two components: the internal exergy loss and the external exergy loss. The calculation of exergy losses or exergy efficiencies can be seen as the main goal of exergy analysis, in order to improve the performances of a system. Woudstra [10] dealt with several ways to present the results of exergy analysis, i.e. graphical representation (Grassmann diagrams or value diagrams) and numerical parameters (universal exergy efficiency and functional exergy efficiency), briefly described below.

The universal efficiency can be calculated starting from the exergy balance for steady-flow systems, shown in Equation 1.11.

$$\sum Ex_{in} = \sum Ex_{out} + \sum Ex_{loss} \tag{1.11}$$

with:

$\sum Ex_{in}$= exergy of energy and mass flows entering the system
$\sum Ex_{out}$= exergy of energy and mass flows leaving the system
$\sum Ex_{loss}$= total exergy loss

The universal exergy efficiency is presented in Equation 1.12.

$$\eta_{ex,u} = \frac{\sum Ex_{out}}{\sum Ex_{in}} = 1 - \frac{\sum Ex_{loss}}{\sum Ex_{in}} \tag{1.12}$$

The problem of using this efficiency is that its value can be insensitive to changes, for example when only part of the flows undergoes a change. The exergy loss is then small if compared to the exergy of the ingoing energy flows, which contain large 'ballast flows', i.e. flows that are not directly involved in the change itself. To avoid this problem, it is prefable to use the functional exergy efficiency, shown in Equation 1.13, and defined as the ratio of the exergy of that part of the outgoing energy flows that can be considered as the product of the system and the exergy of that part of the ingoing energy flows that can be considered necessary for making the product of the system.

$$\eta_{ex,f} = \frac{\sum Ex_{product}}{\sum Ex_{source}} \tag{1.13}$$

with:

$\sum Ex_{source}$=$\sum Ex_{in}$-$\sum Ex_{ballast}$

$\sum Ex_{product}$= $\sum Ex_{out}$-$\sum Ex_{ballast}$

Since exergy of ingoing and outgoing ballast flows is the same, the difference between exergy values of 'source' and 'product' must equal exergy losses:

$$\sum Ex_{source} = \sum Ex_{product} + \sum Ex_{loss} \tag{1.14}$$

The functional efficiency is preferred over the universal efficiency, but strictly depends on the definition of the products and the inputs necessary for making them, that need to be specified for each system, sometimes difficult or completely inconceivable to do [10].

1.3.2 Internal exergy loss

During a thermodynamic process, a system goes from an initial state to a final state and one or more of its thermodynamic properties change. Ideally, a process can be reversed completely and the system can be restored to its initial state without a trace that shows that it went through a thermodynamic change. To have a reversible process, all the steps from the initial to final state should be reversible with and this happens when they are due to infinitesimal gradient. But real processes are not reversible and occur due a finite gradient that subsists between two states of the system (e.g. heat transfer between two bodies of a different temperature).

The internal exergy loss is due to irreversibilities that accompanied real processes and it can be calculated as the difference between the sum of the exergy value of the ingoing flows and the sum of the exergy value of the outgoing flows. The larger the gradient between the two states , the larger the exergy loss.

The internal exergy loss is proportional to the total increase of entropy caused by the process and can be calculated also as shown in Eq. 1.15, without calculating the exergy values of ingoing and outgoing flows.

$$Ex_{loss,int} = T_0 \Delta S_{tot} \tag{1.15}$$

with:
$Ex_{loss,int}$= internal exergy loss [J]
T_0= temperature of the reference environment [K]
ΔS_{tot}= total entropy change [J/K]

1.3.3 External exergy loss

The external exergy loss results from the discharge of waste products of processes to the environment, because the amount of exergy of the waste flows is destroyed in the environment and is lost forever. Waste flows are basicly mass or energy flows, so the external exergy loss can be calculated as the sum of the exergy values of waste flows as shown in Section 1.2.

1.3.4 A brief overview of the applications of exergy analysis

Since exergy analysis is mainly used to assess the efficiency of processes and systems, it can be seen as a multidisciplinary tool applied in several fields, such as engineering, economics, management, physics and biology. As stated by Rosen [9], *"exergy analysis should prove useful to engineers, scientists, and decision makers"*. A description of exergy analysis application is provided by Sciubba et al. [11] and this section gives a brief overview of some of them.

Exergy analysis is commonly applied in engineering applications to analyse thermo-mechanical, chemical or manufacturing processes; it can be used to optimize all types of processes and systems: power cycles and components (e.g. steam power cycles, gas turbine cycles, renewable energy cycles, combined and cogenerating cycle), heat exchangers and heat networking, cryogenic systems, chemical processes, distillation and desalination processes and also agricultural and industrial systems.

Exergy can be also used in combination with economic analysis: the basic idea is to assign a monetary cost to the exergy content of energy carriers and write a monetary balance that can be used for example to analyse the feasibility of a system during its design phase or improvements to be made in an existing system. The difference with a normal thermoeconomic analysis is that costs are associated to exergy flows, instead of materials and energy streams [12]. The name of this discipline is exergoeconomics and it is often used to compare alternatives and in decision-making procedures concerning funding allocation. Just to give an example, applications of exergoeconomics can be found in the assessment of combined heat and power production [13] and steam power plants [14].

Environmental applications of exergy analysis are used to assess the environmental impact of technologies, considering the exergy content of raw materials, resources and emissions as well. Even if the relationship between exergy discharge into the natural environment and pollution is only qualitative, such as for the relationship between exergy losses and depletion of raw materials and natural resources, nowadays exergy analysis is used by industries and governments with the aim to improve energy sustainability. Exergy is not a direct measure of environmental impact, but through the exergy balance of all the life cycle of a product it is possible to understand how many primary resources had been consumed. Some researchers talk about the issue of design 'exergyconscious' production cycles to get a higher level of sustainability [11]. Chapter 2 deals with the relationship between exergy analysis and sustainability in more detail.

Another application of exergy analysis, in some way related to sustainability and decision-making, is the exergetic assessment of societal systems, e.g. regions or countries, with the aim to evaluate their performance. Many papers can be found in literature, concerning application of exergy analysis in this field. The performances of many countries have been assessed, for example of Norway [15], China [16] or United Kingdom [17]. Ertesvåg [18] compares different societies affirming that one of the reasons of conducting this kind of analysis is also to create an awareness on the notion of energy quality and degradation of energy.

Chapter 2

Sustainable development and sustainability assessment methods

This chapter starts with a brief introduction to the concept of sustainable development, after which regular sustainability assessment methods related to environmental, economic and social sustainability are explained in detail. Pointing out the limits of these methods, mainly related to the fact that they do not comply with all the requirements that every sustainability assessment method should meet, the concept of exergy analysis in assessing sustainability of processes is introduced.

2.1 What is sustainable development?

Sustainable development has been defined in many different ways, but the most used and accepted definition goes back to 1987, when the World Commission on Environment and Development published "Our common future" [19], also known as the Brundtland Report. In this document, sustainable development is defined as *"development that meet the needs of the present without compromising the ability of future generation to meet their own needs"*. This definition departs from the classical concept of development, only related to economic growth, and promotes the idea that different aspects must be taken into account: social, environmental and economic progress are strictly connected if we want to achieve sustainable development, as shown in Figure 2.1 .

We cannot solely focus on the economic growth of the society if we want a long-term and enduring development that aids to improve quality of life, because *"money makes life more comfortable, but not more sustainable"* [1].

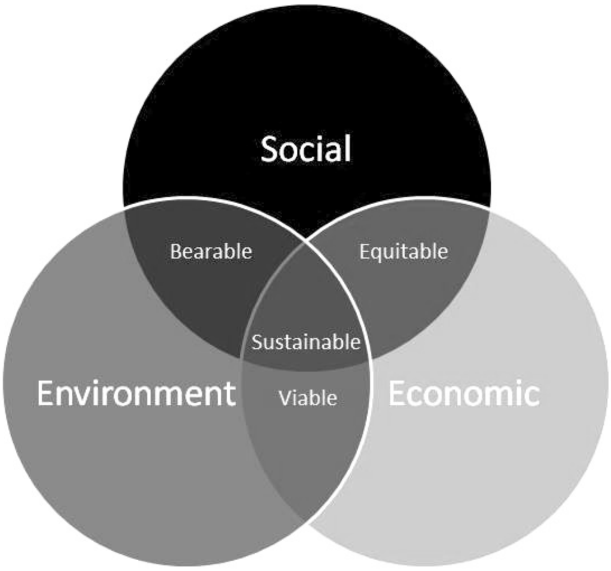

Figure 2.1: The three pillars of sustainability.

Talking about sustainability and sustainable development can be seen only as a temporary trend. Nevertheless it is undeniable that the last decades were characterized by a raising awareness of environmental problems and by an increasing number of consumers that want to understand what is behind the products they buy. People are concerned about global warming, ozone depletion, air and water pollution and are aware that the decisions made today will shape the future of our planet. But what is the real problem of our unsustainable society? It is a fact that present industrial management is based on overexploitation of fossil fuel, resource depletion and environmental destruction. This is the reason why *"industry could be seen partly as the problem as well as the solution for a sustainable development"* [20]. Every technological process and system should be chosen wisely, preferring that one that is more sustainable from the environmental, economic and social point of view. Companies should follow the 'Triple Bottom Line' (TBL) way of doing business, in other words they should think about the impact their actions have under an environmental, economic and social point of view. This concept was introduced and explained for the first time by John Elkington in his book "Cannibal with Forks: The Triple Bottom Line of 21st Century Business" [21] and is a way of encouraging an integrated approach of life cycle sustainability assessment, taking into account the three pillars of the environment, economy and society when evaluating the impact of a company on both a local and a global scale. The TBL can be seen as a different way to express the 3P approach, that involves People, Planet and Profit. While people and planet are related to the collective interest, profit is a more self-interest concept, therefore it should be better to refer to 'People, Planet and Prosperity', as introduced during the World Summit on Sustainable Development in Johannesburg (2002).

In conclusion, even if there are many definitions and interpretations of sustainability, they are all related to environmental, economic and social aspects, that have to be properly assessed and balanced before the development of new products or with the aim to improve an existing product. For this reason reliable and suitable instruments are needed and have been developed by researchers in this field, such as environmental Life Cycle Assessment, Life Cycle Costing, Social Life Cycle Assessment, which will be introduced in Section 2.2..

2.2 Regular sustainability assessment methods

Starting from the established idea that sustainability has an environmental, an economic and a social dimension, the focus shifts to which methods can be used when assessing the sustainability of technological processes or systems. The first aspect to point out is that every sustainability assessment should always be conducted with the so-called 'cradle to cradle' approach, taking into account every phase of the life cycle of the process/system: construction, operational phase and decommissioning of installations, equipment and infrastructure but also the supply chains of raw materials and energy carriers and disposal, abatement of emissions and waste flows. Several methods have been developed and can be found in literature, each one with its own characteristics and usually related to one of the aforementioned aspects. Nevertheless, the fact that an integration or balancing between the three pillars of sustainability is needed, has led to a preliminary development of a Life Cycle Sustainability Assessment by Kloepffer [22]. In his work he introduced two possible options to include the economic and social dimensions in sustainability assessment. The first option formalizes the LCSA in the conceptual formula of Equation 2.1.

$$LCSA = LCA + LCC + SLCA \tag{2.1}$$

The LCSA involves the use of three instruments commonly preferred when assessing the sustainability of a process from an environmental, economic and social point of view, i.e. the internationally standardized environmental Life Cycle Assessment (LCA), the (environmental) Life Cycle Costing (LCC) and the Social Life Cycle Assessment (SLCA), respectively. These methods are explained in detail in sections 2.2.1, 2.2.2 and 2.2.3. When conducting a LCSA, the most important requirement is that the system boundaries and the functional unit of each assessment are identical [22]. The LCSA framework is still under development because researchers have found several difficulties in weighting the three 'pillars' of sustainability, that should always be avoided in this kind of research because leads to loss of objectivity and transparency in results. Another problem is that the SLCA is not fully developed yet, therefore it is not always easy to obtain data related to the social aspect, that anyway are qualitative or semi-quantitative [22]. Furthermore, since that only guidelines are available for LCC and SLCA, while LCA has already been standardized, the first step towards the final LCSA development would be to standardize them as well.

The second option proposed by Kloepffer [22] is to develop a new LCA that includes LCC and SLCA as additional impact categories in the Impact Assessment phase. The advantage of this option is that there is only one Life Cycle Inventory to be defined during the assessment, but on the other hand standard guidelines in how to perform LCC and SLCA are needed also in this case.

2.2.1 Environmental sustainability

Life Cycle Assessment represents the state of the art in applications related to environmental sustainability. According to ISO 14040, environmental LCA is defined as the *"compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle"*. An LCA is carried out in four main phases, shown in Figure 2.2 and briefly explained below:

- **Goal and scope definition**: in this first phase the most important choices of the study are described in detail such as the functional unit, the system boundaries and any assumptions or limitations. The functional unit defines what is being studied and provides a reference to which the inputs and output can be related so that comparison of different systems can be done.
- **Inventory analysis**: the results of this phase are all the quantified inputs and outputs from and to the environment associated with the functional unit.
- **Impact assessment**: in this phase the results of the inventory analysis are used to calculate their contribution to selected impact categories.
- **Interpretation**: in this phase results are analysed and opportunities to reduce energy and material input and environmental impact of each phase of the process are evaluated.

The LCA method has been implemented in several software tools but nowadays SimaPro is one of the most commonly used, also because it offers a large number of information from several databases, such as the Ecoinvent database. One of the methods that can be used to present the Impact assessment phase's results as a number is the Eco-Indicator 99 method [23]. This number results from the weighting of three damage categories: human health, ecosystem quality and resources. A more recent method is the ReCiPe 2008 [24], which allows presenting the environmental impact with 18 midpoint indicators (i.e. 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)

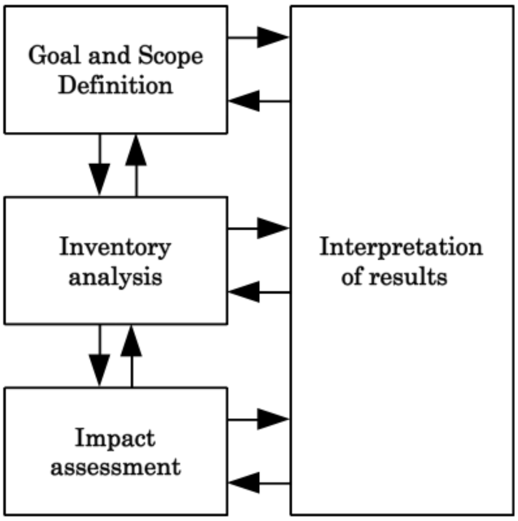

Figure 2.2: Phases of Life Cycle Assessment.

or with 3 endpoint indicators (damage to human health, damage to ecosystem diversity and damage to resources availability). Each method contains factors according to three cultural perspectives that represent a set of choices, such as time or expectation that proper management or future technology development can avoid future damages:

- **Individualist (I)**: short-term model, based on the optimistic idea that technology can avoid many problems in future;
- **Hierarchist (H)**: mid-term model, based on common policy principles, often used as the default model;
- **Egalitarian (E)**: long-term model, based on precautionary principle thinking;

The SimaPro software tool can also combine the three endpoint indicators into one single final score. The user can choose between different normalisation/weighting sets when calculating the overall endpoint indicator: normalisation values of Europe or the World and the weighing set belonging to one of the available perspectives (I/H/E) or the average weighting set (A).

When calculating the Endpoint indicators, the default method and normalisation/weighting set are ‘ReCiPe Endpoint(H) V1.12’ and ‘Europe ReCiPe H’. According to this weighting set the weighting factors are 40, 40 and 20 % for ‘damage to ecosystem diversity’, ‘damage to human health’ and ‘damage to resources availability’, respectively. After weighting each category, the overall score is obtained by the summation of the results and it is expressed in Points (Pt), proportional to the environmental impact.

Figure 2.3 shows how the overall indicator is obtained, starting from the impact categories which are summed in three different groups to calculate the Endpoint indicators, subsequently normalized and weighted.

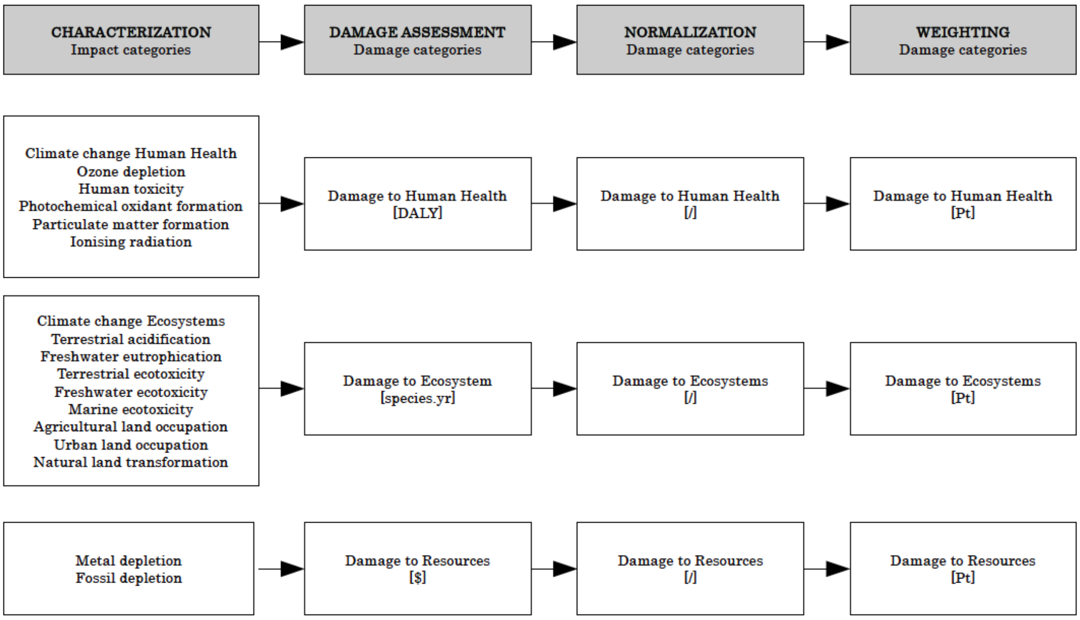

Figure 2.3: Impact categories and damage categories obtained with a LCA [24].

A brief explanation of the concepts used to assess damages to human health, ecosystem diversity and resources is presented below, referring to a report of the Dutch National Institute for Public Health and Environment (RIVM) [24].

Damage to human health

The damage to human health is assessed using the concept of ‘disability-adjusted life years’ (DALY), carried out in the work of Murray and Lopez for the World Health Organisation [25]. This index takes into account damages as diseases, premature death and disabilities due to causes related to environmental issues (e.g. climate change, ozone depletion, ionising radiation). If one year of life lost has the same importance for all ages and without considering any discount for future damages, DALY is the summation of years of life lost (YLL) and years of life disabled (YLD):

$$DALY = YLL + YLD \tag{2.2}$$

where YLD is obtained multiplying w, a severity factor between 0 (complete health) and 1 (dead), and D, the duration of the disease.

Damage to ecosystem diversity

The assessment of damage to ecosystems is in general more complex, since ecosystems are heterogeneous and not easy to monitor [24]. In the ReCiPe 2008 model, the assumption that the diversity of species represents the quality of ecosystems is made. Therefore the damage category to ecosystem diversity is evaluated through the loss of species during a certain time and in a certain area, considering both terrestrial, freshwater and marine water ecosystems. The endpoint characterization factor for ecosystem damage can be calculated using Equation 2.3 [24]:

$$CF_{ED} = PDF_{terr} \cdot SD_{terr} + PDF_{fw} \cdot SD_{fw} + PDF_{mw} \cdot SD_{mw} \tag{2.3}$$

where *PDF* is the potentially disappeared fraction of species integrated over area (for terrestrial ecosystems) or volume (for aquatic ecosystems) and time and *SD* is the species density factor for species.

Damage to resource availability

The last important issue to evaluate is the depletion of resources, that for many research groups is the only issues that should be monitored [24]. The ReCiPe 2008 model evaluates how the use of mineral and fossil resources cause marginal increases in costs of extraction of future resources. The generic formula used to calculate the endpoint indicator of damage to resources is shown in Equation 2.4:

$$D = \frac{\Delta C_r}{\Delta Y_r} \cdot P_r \cdot \sum_t \frac{1}{(1-d)^t} \tag{2.4}$$

where ΔC_r is the cost increase for resource r (\$/kg), ΔY_r is the extracted yield of resource r (kg), $\mathrm{P_r}$ is the global production amount of resource r per year (kg/yr) and the last term is the NPV of spending one dollar a year over a time T, considering a discount rate d.

2.2.2 Economic sustainability

In investments decision-making regarding environmental costs, traditional methods used to compare different systems could lead to the wrong choice, because they don't take into account all costs related to the systems, such as dismantling of installations and recycling of materials. A possible solution, when assessing the economic aspects of a technological system, is to use a method that follows a life cycle approach, the so-called Life Cycle Costing (LCC). There are different variants of LCC, therefore also many definitions. One general definition states that LCC is a method to establish Life Cycle Cost, defined as *"the cost induced by a product (good or service) in its life cycle as borne directly and indirectly by public and private actors involved, and possibly including cost of external effects as resulting for current and future generations through environmental mechanisms"* [26].

According to SETAC-Europe Working Group on LCC, there are three types of Life Cycle Costing: conventional LCC, environmental LCC and societal LCC. The conventional LCC is a current practice, which evaluates in a purely economic way the costs related to a product. It can be used to assess the economic sustainability but it often neglects external costs, e.g. end-of-life costs. Therefore, the recommended method is the environmental LCC, because it is more complete and useful when comparing life cycle costs of alternatives. A definition of environmental LCC has been given by the SETAC-Europe Working Group on LCC: *"LCC is an assessment of all costs associated with the life cycle of a product that are directly covered by any one or more of the actors in the product life cycle (supplier, producer, user/consumer, EOL-actor) with complimentary inclusion of externalities that are anticipated to be internalized in the decision-relevant future"* [27]. What makes the environmental LCC an interesting tool is that it is not a stand-alone method, since that it can be used in parallel with environmental LCA; obviously the functional unit and the system boundaries must be chosen appropriately to have consistent overall results. The societal LCC is used for socio-economical evaluation and it includes all costs of environmental LCC and further externalities, taking into account also governments and public bodies that could be affected indirectly by externalities.

When comparing the results of an LCC analysis with environmental and social data, it is convenient to get an aggregated value which takes into account all the cost components of a product. This indicator can be a sum total or an yearly flow, for example. Huppes et al. presented several ways to aggregate costs in "Life Cycle Costing and the Environment" [26] , some of which are described below.

Steady State Costs (SSC) and Average Yearly Cost (AYC)

The Average Yearly Cost is the sum of the yearly costs, divided by the number of functional years, while the Steady State Cost can be seen as an average yearly cost where the number of functional years is infinite. This indicators do not involve a discount rate, and can be calculated as shown in Equation 2.5 [26].

$$SCC = AYC = \frac{\sum_{t=1}^{t=n} C_t}{fn} \tag{2.5}$$

Net Present Value (NPV)

Even if LCA is a steady-state type of analysis, it is common to calculate the Net Present Value (NPV) that considers a discount rate, when performing an environmental LCC. The NPV is shown in Equation 5.10 [26].

$$NPV = \sum_{t=0}^{t=n} \frac{C_t}{(1+r)^t} \tag{2.6}$$

with:

C_t= net cash flow in year t

n= number of year

r= discount rate

Internal Rate of Return (IRR)

The IRR is defined as that discount rate which makes the NPV equal to zero, or in other words the present value of benefits equal the present value of costs.

Pay-back Time

The Pay-back Time represents the time needed to return the initial investment, therefore it is calculated dividing it for the yearly net benefits [26]. When comparing alternatives, the one with the shortest pay-back period is obviously preferred. Considering a constant yearly net return, the Pay-back Time is calculated with Equation 2.7.

$$N_{pb} = \frac{C_0}{B} \tag{2.7}$$

Present Worth Ratio (PWR)

When assessing the economic sustainability of different systems with the aim to compare options, it is preferred to use the Present Worth Ratio (PWR) as economic indicator, calculated as shown in Equation 2.8, because it takes into account the NPV and the investment costs of the technological system as well [28]. When the PWR is positive, the investment is profitable.

$$PWR = \frac{NPV}{\sum\limits_{t=0}^{t=n} \frac{I_t}{(1+r)^t}} \tag{2.8}$$

with:

$\mathrm{I_t}$= investment cost in year t

i= number of years of construction

2.2.3 Social sustainability

As explained in Section 2.2, environmental and economic methods to assess the sustainability of processes and products have been developed and are commonly applied, even if LCC is not yet standardized. The last aspect to consider is the social dimension of sustainability, related to 'the needs of current and future generations'. The social component has been neglected in the past but researchers started to develop guidelines to assess it and Social Life Cycle Assessment (SLCA) has been sketched by Benoît et al. in [29], taking into account social aspects such as working hours, forced labour, etc. The SLCA is defined as *"a social impact (and potential impact) assessment technique that aims to assess the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycle"*. Limitations of this method are related to the lack of a database, the difficulty to get an overall indicator and how to relate it to the functional unit of the product/process. Furthermore social issues are not always easy to quantify and many of the social indicators developed refer also to qualitative aspects. Too many indicators have been developed and a standardization of the method is needed also to restrict these indicators to a manageable number.

Since that conducting a SLCA is not always easy, researchers have proposed alternative ways to evaluate social aspects, such as methods that make use of man-hours needed through the supply chain and the average salary to evaluate the access to services (e.g. health care, education etc.) or social indicators available for many countries.

2.3 Requirements to sustainability assessment methods

Considering a process or a system used for the production of a product, several aspects should be taken into account with the aim to assess its sustainability from a life cycle point of view. The ideal sustainability assessment method should take into account environmental, economic and social aspects and should be as objective as possible (e.g. not making use of weighting factors or data that changes over time) and make use of easily available data. Aspects that should be considered are listed below, referring to Stougie [1]:

- **Phases of construction, operation and decommissioning of installations, equipment and infrastructure**. They are related to the environmental aspect but also to the economic aspect.

- **Amounts of inputs (materials, feedstock, energy carriers) and outputs (products, emissions, waste flows) but also the scarcity and depletion of the inputs and the distinction between renewable and non-renewable resources**. All these aspects are related to the environmental impact but inputs and outputs have an economic component too, in terms of production costs and prices, respectively.

- **Disposal and/or abatement of emissions and waste flows**. It takes into account the environmental impact of these outputs, but the economic point of view is important as well.
- **Man-hours**. They are needed in every phase of the life cycle of a system/process and represent an economic component because associated to money-flows, but also a social component, e.g. working conditions.
- **Land use**. It is related to all three sustainability aspects, because its acquisition costs money, it implies the occupation and exploitation of the natural environment and landscape destruction can be seen as a social component.
- **Exergy loss**. The degradation of energy quality accompanies every process and it is somehow related to each aspect of sustainability.

Only the evaluation of all these aspects makes possible to assess the overall impact that a process has on the environment, the economy and the society. Each method presented in this chapter has shortcomings when assessing the sustainability of a technological system, especially with regard to this list of requirements. For example the environmental life cycle assessment methods cannot be consider fully objective because of the use of weighting factors, while the economic methods do not consider all the costs related to the system. Social sustainability assessment methods are not completely developed and are characterized by lack of data available in literature. Furthermore, as already mentioned, each method considers only one of the aspects of sustainability (i.e. environmental, economic or social sustainability), and more important none of these regular methods considers the loss of work potential that accompanied every process. As already mentioned, when exergy is lost, is cannot be used anymore, therefore trying to contain exergy losses is important in order to use energy in a more sustainable way. The relationship between exergy losses and sustainability aspects is explained in Section 2.4.

2.4 Exergy and sustainability

Among the applications of exergy analysis, its use in sustainability assessment is one of the more recent and that has to be investigated more deeply, since the relationship between exergy and sustainability is not completely clear yet. This section gives information on what is known about the relationship between exergy, and more in specific exergy losses, and sustainability aspects and a brief overview of exergetic methods used in sustainability assessment.

2.4.1 Relationship between exergy losses and sustainability

The relationship between exergy and sustainability has been deeply investigated by researchers in this field, getting remarkable conclusions such as that exergy losses should be decreased in trying to improve sustainability [30] and that exergy analysis should be applied in combination with other assessment tools [36]. In order to understand the reasons that led to these conclusions, it is important to analyse in which way exergy is related to the environmental, economic and social aspects of sustainability.

Exergy and the environment

The aspects that influence environmental impact and that are connected to exergy are the use of raw materials and energy carriers, the dispersion of emissions and land use.

In terms of raw materials, extraction, scarcity and depletion are linked to exergy losses. Extraction of raw materials, as every technological process, is always accompanied with exergy losses. Since scarcity and depletion are not technological processes, they cannot be directly associated with a loss of exergy. Anyway they are connected in some way to extraction, because every extraction of raw materials implies a decrease or even depletion of those materials. Exergy losses are higher if the materials are scarcer because the extraction process will be more demanding. Also the amount of materials used as inputs has an exergy value, but just a part of it is lost during the process, so this value cannot be added to exergy losses. Nevertheless the amount of raw materials used is expected to be connected to the exergy loss in a proportional way.

The use of energy carriers is linked to exergy because there are exergy losses that occurs during the processes needed for their production (e.g. the exergy loss that accompanied electricity or fuels production).

Finally, every emission, such as every other material or energy flow, is characterised by an exergy value which is part of the external exergy loss related to a process. Anyway, since that this value does not measure the environmental impact of the emission, a way to consider it is to calculate the exergy loss accompanied with the abatement process of the emission to an acceptable level. Substances that have a worse impact on the environment would probably be characterised by a lower level of allowed emissions, therefore the abatement exergy value would be more significant.

All these conclusions about the relationship between exergy losses and environment were carried out during a research project conducted by Stougie et al. [37], who took into account several aspects related to environmental impact (e.g. global warming, ozone depletion, eutrophication) with the aim to understand if exergy can be used in environmental policy making.

Concerning land use, every process or system needs a certain surface of the earth to be used for installations, equipment and infrastructure. The link with exergy is due to the fact that if land is occupied by facilities, it is impossible to capture new exergy from sunlight via photosynthesis, therefore there is a exergy loss caused by land occupation.

Exergy and economic and social aspects

Exergy losses and economic and social aspects are somehow related, but their relationship is not that obvious and easy to point out, and not completely clear.

Concerning economic aspects, both construction and operational costs have to be considered: the economic sustainability is higher for systems that are not too big or too small, as explained below. Internal exergy losses are due to irreversibilities of real processes: in case of infinitesimal gradients, exergy losses are low, and viceversa. Therefore, in terms of dimensions of installations, a small gradient implies bigger dimensions and higher construction cost: exergy losses are lower, but also the economic sustainability. On the other hand, lower exergy losses imply a lower exergy input, i.e. a smaller amount of materials needed as input and consequently a lower operational cost. Anyway, this kind of relationship is expected especially for systems that use the same technology, but have different sizes, because comparing really different systems do not necessarily leads to the same conclusions.

Social aspects are somehow related to exergy losses because people work in every process needed to obtain products and every process implies exergy losses. Anyway it is not easy to predict the relationship between social sustainability and exergy losses [1].

2.4.2 Exergetic methods applied in sustainability assessment

Several approaches that make use of exergy analysis to assess the sustainability of processes and systems can be found in literature. Some of these methods are listed below:

- The **Cumulative Exergy Consumption (CExC)** was taken as starting point for the development of other exergetic methods; the CExC is defined as *"the sum of the exergy of natural resources consumed in all the steps of a production process"* [6]; this method calculates the total exergy needed to produce a product but not the exergy loss. Anyway the cumulative exergy loss can be calculated as the difference between the CExC and the specific exergy of the product of the process [31].
- The **Cumulative Exergy Consumption for Construction and Abatement (CExCA)** takes into account the cumulative exergy consumption for the construction and operation of the system and the one associated to the abatement of emissions and the system after the utilization [32].
- In the **Cumulative Exergy Extraction from the Natural Environment (CEENE)** exergy data on fossil, nuclear and metal ores, minerals, air, water, land occupation and

renewable energy sources are elaborated to quantify the exergy 'taken away' from natural ecosystems [33]. This method is considered an improvement over the CExD method because it is more consistent and because it was developed to be compatible with existing life cycle databases [33].

- The **Cumulative Exergy Demand (CExD)**, defined as *"the sum of exergy of all resources required to provide a process or product"*, was developed by Bösch et al. to make easier the calculation of the total exergy required for the production of products and processes present in the Ecoinvent database [34].

- The **Exergetic Life Cycle Analysis (ELCA)** can be seen as an extension to a regular LCA, which consider also exergy losses [30]. This method enables to quantify depletion of natural resources in the LCA and it is an instrument to assess the efficiency of the use of resources [35]. The Zero-ELCA is a variant that takes into account also abatement exergy values of emissions.

Nevertheless, also exergetic methods present shortcomings when assessing the sustainability of technological processes and systems from a life cycle point of view, since they not comply with all the requirements listed in Section 2.3. For example the methods listed above, with an exception for the CEENE method, do not consider the exergy loss caused by land use. Therefore Stougie [1] developed a new method that will be introduced in Chapter 3, and that can be regarded as a combination of the methods explained in this section.

Chapter 3

The Total Cumulative Exergy Loss method

As introduced in Section 1.3.4, exergy analysis is already used in sustainability assessment and several methods that make use of exergy analysis to evaluate the sustainability of technological processes and systems have been developed. Anyway they are not always suitable and present limits concerning the requirements to sustainability assessment, listed in Section 2.3. For this reason this research makes use of a new method, developed by Stougie [1] , i.e. the Total Cumulative Exergy Loss method, that presents the advantages of exergy analysis in sustainability assessment and has already been used in different case studies.

This chapter deals with the requirements met by the TCExL method and explain how to calculate each component of the Total Cumulative Exergy Loss. In Section 3.1.1 it is explained how to calculate the internal exergy loss, in Section 3.1.2 the calculation of abatement exergy loss is presented and finally Section 3.1.3 deals with the calculation of exergy loss caused by land use.

3.1 Requirements met by the TCExL method

One of the reasons for conducting an exergy-based analysis to assess the sustainability of a process is that energy degradation can only be taken into account in this way. Every exergetic method involves the calculation of exergy losses that occur during a process, but in the specific case of the TCExL method these losses are the final result of the analysis, instead of exergetic efficiencies or diagrams. Since the calculation of exergetic efficiency strictly depends on the definition of inputs and outputs, using exergy losses as the result allows to compare different alternatives without uncertainties of interpretation and makes the method more objective. The objectivity of the method is also due to the fact that it is based on standard thermodynamic equations, which are not changing over time, and that it does not make use of weighting factors, whose choice is subjective, unlike the case of regular sustainability assessment methods. Furthermore data about exergy values or methods to calculate them can be easily found in literature, because the concept of exergy has been studied more and more in the past decades.

Calculating exergy losses that occur during a process makes it possible to take into account several of the requirements that every sustainability assessment method should meet, according to Stougie [1]. First of all, the analysis can be conducted with a life cycle approach, considering all the phases of the life cycle of the product, including construction and decommissioning of installations, equipment and infrastructure. Concerning the amount of inputs and outputs, they are taken into account through their exergy values and a proportional relationship is expected between the amount of inputs and the exergy loss that accompanies the process. The abatement of emissions and waste flows is considered as well in the TCExL method, not only calculating their exergy values, which do not represent the impact of releasing them in the natural environment (e.g. their toxicity or contribution to global warming), but also evaluating the exergy loss associated with processes needed to abate emissions to a reasonable level. Also the distinction between renewable and non-renewable resources can be taken into account via the abatement exergy value, i.e by not considering the abatement of emissions associated with renewable exergy sources. Finally, the exergy loss associated to land occupation by installations and equipment is part of the TCExL.

Like all exergetic methods, the TCExL method, cannot consider all aspects related to sustainability. For example scarcity and depletion of raw materials are only indirectly taken into account, and also economic and social aspects, as explained in Section 3.1.

3.2 Definition of the TCExL

The TCExL method has already been used in other research and is used also in this research to assess the sustainability of technological systems in comparison with regular methods. This method is based on the calculation of exergy losses through thermodynamic equations and takes into account all exergy losses caused by a technological system during its life cycle.

Equation 3.1 presents TCExL method as a formula.

$$TCExL = Ex_{loss,internal} + Ex_{loss,abatement} + Ex_{loss,landuse} \tag{3.1}$$

The TCExL is the sum of the internal exergy loss, the abatement exergy loss and the exergy loss caused by land use. The internal exergy loss is caused by the technological system during the construction, operation and decommissioning of installations, equipment and infrastructure. The abatement exergy is caused by the abatement of emissions and waste flows to an acceptable level, while the exergy loss caused by land use is related to land occupied by the technological system including its supply chains.

3.2.1 Internal exergy loss

The internal exergy loss is calculated from the difference between the ingoing amount of exergy and the outgoing amount of exergy of the process or system, i.e. the exergy represented by inputs and outputs.

$$\begin{aligned} Ex_{loss,internal} &= Ex_{inputs} - Ex_{outputs} \\ &= Ex_{inputs} - Ex_{products} - Ex_{emission,wasteflows} \end{aligned} \tag{3.2}$$

Inputs and outputs are mass flows and energy flows, therefore their exergy values can be calculated as shown in Section 1.2.

3.2.2 Abatement exergy loss

The abatement exergy loss represents the loss of work potential that accompanies the abatement of emissions and waste flows until their effects on the environment are negligible, i.e. considering the exergy losses caused by processes that abate these emission to an acceptable level.

A relevant limit in the calculation of the abatement exergy values is that data of only few emissions can be found in literature, such as carbon dioxide, sulphur dioxide, nitrogen oxides and phosphate, therefore not all the emissions caused by a process can be taken into account. A way to estimate the abatement exergy values of other emissions, mentioned in literature [38], is to multiply the abatement exergy value of carbon dioxide with the Global Warming Potential index (GWP) of the other emissions; anyway, this approach presents low accuracy and it is not a real measure of the exergy loss caused by the abatement of the emission, therefore it is not applied in this research.

Several researchers in this field have calculated the abatement exergy values of emissions, considering different abatement processes. Cornelissen [30] introduced an abatement exergy value of 3 MJ/kg for CO_2, based on separation of 90% of carbon dioxide out of the flue gases, compression and storage in empty fields, but this value is probably an underestimation. Dewulf et al. [39] introduced a value of 5,862 MJ/kg, based on CO_2 recovery via ethanolamine absorption and stripping, followed by compression to 80 atm for underground storage. The abatement exergy values of SO_2, NO_x and phosphate are introduced by Cornelissen [30] are 57, 16 and 18 MJ/kg, respectively. The first value is based on a 90% removal of sulphur dioxide in a flue gas desulphurisation unit of a coal-fired power plant by means of limeston and its subsequent conversion to gypsum. The abatement exergy value of NO_x is based on a 80% removal in a DeNOx unit of a coal-fired power plant and finally the last value is based on a 99% removal.

3.2.3 Exergy loss caused by land use

As already mentioned, occupation of land by technological systems (e.g. installations, equipment, infrastructure) is taken into account in the calculation of exergy loss because it prevents capturing new exergy from the sun via photosynthesis, that is the only way to replenish a loss of work potential. Two methods can be applied to evaluate the exergy loss caused by land use. The first method refers to the CEENE method [33], where exergy loss is calculated multiplying the average solar irradiation by the exergy/energy factor of sunlight, i.e. 0.9327 , and the efficiency of photosynthesis, as shown in Equation 3.3. This value of exergy is then multiplied by the amount of land used per year.

$$Ex_{loss,landuse} = IRR \cdot \eta_{photosynthesis} \cdot 0.9327 \tag{3.3}$$

with:
IRR= average solar irradiation [GJ/ha year]
$\eta_{photosynthesis}$= efficiency of photosynthesis

In the CEENE method, using a photosynthesis efficiency of 2% and an average solar irradiation for Western Europe of 2.78 kWh/m^2, a solar exergy flow of 681.4 GJ/ha per year can be calculated [33]. Anyway, it is more realistic to use an efficiency between 0.5 and 1%, therefore, considering an average value of 0.75%, the solar exergy loss caused by land use decreases to 256 GJ/ha per year [40].

The second method used to calculate the exergy flow deprivation to the natural ecosystem was developed by Alvarenga et al. [41] and relates land occupation to the potential Net Primary Production (NPP), defined as the difference between the total amount of carbon dioxide fixed by photosynthesis and the carbon dioxide lost to autotrophic respiration, i.e. assimilated by plants for their own metabolism, referred to a certain area and timeframe. The NPP is an indicator that takes into account many factors, such as water availability, soil quality etc. Considering an area occupied by men, the potential NPP represents the biomass production that would be available if the land was not being used. In literature we can find a really detailed world map on potential NPP, modeled by Haberl et al.[42] and characterization factors (in MJ_{ex}/m^2 year) calculated by Alvarenga et al [41].

Considering a biomass exergy conversion factor of 42.9 MJ_{ex} / kg of CO_2, the world average value results in 21.5 MJ/m^2 and it equals the value obtained with the CEENE method, considering an efficiency of photosynthesis of 0.63.

These two approaches do not differ much in results, therefore since that the method based on solar irradiation can lead to inaccurate estimation due to the fact that shares for photosynthesis are influenced by several factors (e.g. water availability, soil quality and temperature) and thanks to the large availability of data on the Net Primary Production, the second method is considered preferable to use and will be applied in this research.

Chapter 4

Introduction to the case study

This chapter deals with the reasons that led to the choice of the specific case study conducted in this research. After an introduction to the current global situation concerning environmental problems and political decisions made in the last year, general information about the systems analysed in the case study are presented and followed by a description of how methods described in the previous chapters are used in this research. Furthermore, other choices needed before the sustainability assessment, such as functional unit and system boundaries, will be explained.

4.1 Rising global awareness of environmental issues

The choice of the case study of this research, dealt with in Section 4.2, finds its origin in the transitional period to a sustainable economy Europe is working on. It is a fact that environmental awareness has characterised more and more the past decades and that nowadays politicians and citizens are conscious that protecting our fragile environment is a common objective [43]. After the commitment made in 2010 by the European Union with the Europe 2020 strategy, each country has started to work in order to be able to meet its targets, but in the last few years the change towards a more responsible society is becoming more visible.

According to the analysis of preliminary data for 2015 conducted by the International Energy Agency (IEA), the global energy-related carbon dioxide emissions amounted to 32.1 billion tons, having remained essentially flat since 2013, as it is shown in Figure 4.1 [44]. This is principally due to the fact that 90% of the new energy systems for power generation put into operation in 2015 were those based on renewable energy sources [44]. The driver is the growing consciousness that the most effective way to decrease CO_2 emissions to the environment is to reduce fossil fuel consumption [45]. For the first time, the emission level didn't increase despite of the world economy, that can account a growth of more than 3%: in the past every time there was a drop in emissions it was because of an economic crisis, as pointed out in Figure 4.1.

What is happening now is clearly a sign that economic growth and emissions are not strictly connected, therefore it is hopefully possible to achieve the sustainable development the modern society is trying to promote.

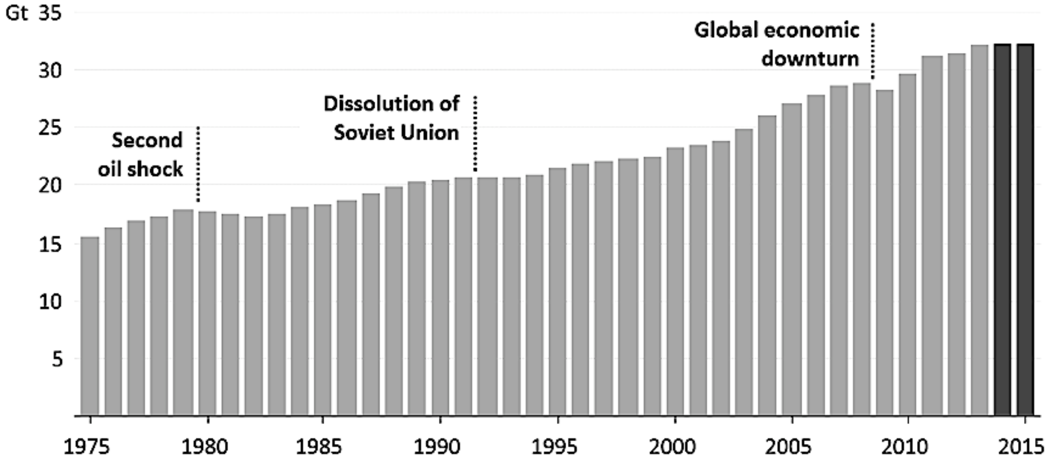

Figure 4.1: Global energy-related CO_2 emissions from 1975 to 2015 [44].

The last important sign of change involves the decisions made during the 21th Conference of Parties, held in Paris in December 2015, dealing with environmental issues with the aim to adopt a new global agreement to limit greenhouse gas emissions. The main purpose agreed during the conference is to keep the global temperature rise below 2°C and to put efforts to limit this value even further to 1.5°C, as a defense line against the impacts of climate change. The ability to achieve these goals will depend on the guidelines adopted from now.

4.2 Choice of the case study

In order to investigate the value of exergy analysis in sustainability assessment of technological systems, Stougie [1] has conducted two different case studies, applying the TCExL method and comparing the results with the ones obtained through non-exergetic methods. The case studies analyse the production of electricity in the Netherlands, using different systems of power generation, and are summarised below:

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

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

In this research another case study about power generation will be conducted, focusing on renewable energy power plants located in the Netherlands. With the goal to generate 14% renewable energy by 2020 (and 16% by 2023), the Netherlands has started to adopt a new policy for renewable energies: several new power plants that make use of renewable resources are under study or under construction and some of them are analysed in this research. The Netherlands is trying to promote a sustainable, reliable and affordable energy supply due to the growing concern about climate change and environmental problems, depletion of fossil fuels and the dependence on foreign suppliers.

The case study assesses the sustainability of three different power generation systems, with the aim to highlight which system is preferred from each point of view (environmental, economic and exergetic). As already mentioned in Chapter 2, environmental, economic and social aspects should be taken into account with the aim to assess the sustainability in a complete way. Nevertheless, this research will not focus on social sustainability assessment because a standardized method has not been developed yet and the low availability of data would make it difficult to calculate other social indexes.
The analysed systems are listed below:

- **Offshore Wind Farm**: this system consists of 190 offshore wind turbines, each with a capacity of 4 MW, and is based on the construction of sites I and II of the Borssele Wind Farm;

- **Photovoltaic Park**: this system is based on the construction of the largest solar park of the Netherlands, the Sunport Delfzijl, with a peak power of 30 MW;

- **Biomass-fired Power Plant**: this system refers to a case study conducted by CE Delft concerning the conversion of Unit 8 of Amer Power Plant to become 100 % biomass-fired, with a total capacity of 645 MW_e;

A more detailed description of the systems and of data used in this research can be found in chapter 5, 6 and 7, respectively.

4.3 Calculation methods used in this research

As already mentioned, to assess the sustainability of a system or process, environmental, economic and social aspects should be considered together. Nevertheless this research makes use of regular sustainability assessment method only to evaluate environmental and economic aspects. However, the fact that a social sustainability assessment is not conducted, does not constitute a big lack with regard to the aim of this research, i.e to investigate the suitability of the TCExL method in sustainability assessment. It was already stated that exergy losses are mainly related to environmental aspects [1], therefore interesting results can be achieved also without a social assessment. Obviously, if data related to social sustainability are available, it is always preferable to conduct also a social assessment to get a more complete comparison of the results.

4.3.1 Environmental sustainability

To assess the environmental sustainability, a classical LCA is conducted with the help of SimaPro version 8.0 and the Ecoinvent database version 3.1. Both the Midpoint and the Endpoint indicators are calculated, and both will be used in Chapter 8 to compare the environmental impact of the systems. The default method and normalisation/weighting set has been used, i.e. “ReCiPe Midpoint(H) V1.12/Europe Recipe H” and “ReCiPe Endpoint (H) V1.12/Europe ReCiPe H/A” for Midpoint and Endpoint indicators, respectively.

4.3.2 Economic sustainability

Section 2.2.2 deals with several indicators that can be used to assess the economic sustainability of a process or technological system. In this research the Net Present Value (NPV) and the Present Worth Ratio (PWR) were chosen. The discount rate used in the calculations is specified at 8 %, according to the value used for private effects in social cost-benefit analyses in the Netherlands [46]. In the economic assessment, the lifetime of all installations and the construction period are assumed to be 20 and 3 years, respectively except for the photovoltaic park which has a lifetime of 30 years. Costs and benefits that considered in this analysis are investment cost, O&M costs, subsidies and revenues from electricity. R&D and decommissioning costs are neglected because are usually lower than all the other costs.

Investment costs are related to the overall installation, but sometimes the capacity of the installation differs from the one needed for the production of the functional unit. Therefore for larger installations the investment cost associated to the functional unit is considered proportional to the original investment cost, while it is calculated by applying the six-tenths rule for smaller installations, in according to what was done by Stougie [1]. The six-tenths rule states that cost are proportional to the size of the system raised to the power 0.6, therefore the investment cost C_1 of a system with a capacity x_1 can be calculated as shown in Equation 4.1:

$$C_1 = C_2(x_1/x_2)^{0.6} \tag{4.1}$$

Investment costs are spread over the construction period, i.e. 3 years. Yearly operational and maintenance costs are assumed to be 4% of the initial investment costs [47] and electricity selling price is assumed to be 60 €/MWh [48]. Specific data for the Offshore Wind Farm, the Photovoltaic Park and the Biomass-fired Power Plant are presented in Section 5.3, 6.2 and 7.3, respectively.

4.3.3 Exergetic sustainability

The exergetic analysis is based on the calculation of the Total Cumulative Exergy Loss, which is the sum of the internal exergy loss, the exergy loss due to land occupation and the abatement exergy loss. The first of the three components, the internal exergy loss, is obtained with the help of SimaPro that, besides the calculation of the ReCiPe indicators, can also be used to calculate an exergy indicator, i.e. the Cumulative Exergy Demand (CExD). This indicator depicts the total exergy removal from nature to provide a product and it is obtained summing up exergy values of all resources required.

Once the CExD is known, the internal exergy loss can be calculated as shown in Equation 4.2:

$$Ex_{loss,internal} = CExD - Ex_{products} - Ex_{emissions} \tag{4.2}$$

The exergy values of the products are calculated manually, while the amount of exergy that represented the emissions is calculated from the amounts of emissions reported by SimaPro multiplied by the standard chemical exergy values of the emissions. These exergy values can be found in literature or are calculated from data reported by researchers [49],[50]. Since the inventory data reported by SimaPro count a large number of emissions, only the values of the largest emissions are considered, until at least the exergy values of 99% by mass of emissions are known. The standard exergy values of emissions are listed in Appendix A.

When calculating the exergy values of waste heat flows, the following values of temperature are assumed [1]:

- **Waste heat emitted to air**: 110° C, based on the temperature of flue gases from a power plant;
- **Waste heat emitted to water**: 30°C, based on the maximum allowed temperature of waste water emitted to surface water in the Netherlands;
- **Waste heat emitted to soil**: 30°C, considering the same value used for waste heat emitted to water;

Note that the calculated exergy value of emissions is probably higher than the real value, because SimaPro does not report which emissions belong to the same waste flow and therefore does not consider the mixing of components, always accompanied with exergy losses, as explained in Section 1.2.3. Consequently the internal exergy losses are lower than in reality, but the error can be neglected since the exergy values of emissions are usually small compared to the exergy values of inputs and products [1].

The exergy loss related to emission abatement is calculated from emissions reported by SimaPro and the abatement exergy values that can be found in literature. Table 4.1 presents an overview of the values of the abatement exergy used in this research.

Table 4.1: Abatement exergy values for emissions of carbon dioxide, sulphur dioxide, phosphate and nitrogen oxides.

Emission	**Abatment exergy values [MJ/kg]**
Carbon dioxide	5.86
Sulphur dioxide	57
Phosphate	18
Nitrogen oxides	16

The exergy loss caused by land use is calculated using the world average exergy loss of 21.5 MJ/m^2 per year, calculated by Alvarenga et al. [41]. This value is multiplied by the land occupation in m^2 per year reported by SimaPro and a factor that can be 1 or 0, depending on the land use type, according to [1]. This factors are reported in Table 4.2 and are used to prevent double-counting of land when evaluating exergy losses caused by land use. Since the use of biomass is already taken into account in the calculation of the internal exergy loss in the CExD, all types of land used for growing trees or biomass are not considered and those related to marine ecosystems are neglected as well, because the exergy captured by them is really small. Only land occupation is considered and not land transformation, because the use of land itself prevents capturing new exergy via photosynthesis, independently from what type of land it was before the construction of the system.

Table 4.2: Factor multiplied for exergy values related to land use.

Land use type	Factor related to industrial area
Occupation, arable	1
Occupation, arable, irrigated	1
Occupation, arable, irrigated, intensive	1
Occupation, arable, non-irrigated	1
Occupation, arable, non-irrigated, extensive	1
Occupation, arable, non-irrigated, intensive	1
Occupation, construction site	1
Occupation, dump site	1
Occupation, industrial area	1
Occupation, industrial area, built up	1
Occupation, industrial area, vegetation	1
Occupation, mineral extraction site	1
Occupation, traffic area, rail embankment	1
Occupation, traffic area, rail network	1
Occupation, traffic area, rail/road embankment	1
Occupation, traffic area, road embankment	1
Occupation, traffic area, road network	1
Occupation, urban, discontinuously built	1
Occupation, urban/industrial fallow	1
Occupation, dump site, benthos	0
Occupation, forest, extensive	0
Occupation, forest, intensive	0
Occupation, forest, intensive, normal	0
Occupation, forest, intensive, short-cycle	0
Occupation, grassland, not used	0
Occupation, industrial area, benthos	0
Occupation, pasture and meadow, extensive	0
Occupation, pasture and meadow, intensive	0
Occupation, permanent crop	0
Occupation, permanent crop, fruit, intensive	0
Occupation, seabed, drilling and mining	0
Occupation, seabed, infrastructure	0
Occupation, shrub land, sclerophyllous	0
Occupation, water bodies, artificial	0
Occupation, water courses, artificial	0

4.4 Further information related to LCA

During the calculation setup in SimaPro, some choices can be made before assessing the environmental impact of the systems. For example it can be decided to exclude infrastructure processes or long-term emissions but more important the analysis method and the functional unit have to be set. The choices made in this case study are presented in Section 4.4.1. Another important aspect to consider before analysing Ecoinvent processes that have more than one output, is to choose a products allocation method: in Section 4.4.2 the allocation of heat and electricity generated by the Biomass-fired Power Plant is explained in more detail.

4.4.1 Functional unit and system boundaries

This research focuses on the sustainability assessment of three power generation systems located in the Netherlands, which use renewable resources. Since that electricity is the main, if not the only, product of each system, the chosen functional unit is the production of 1 PJ of electricity, also because it is an electricity amount that all the systems can produce during their lifetime.

Concerning the choice of the system boundaries, every process needed for the production of electricity is taken into account and will be described in more detail for each system. On the other hand, the transport, distribution, use and storage of the produced electricity are not considered because all the systems under study are located in the Netherlands and the results for these processes would be the same for each system, i.e the grading of the systems would not change taking into account these processes.

Other two important aspects were not considered in this research, when assessing the electricity generation from wind and solar energy.

In regard to wind energy, to avoid sudden break of wind turbines due to fluctuating wind speed, a reserve capacity must be maintained to enhance grid reliability, therefore greenhouse gas emissions occurring during the operation of the backup system should be taken into account in the LCA of the installation [51]. Anyway, Yang and Chen pointed out that considering the reserve capacity has a little impact on energy and greenhouse gas emissions [52], but its incorporation in the analysis should be further investigated to improve the accuracy of the assessment [51].

Similar considerations can be made for solar energy, since solar irradiation varies by season, time of day and weather. Clearly, assuming an average solar irradiation value implies emissions which are different from the real ones (higher if the assumed solar irradiation is lower and viceversa) [53].

4.4.2 Products allocation

In the specific case of the biomass-fired power plant, production of electricity is accompanied with production of process heat, which is seen as a co-product. In order not to associate all the impact of the system to the produced electricity, the allocation factor related to electricity is not 100%. The products allocation can be made in different ways (e.g. according to exergy or energy content, according to product prices), and in this specific case an exergy-based allocation is chosen, i.e. the total impact is multiplied by an exergy allocation factor, calculated as shown below. The sum of allocation factors must be 100% and SimaPro checks automatically if this rule is respected. Exergy factors for electricity and heat are calculated in the way presented in Equations 4.3:

$$f_{ex,el} = \frac{Ex_{el}}{Ex_{el} + Ex_{th}} \qquad f_{ex,th} = \frac{Ex_{th}}{Ex_{el} + Ex_{th}} \tag{4.3}$$

where $\mathrm{Ex_{el}}$ and $\mathrm{Ex_{th}}$ are the exergy values of electricity and heat associated to the functional unit, which can be calculated as explained in Section 1.2. The allocation factors result in 0.87 and 0.13 for electricity and heat, respectively, considering heat at a temperature of 423 K.

4.4.3 Infrastructure in the Ecoinvent processes

When modeling the Ecoinvent unit processes, the use of infrastructure like power plant and wind turbines has to be calculated in a certain way. It is expressed as the number of installations needed for amount of product generated in the unit process itself. This value is calculated dividing the amount of product generated with the unit process by the total amount of product generated during the lifetime of the installation.

For example, the number of fixed and moving parts of a wind turbine needed for the generation of 1 kWh of electricity is calculated as shown in Equation 4.4:

$$\frac{1}{20 \cdot 18000000} = 2.8 \cdot 10^{-9} \tag{4.4}$$

where 20 is the lifetime of the installation and 18000000 are the kWh generated in one year from each wind turbine.

Chapter 5

Offshore wind farm

Wind power has always been widely used in the Netherlands, especially in onshore wind farms. In the last decade, in addition to the wind farms built onshore, several wind farms were built out in the sea and nowadays they provide renewable energy to consumers. On 26 September 2014, one year later than the publication of the Dutch Energy Agreement [54], the Dutch Minister of Economic Affairs provided the "Road Map" for reaching the targets for offshore wind, stating an increase of the offshore wind capacity from the 1000 MW, operative or under construction at that time, to 4500 MW in 2023. Three offshore wind farm zones were designed for the development of the new capacity and will be built in the next few years: Borssele (1400 MW), South Holland (1400 MW) and North Holland (700 MW).

Borssele Wind Farm, located 22.2 km off the coast of Zeeland, will be the first to be built and it will be divided into four sites. The wind farm system analysed in this research is based on the construction of sites I and II of Borssele Wind Farm, that are scheduled to be taken into operation in 2019. Depending on the type of turbine that will be chosen, it was allowed to increase the capacity of each site from 350 to 380 MW [55]. An assumption of 95 turbines with a capacity of 4 MW (Siemens SWT-4.0-130) for each site is made, based on a list of requirements (e.g. maximum number of wind turbines to be installed in each site, minimum and maximum total swept area permitted, minimum distance between wind turbines, etc.), as it is not yet known which wind turbines will be chosen.

5.1 General description of the Offshore Wind Farm

As already mentioned, the wind farm assessed in this research is based on the construction of Site I and II of Borssele Wind Farm. The Borssele Wind Farm Zone (BWFZ) measures approximately 234 km^2, excluding maintenance and safety zones, and is located 22.2 km from shore. Figure 5.1 shows the boundaries of the BWFZ. Site I and II have an effective area of development of 49.1 km^2 and 62.6 km^2, respectively. As already mentioned, the type of turbine has not yet been chosen, but each site has to meet several design requirements, some of which are shown in Table 5.1. Other requirements related to financial and legal aspects, construction, operation and decommissioning of the sites are presented in the *Project and Site Description* of the wind farm zone [55].

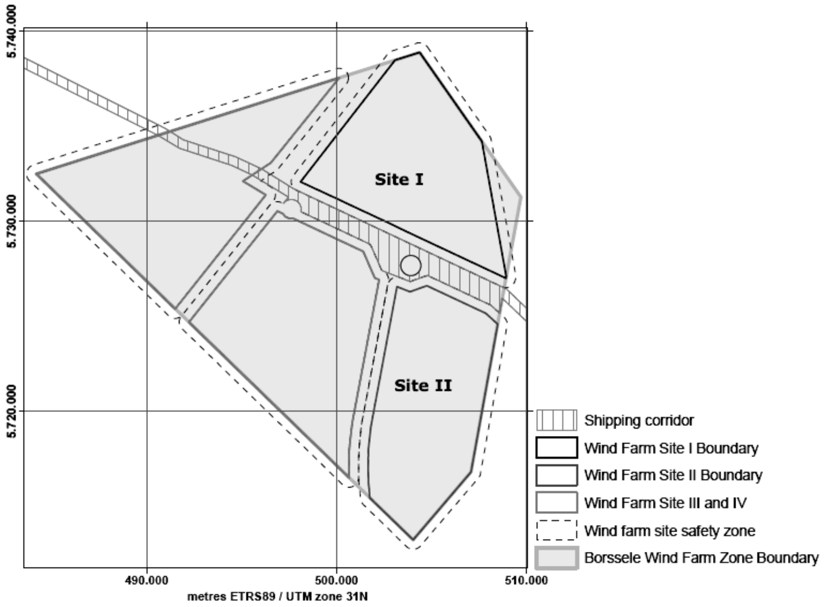

Figure 5.1: The Borssele Wind Farm Zone [55].

Table 5.1: Design requirement for the Borssele Wind Farm Zone.

Subject/variable	**Bandwidth**
Capacity individual turbine	3-10 MW
Tip height individual wind turbine	125-250 m
Tip lowness individual wind turbine	25-30 m
Rotor diameter individual wind turbine	100-220 m
Distance between each wind turbine	At least 4 x rotor diameter
Number of blade per wind turbine	2-3
Type of foundations (substructures)	Monopile, jacket, tripile, tripod, gravity-based structure
Type of foundation (foundation)	Pile foundations, suction buckets, gravity-based structures

The assumption of 95 Siemens turbines with a capacity of 4 MW complies with the list of requirements and is plausible because this type of wind turbine has already been used in the Gemini offshore wind farm, a 600 MW offshore wind power farm located in the Netherlands, whose construction started in 2016 and is expected to be completed in 2017 [56]. The main features of the SWT-4.0-130 are presented in Table 5.2 and other information can be found in the technical specification of the wind turbine, provided by the construction company [57]. The annual electricity production per turbine, based on an expected average wind speed of 10 m/s, is approximately 18000 MWh, in according to data found in an LCA study of a wind farm equipped with this turbines, conducted by Siemens [58]. The lifetime of the offshore wind farm is assumed to be 20 years.

Table 5.2: Main features of the SWT-4.0-130 wind turbine.

SWT-4.0-130	
Operational data	
Cut-in wind speed	3-5 m/s
Nominal power at	11-12 m/s
Cut-out wind speed	32 m/s
Nominal power	4000 kW
Maximum 3s gust	70 m/s
Rotor	
Weight	100 t
Type	3-bladed, HAWT
Diameter	130 m
Swept area	13300 m^2
Speed range	5-14 rpm
Nacelle	
Weight	140 t
Blades (B63)	
Length	63,45 m

5.2 Data used for the environmental and economic assessments of the Offshore Wind Farm

A schematic description of the system under study is shown in Figure 5.2, in which fixed and moving parts of the wind turbines are taken into account separately.

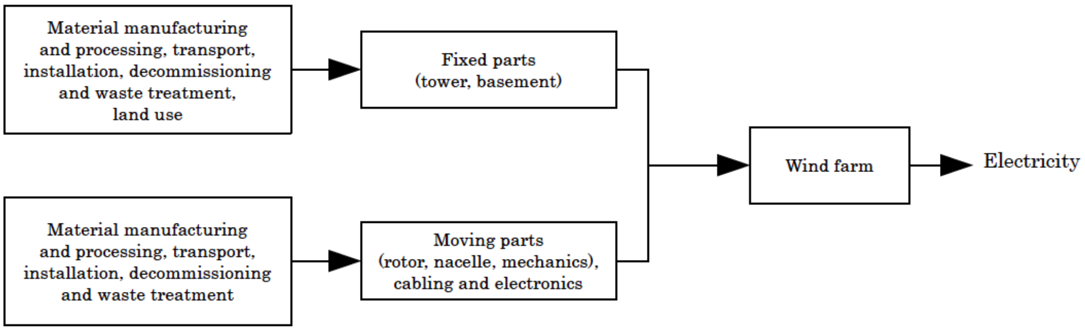

Figure 5.2: Wind energy supply chain.

The Ecoinvent datasets for fixed parts (basement and tower), for moving parts (rotor, nacelle) and for cabling and electronic components take into account the construction materials, their processing and their transport to the manufacturing company and from this to the site of the installation. Land use for the basement, energy requirements for tower installation, material disposal and waste treatment are considered as well.

5.2.1 Materials, processes and energy requirements

This section gives an overview of materials and manufacturing processes used for the construction of the different parts of the 4 MW wind turbine. Table B1 and B2 were obtained using information provided in the datasheet of the SWT-4.0-130 wind turbine to modify the Ecoinvent unit processes taken as reference.

Table 5.3: Material use for the construction of the moving parts of the 4 MW wind turbine.

MOVING PARTS	**MATERIAL**	**MASS [kg]**
ROTOR		
Blades	Glass fibre reinforced plastics	57000
Extender	Chromium steel	21000
Hub	Cast iron	22000
NACELLE		
Mechanic parts		
Shaft	Steel, low alloyed	21465
Main bearing	Cast iron	1738
	Chromium steel	1738
	Cast iron	15494
	Chromium steel	15494
	Rubber	169
Generator	Cast iron	5734
	Chromium steel	15050
	Aluminium 0% recycled	1433
	Copper	1671
Brake	Chromium steel	1039
Casing		
Frame	Chromium steel	28719
Cover	Glass fibre reinforced plastics	19029
Yaw system		
Ball bearing	Steel, low alloyed	4050
Drive	Chromium steel	2077
Brake	Chromium steel	1383
Hydraulic system		
	Chromium steel	3462
	Lubricant	254
TRANSFORMER		
	Cast iron	1500
	Copper	600
	Steel, low alloyed	800
	Lubricant	1000

The rotor is made of glass fibre reinforced plastics (with the assumption that blades are made of 65% glass and 35% plastic) and small amounts of steel and cast iron, with a total mass of 100 tons [57]. The nacelle weights 140 tons [57] and consists of several components, whose materials are different types of steel and plastics and also aluminium and copper. The total mass of the tower is about 176 tons, considering also the steel used for welding as soldering metal. The foundations chosen in this research are the same as in the Ecoinvent unit process (gravity based foundation) but dimensions and weight are adapted to a capacity of 4 MW. According to Zaaijer [59], a foundation of 4100 tons with a 22 m diameter and 2,7 m height is chosen.

Also materials used for the connection between the generator and the electric grid are taken into account in the Ecoinvent dataset of the fixed parts.

The processes used for the construction materials are presented in Table 5.5. These processes include most of the total energy requirements for the infrastructure of the wind power plant; nevertheless also the energy requirements (diesel and electricity) for final assembling are considered, according to the Ecoinvent report related to wind energy [60].

Table 5.4: Material use for the construction of the fixed parts of the 4 MW wind turbine.

FIXED PARTS	**MATERIAL**	**MASS [kg]**
TOWER		
	Steel, low alloyed	175475
	Epoxy resin	848
BASEMENT		
	Concrete	2460000
	Reinforcing steel	1640000
	Gravel	300000
CONNECTION TO GRID		
	Copper	3900
	Lead	7575
	Steel, low alloyed	8766
	PVC	3500

Table 5.5: Material processing for the construction of wind turbines.

Material	**Processing**
Copper	Copper, wire drawing
Aluminium	Aluminium, sheet rolling
Chromium steel	Chromium steel, sheet rolling
Cast iron	Steel, section bar rolling
Steel, low alloyed	Steel, sheet rolling

5.2.2 Transport

Standard distances in Europe, defined in the general Ecoinvent guidelines [60], are used for the transport of the construction materials to the manufacturing company and for the transport of wastes to waste treatment and disposal. Gravel, concrete and reinforcing steel used for the basement are assumed to be transported by lorry directly to the location of the wind farm. The

Ecoinvent process considered is *"Transport, lorry* $>$ *16t, fleet average/RER U"*. For the rail transport of each part of the wind turbine from the manufacturing company to the location, a distance of 900 km is considered, with the assumption that the construction of the wind turbines will take place in the Siemens wind turbine manufacturing facility in Esbjerg, Denmark. At the end, each component of the wind turbine is moved from the shore to the sites by ships, considering a distance of 45 km (round trip). The Ecoinvent processes considered are *"Transport, freight, rail/RER U"* and *"Transport, barge/RER U"*, respectively.

According to the Ecoinvent report, it is assumed that equipment needed for the final assembly of the installation, such as concrete mixers and cranes, has a total weight of 60 t and is transported to the location by truck, for a distance of 80 km (round trip) [60].

5.2.3 Land use

Land occupation is taken into account in the Ecoinvent unit process related to the fixed parts of the wind turbine. According to the directives of the Ecoinvent report, only the area of the foundation is considered when evaluating the land occupied by the installation.

5.2.4 Operation, waste treatment and disposal of the wind power plant

Several assumptions and modifications of data related to the largest offshore wind power plant modeled in the Ecoinvent database have been made to model the construction of the wind turbines of the Offshore Wind Farm. Two processes were modified, i.e. *"Wind power plant 2 MW, offshore, moving parts/OCE/I U"* and *"Wind power plant 2 MW, offshore, fixed parts/OCE/I U"*. The electricity produced is based on the Ecoinvent process *"Electricity, at wind power plant 2 MW, offshore/kWh/OCE"* considering $2.8 \cdot 10^{-9}$ p of the *"Wind power plant 4 MW, offshore, moving parts"* and the same amount of the *"Wind power plant 4MW, offshore, fixed parts"*. A detailed overview of the amounts of materials, fuels and wastes related to the construction of moving and fixed parts of the 4 MW wind power plant can be found in Appendix B.

Figure 5.3 shows the Ecoinvent unit processes, found in the Ecoinvent database and taken as reference to model the Offshore Wind Farm of the case study, and the modifications made to model it in the most consistent way.

All metals, except the reinforcing steel of the basement, are assumed to be recycled at the end of life of the wind power plant, while plastics and glass will be burned in municipal waste incinerators, assuming that the composition of the blades is 65% glass and 35% plastics. Lubricant is burned in incinerators as well, but is considered as hazardous waste, therefore a different Ecoinvent unit process is chosen for its disposal.

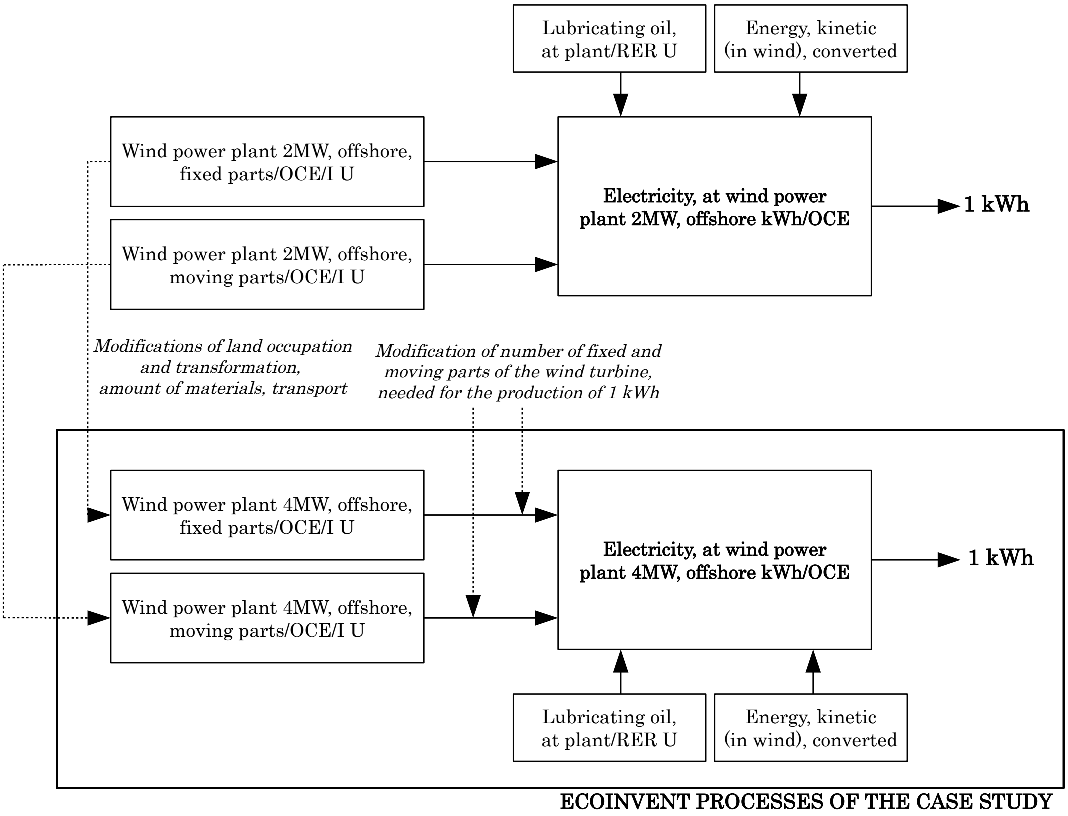

Figure 5.3: Ecoinvent unit processes found in the Ecoinvent database and modifications made to model Sites I and II of Borssele Wind Farm.

5.2.5 Economic data

Table 5.6 presents an overview of data used for the economic assessment of the wind farm, i.e. investment costs, operation and maintenance costs, subsidies and revenues of electricity, related to the production of 1 PJ of electricity. The total investment cost considered is 2 billions euros [61] and the Dutch government will provide a subsidy of €0.086 per kWh produced, for a maximum of 15 years [62].

Table 5.6: Economic data of the Offshore Wind Farm related to the production of 1 PJ of electricity.

Economic data	
Investment cost [10^6 €]	162.4
Operation and maintenance costs [10^6 €/year]	6.5
Revenues of electricity [10^6 €/year]	16.6
Subsidy [10^6 €/year]	23.8

5.3 Results

This section gives an overview of results of the environmental, economic and exergetic sustainability assessment of the offshore wind farm, followed by some considerations. A compared analysis of the results of the three systems can be found in Chapter 8.

5.3.1 Environmental assessment

SimaPro, in combination with the Ecoinvent database, was used to calculate the ReCiPe Midpoint indicators and the ReCiPe Endpoint indicators, with normalisation/weighting set described in Section 5.2.1. The results are shown in Table 5.7 and Table 5.9.

Table 5.7: ReCiPe Midpoint indicators derived from the LCA of the Offshore Wind Farm.

Impact category	**Unit**	**Score**
Climate change	[$\text{kg}_{\text{CO2,eq}}$]	$3.64 \cdot 10^{6}$
Ozone depletion	[$\text{kg}_{\text{CFC-11,eq}}$]	$2.00 \cdot 10^{-1}$
Terrestrial acidification	[$\text{kg}_{\text{SO2,eq}}$]	$1.30 \cdot 10^{4}$
Freshwater eutrophication	[$\text{kg}_{\text{P,eq}}$]	$1.96 \cdot 10^{3}$
Marine eutrophication	[$\text{kg}_{\text{N,eq}}$]	$1.02 \cdot 10^{3}$
Human toxicity	[$\text{kg}_{\text{1,4-DB,eq}}$]	$2.61 \cdot 10^{6}$
Photochemical oxidant formation	[kg_{NMVOC}]	$1.22 \cdot 10^{4}$
Particulate matter formation	[$\text{kg}_{\text{PM10,eq}}$]	$1.03 \cdot 10^{3}$
Terrestrial ecotoxicity	[$\text{kg}_{\text{1,4-DB,eq}}$]	$3.43 \cdot 10^{2}$
Freshwater ecotoxicity	[$\text{kg}_{\text{1,4-DB,eq}}$]	$8.46 \cdot 10^{4}$
Marine ecotoxicity	[$\text{kg}_{\text{1,4-DB,eq}}$]	$8.61 \cdot 10^{4}$
Ionising radiation	[$\text{kBq}_{\text{U235,eq}}$]	$5.80 \cdot 10^{5}$
Agricultural land occupation	[m^{2}a]	$7.68 \cdot 10^{4}$
Urban land occupation	[m^{2}a]	$3.48 \cdot 10^{4}$
Natural land transformation	[m^{2}]	$7.68 \cdot 10^{2}$
Water depletion	[m^{3}]	$1.01 \cdot 10^{5}$
Metal depletion	[$\text{kg}_{\text{Fe,eq}}$]	$2.90 \cdot 10^{6}$
Fossil depletion	[$\text{kg}_{\text{oil,eq}}$]	$1.07 \cdot 10^{6}$

The generation of electricity from wind energy presents a really low impact on ozone depletion and higher impact especially on resources depletion, i.e. metal and fossil depletion. The impact category of human toxicity and climate change present a score quite high as well. SimaPro enables also to investigate which substances or processes contribute to each Midpoint indicator. An example is shown in Table 5.8, which presents all the substances that have an impact on fossil depletion.

Table 5.8: Substances contribution to the impact category of fossil depletion.

Substance	[$\mathbf{kg_{oil,eq}}$]	[%]
Coal, brown	0.6 10^5	5
Coal, hard	5.2 10^5	49
Gas, mine, off-gas, process, coal mining/m3	0.1 10^5	1
Gas, natural/m3	2.6 10^5	24
Oil, crude	2.2 10^5	21
Total	10.7 10^5	100

Table 5.9 presents the ReCiPe Endpoint indicators resulting from the damage assessment and scores obtained after normalization and after weighting. As already mentioned, according to the default weighting set, more importance is given to damage to human health and to ecosystem diversity (40%) and less to resources (20%). Anyway, the damage category that presents the highest score is the one related to resources, followed by human health and ecosystems. The overall score results in a quite low value.

Table 5.9: ReCiPe Endpoint indicators derived from the LCA of the Offshore Wind Farm.

Damage category	**Unit**	**Score**
Human Health	[DALY]	9.6
Ecosystems	[species.yr]	0.032
Resources	[$]	384513
Human Health	[/]	475.25
Ecosystems	[/]	175.36
Resources	[/]	1245.86
Human Health	[MPt]	0.19
Ecosystems	[MPt]	0.07
Resources	[MPt]	0.25
Total	**[MPt]**	**0.51**

Figure 5.4 shows that the overall scores are mostly due to the construction of the fixed parts of the wind turbines, followed by the moving parts that present a lower impact. The impact of the use of lubricating oil and of its disposal is almost negligible.

Figure 5.5 shows the 10 processes that contribute most to the overall ReCiPe score with a contribution of almost 60%. It can be noted that 15% of the total impact is given by the process *"Iron ore, 46% Fe, at mine/GLO U"*, due to the fact that wind turbines are mainly composed of steel, produced from iron ore. A more detailed overview of the processes that contribute at least for 80% to the ReCiPe score can be found in Appendix C.

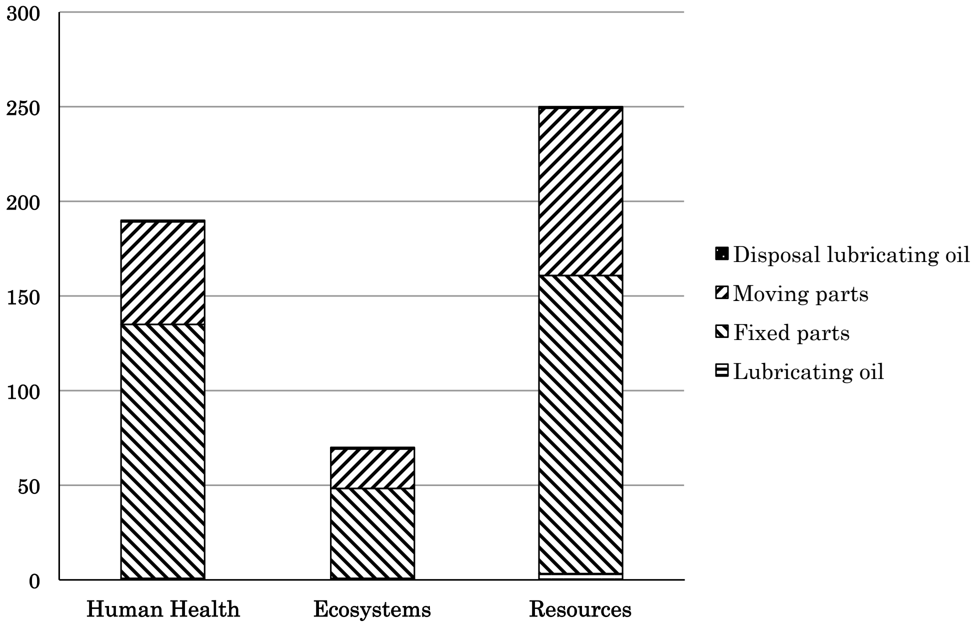

Figure 5.4: Process contribution to the ReCiPe Endpoint indicators of the Offshore Wind Farm.

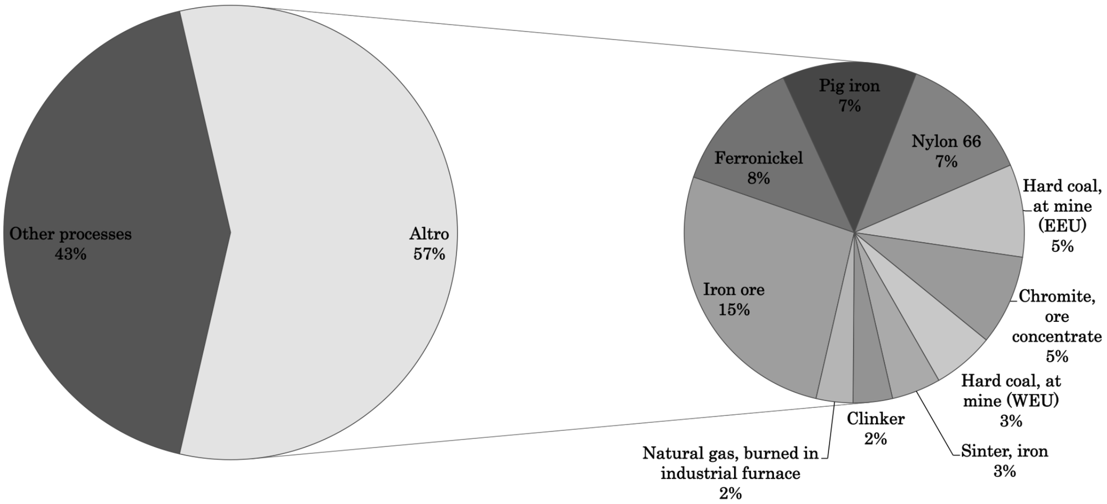

Figure 5.5: Processes that contribute for about 60% to the overall ReCiPe score of the Offshore Wind Farm.

5.3.2 Economic assessment

The NPV and the PWR of the wind farm were calculated with and without considering subsidies, to evaluate their influence. The investment costs were spread over the construction period, the O&M costs were considered for all the lifetime of the installation, included the construction period, and subsidies were taken into account starting from the first year of operation of the wind farm, for 15 years.

Table 5.10 presents the results of the assessment. Considering subsidies, the NPV equals 91 million euros and the PWR is 0.6. Without considering subsidies, the NPW and the PWR result in -83.6 million euros and -0.55. This means that the investment would not be profitable if the system was not subsidised by the Dutch government. Anyway it is reasonable to assume that the wind farm will be subsidised, because subsidies provided by the government for the use of renewable energies are at the basis of the Dutch energy policy.

Table 5.10: Results of the economic assessment of the Offshore Wind Farm.

	With subsidies	**Without subsidies**
NPV [10^6 €]	91	-83.6
PWR [-]	0.6	-0.55

5.3.3 Exergetic assessment

Table 5.11 presents the results of the exergetic assessment of the wind farm. Each component of the TCExL was calculated as explained in Section 4.3.3. It can be easly noticed that the Total Cumulative Exergy Loss is mostly due to the internal exergy loss, which contributes for 86% of the total exergy loss, and that the exergy loss related to land use is quite small, compared to the other components.

The Total Cumulative Exergy loss caused by this system, for the production of 1 PJ of electricity results in about 0.14 PJ, which is a quite small value.

Table 5.11: Total Cumulative Exergy Loss caused by the Offshore Wind Farm.

	[PJ]
CExD	1.1446
$\mathbf{Ex_{products}}$	1
$\mathbf{Ex_{emissions}}$	0.0168
$\mathbf{Ex_{loss,internal}}$	0.1278
$\mathbf{Ex_{loss,land\ use}}$	0.0006
$\mathbf{Ex_{loss,abatement}}$	0.0206
TCExL	0.1490

Chapter 6

Photovoltaic park

According to Vasseur [63], solar energy systems are one of the most promising sustainable energy technologies, nevertheless the implementation of photovoltaic panels is slower and more difficult than expected in many countries. Also in the Netherlands, even if policy makers are trying to promote and stimulate the use of photovoltaic systems, the diffusion of this technology is still low. At the end of 2015, the Dutch photovoltaic systems registered online (www.energieleveren.nl) had a cumulative capacity of 1.32 GW and this capacity will probably grow since that new projects are under development.

It was decided to analyse the largest solar energy park under construction in the Netherlands, the Sunport Delfzijl, located in the area of Groningen Seaports. With a total capacity of 30 MW, this solar park will provide energy for industries in the Eemsdelta region.

6.1 Data used for the environmental and economic assessment of the Photovoltaic Park

The project of the Sunport Delfzijl is still under development, and very little is known about its characteristics. It was impossible to get all the information needed to model the Photovoltaic Park in Ecoinvent, therefore the system was modeled using some information provided by the companies involved in the project (Groningen Seaports, Sunport Energy, WIRSOL) and modifying Ecoinvent datasets of smaller photovoltaic parks located in Europe, especially with regard to electric installation and inverters.

The supply chain of the electricity production from solar energy takes into account each process needed for the construction, operation, maintenance and decommissioning of the open ground power plant.

6.1.1 Components and installation of the photovoltaic park

Every photovoltaic system can be considered to be composed of four parts, as shown in Figure 6.1: the photovoltaic panels themselves, a support system to fix the panels on the ground (in the specific case of photovoltaic systems installed on open ground), electric wiring and inverters that convert the direct current into alternating current that can be injected into the grid. In this section it is explained how the processes for each part were modeled.

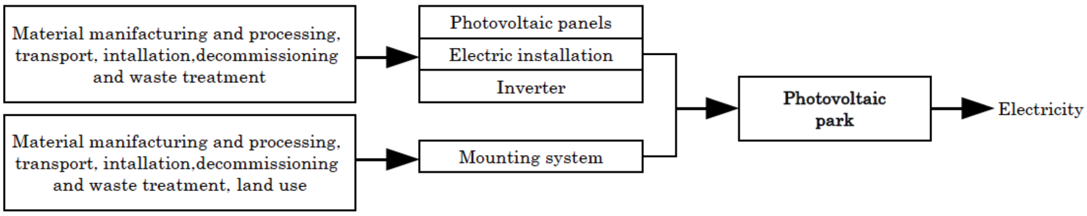

Figure 6.1: Solar energy supply chain.

Photovoltaic panels

The constructor company of the Sunport Delfzijl has not yet decided the type of panels to be installed and currently there are two type of panels under discussion, with a peak capacity to be chosen between 260 or 265 W. For this research, the panels with the largest peak capacity were used to model the power plant in Ecoinvent:

1. **CS6P-265P**(Canadian Solar Inc.), poly-crystalline panels with a peak capacity of 265 W and a module efficiency in Standard Test Condition (STC) of 16.47%;
2. **ASM6610P-265**(Astronergy), poly-crystalline panels with a peak capacity of 265 W and a module efficiency in Standard Test Condition (STC) of 16.20%;

The Ecoinvent process was modeled twice, considering both solutions of panels produced in Canada and in Germany, to compare the sustainability assessment of photovoltaic installations of panels manufactured in different countries. In order to account for the photovoltaic panels imported to Europe from Canada, the consumed electricity for silicon, ingots, wafers, cells and panels production is modified considering the Canadian electricity mix and also the transport of the panels to Europe by transoceanic freight ships.

The results of the assessments can be different, since electricity consumption for panels manufacturing is one of the most relevant factors when assessing the environmental performance of electricity production from solar energy [64].

Considering a total capacity of 30 MW and solar panels with a peak capacity of 265 W, the number of panel needed results in 113208. The total active area needed is calculated multiplying the number of panels by the area of a single panel, that can be found in the datasheet provided by the construction companies. The total number of square meters of photovoltaic panels is calculated considering also a 2% replacement of damaged panels during lifetime and a further production loss during handling of 1 %, following Ecoinvent directives [64]. All the processes needed for the production of panels are taken into account in the Ecoinvent unit process *"Photovoltaic panel, muti-Si, at plant/RER/I U"*, starting from quartz reduction, silicon purification, silicon ingots, wafers and cells production to the final manufacturing of panels themselves.

Mounting system, electric installation and inverters

For the open ground mounting system, including also the fence built to prevent the access to the high voltage area, a dataset per m^2 of installed panels was found [64]. Because of the lack of data found about inverters and electric wiring used in the Sunport Delfzijl solar park, data were scaled from smaller plants [64].

Electricity consumption for the installation of the system

The electricity consumption of all processes along the supply chain is taken into account. For the final assembly of the installation, electricity and diesel consumption are estimated considering data related to other photovoltaic power plant, found in the Ecoinvent database.

All the inputs and emissions to air for the construction of the 30 MW_p power plant can be found in Appendix B. Every process refers to an Ecoinvent unit process found in the database, with several modifications and educated guesses.

6.1.2 Transport

The life cycle inventory of each part of the Photovoltaic Park takes into account the transport of materials, energy carriers and semi-finished products needed for its construction. In the Ecoinvent unit process *"30MWp open ground installation, multi/Si, on open ground"* the transport of the equipment is considered and differs between the 2 alternatives:

- In the first alternative, panels are assumed to be manufactured in the Canadian Solar's facility located in Ontario (Canada), while the other parts of the installation are assumed to be produced in the Netherlands. With these assumptions panels are transported for a distance of 6500 km by transoceanic ship and for 300 km by lorry. For inverters, mounting system and electric components a standard distance of 150 km by lorry is assumed.
- In the second alternative, panels are assumed to be manufactured in the Astronergy's facility located in Frankfurt (Germany), therefore they are transported by train for a

distance of 650 km and for other 50 km by lorry. The same transport distance applied in the first solution for the other parts of the installation is used in this case as well.

The Ecoinvent unit processes used for the transport are *"Transport, transoceanic freight ship/OCE U"*, *"Transport, freight, rail/RER U"* and *"Transport, lorry* $> 16t$*, fleet average/RER U"*.

6.1.3 Land use

The land use of the open ground installation is taken into account in the inventory of the mounting system, considering 4.7 m^2 per m^2 of installed panels, based on information found in the Ecoinvent report that refers to data related to large scale power plants [64]. In the inventory, 1.5 m^2 are considered as built up industrial area and 3.2 m^2 as industrial area with vegetation.

6.1.4 Operation and decommissioning of the photovoltaic system

The electricity produced is based on the Ecoinvent unit process *"Electricity, PV, at 30 MW_p power plant, multi-Si, panel, kWh/NL U"* , which is a modification of the process *"Electricity, PV, at 3 kW_p slanted-roof, multi-Si, panel, mounted/CH U"*, found in the Ecoinvent database.

Both processes consider an amount of 3.85 MJ of solar energy as input, and an amount of 0.25 MJ of waste heat per kWh produced.

The installation needed to produce 1 kWh was calculated as explained in Section 4.4.3 and results in $1.27 \cdot 10^{-9}$ p.

Also the use of water needed to clean the panels and its treatment after use are included in the unit process. The amount of water is obtained multiplying the number of installations needed for the production of 1 kWh by 20 l/m^2 per year, i.e. the estimated use of water, and by the total area of panels.

All the information needed to model the Photovoltaic Park can be found in the Ecoinvent report about the LCI of photovoltaics [64].

The lifetime of the installation and inverters is assumed to be 30 years and 15 years, respectively, therefore the inverters must be changed once during the lifetime of the photovoltaic system. The amount of electricity generated by the plant is calculated from the installed capacity multiplied by a specific yield value of 875 kWh per kW_p installed. Van Sark et al. [65] reached the conclusion that this specific annual yield should be used when calculating the amount of electricity generated by photovoltaic systems located in the Netherlands, from 2011 onwards.

Figure 6.2 shows how the main process was modeled, taking as reference one of the processes for electricity production from a 3 kW_P installation, found in the Ecoinvent database. The process for the construction of the photovoltaic system itself was modeled from the beginning, as described in Section 6.1.1, since it was not possible to find a process suitable for the photovoltaic system of this case study in the Ecoinvent database.

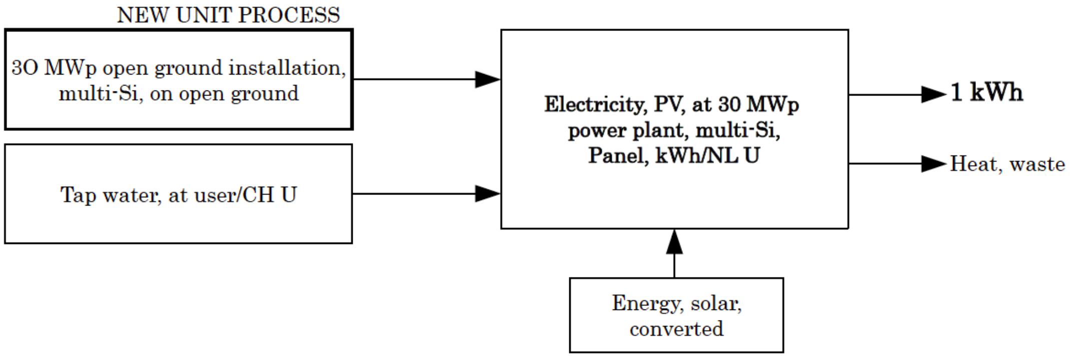

Figure 6.2: Ecoinvent unit process of Photovoltaic Park, modeled in the case study.

6.1.5 Economic data

Table 6.1 presents an overview of data used for the economic assessment, to calculate the Net Present Value (NPV) and the Present Worth Ratio (PWR), referring to the production of 1 PJ of electricity. Since the photovoltaic park capacity is lower than the one needed to produce the functional unit, i.e. 1 PJ, the total investment cost was calculated as described in Section 4.3.2, and results in 123.5 millions of euro, considering an investment cost of 30 millions euro for a peak capacity of 30 MW [66]. The photovoltaic park will be subsidized by the Dutch government, and subsidies related to electricity production from photovoltaic systems can be found in the SDE+2016 provided from RVO [62]. In this research the subsidy of the last phase of tendering was taken into account, i.e. €0.084 per produced kWh.

Table 6.1: Economic data of the Photovoltaic Park related to the production of 1 PJ of electricity.

Economic data	
Investment cost [10^6 €]	123.5
Operation and maintenance costs [10^6 €/year]	4.9
Revenues of electricity [10^6 €/year]	16.6
Subsidy [10^6 €/year]	23.3

6.2 Results

This section presents the results of the environmental, economic and exergetic assessment of the Photovoltaic Park, pointing out the differences between the two alternatives analysed. Since the results of the two systems do not differ too much, one system will be compared with the other systems of the case study, i.e. the photovoltaic park equipped with panels produced in Germany. The choice of this system was driven by the idea that the construction company will probably choose the panels produced in Europe.

6.2.1 Environmental assessment

The results of the environmental assessment of the Photovoltaic Park are the ReCiPe Midpoint and Endpoint indicators, presented in tables 6.2 and 6.3, respectively.

Table 6.2: ReCiPe Midpoint indicators derived from the LCA of the Photovoltaic Park.

Impact category	**Unit**	**Canada**	**Germany**
Climate change	[$kg_{CO2,eq}$]	$1.47 \cdot 10^7$	$1.63 \cdot 10^7$
Ozone depletion	[$kg_{CFC\text{-}11,eq}$]	$3.22 \cdot 10^0$	$3.46 \cdot 10^0$
Terrestrial acidification	[$kg_{SO2,eq}$]	$6.52 \cdot 10^4$	$5.84 \cdot 10^4$
Freshwater eutrophication	[$kg_{P,eq}$]	$8.26 \cdot 10^3$	$1.09 \cdot 10^4$
Marine eutrophication	[$kg_{N,eq}$]	$6.09 \cdot 10^3$	$5.98 \cdot 10^4$
Human toxicity	[$kg_{1,4\text{-}DB,eq}$]	$1.45 \cdot 10^7$	$1.62 \cdot 10^7$
Photochemical oxidant formation	[kg_{NMVOC}]	$5.58 \cdot 10^4$	$5.45 \cdot 10^4$
Particulate matter formation	[$kg_{PM10,eq}$]	$2.60 \cdot 10^4$	$2.47 \cdot 10^4$
Terrestrial ecotoxicity	[$kg_{1,4\text{-}DB,eq}$]	$3.23 \cdot 10^4$	$3.31 \cdot 10^4$
Freshwater ecotoxicity	[$kg_{1,4\text{-}DB,eq}$]	$2.89 \cdot 10^5$	$3.32 \cdot 10^5$
Marine ecotoxicity	[$kg_{1,4\text{-}DB,eq}$]	$3.44 \cdot 10^5$	$3.87 \cdot 10^5$
Ionising radiation	[$kBq_{U235,eq}$]	$5.39 \cdot 10^6$	$3.35 \cdot 10^6$
Agricultural land occupation	[m^2a]	$7.02 \cdot 10^5$	$7.86 \cdot 10^5$
Urban land occupation	[m^2a]	$9.20 \cdot 10^6$	$9.35 \cdot 10^6$
Natural land transformation	[m^2]	$3.02 \cdot 10^3$	$3.06 \cdot 10^3$
Water depletion	[m^3]	$1.63 \cdot 10^6$	$1.59 \cdot 10^6$
Metal depletion	[$kg_{Fe,eq}$]	$3.81 \cdot 10^6$	$3.88 \cdot 10^6$
Fossil depletion	[$kg_{oil,eq}$]	$4.17 \cdot 10^6$	$4.58 \cdot 10^6$

Concerning the Midpoint indicators, the impact categories that present different scores in terms of order of magnitude are freshwater and marine eutrophication, with higher values for German panels. Investigating which substances contribute more to these categories for German panels, it is pointed out that freshwater eutrophication is due especially to phosphate emissions to water while marine eutrophication to nitrate emissions to water.

Focusing on the Endpoint indicators, the category that has the highest score is ‘damage to human health’, followed by ‘damage to ecosystems’ and ‘damage to resources’. The system equipped with panels produced in Germany presents a slightly highest environmental impact. Nevertheless, the total scores do not differ too much since the only differences are transport and electricity mix used in panels manufacturing processes.

Table 6.4 presents the 15 processes that contribute most to the final ReCiPe score and the corresponding shares, for both alternatives. Most of the processes are the same for both systems but it can be noticed that the German electricity mix includes electricity production by lignite, that does not appear at least in the 15 most impacting processes for Canada. Lignite, also called brown coal, is the type of coal with the lower quality, mainly used for electric power generation. Burning lignite is one of the most polluting ways to produce electricity. In Germany lignite is still the main technology and statistics of 2014 show that about 24 % of the total electricity generated was produced from lignite [67]. This is probably the main factor that led to different results in the environmental assessment of the two photovoltaic park.

Table 6.3: ReCiPe Endpoint indicators derived from the LCA of the Photovoltaic Park.

Damage category	**Unit**	**Canada**	**Germany**
Human Health	[DALY]	37.6	40.6
Ecosystems	[species.yr]	0.328	0.346
Resources	[$]	960943	1034169
Human Health	[/]	1863	2012
Ecosystems	[/]	1817.10	1912.82
Resources	[/]	3113.45	3350.70
Human Health	[MPt]	0.74	0.80
Ecosystems	[MPt]	0.73	0.77
Resources	[MPt]	0.62	0.67
Total	[MPt]	2.09	2.24

Table 6.4: Processes with the most important contribution to the total ReCiPe score of the Photovoltaic Park.

Germany	**[MPt]**	**Share** [%]
Open ground construction, on open ground	0.42	19
Electricity, at cogen 1MWe lean burn/RER	0.11	5
Disposal, sulfidic tailings, off-site/GLO	0.09	4
Natural gas, at production onshore/RU	0.07	3
Photovoltaic cell, multi-Si, at plant/DE	0.06	3
Electricity, high voltage {DE}, electricity production, lignite	0.06	2
Aluminium, primary, liquid, at plant/RER	0.05	2
Copper concentrate, at beneficiation/RER	0.05	2
Iron ore, 46% Fe, at mine/GLO	0.04	2
Electricity, high voltage {DE}, electricity production, hard coal	0.04	2
Copper concentrate, at beneficiation/RLA	0.03	2
Lignite {RER}, mine operation	0.03	1
Hard coal {WEU}, mine operation	0.03	1
Flat glass, uncoated, at plant/RER	0.03	1
Natural gas, at production onshore/DZ	0.03	1
	1.14	51
Canada	**[MPt]**	**Share** [%]
Open ground construction, on open ground	0.42	20
Electricity, at cogen 1MWe lean burn/RER	0.11	5
Disposal, sulfidic tailings, off-site/GLO	0.09	4
Natural gas, at production onshore/RU	0.06	3
Photovoltaic cell, multi-Si, at plant/CA	0.06	3
Aluminium, primary, liquid, at plant/RER	0.05	3
Electricity, high voltage {CA-ON}, electricity production, hard coal	0.05	2
Copper concentrate, at beneficiation/RER	0.05	2
Iron ore, 46% Fe, at mine/GLO	0.04	2
Copper concentrate, at beneficiation/RLA	0.03	2
Flat glass, uncoated, at plant/RER	0.03	1
Natural gas, at production onshore/DZ	0.03	1
Hard coal, at mine/WEU	0.03	1
Natural gas, at production offshore/NO	0.03	1
Hard coal {RNA}, mine operation	0.03	1
	1.11	53

It was also analysed the environmental impact of the amount of the photovoltaic system needed for the production of 1 PJ. Referring to the photovoltaic system equipped with German panels, it can easily be noticed that the main contribution to the final scores is given by processes used for panels and mounting system production, as shown in Figure 6.2. This analysis was conducted also for the system with Canadian panels, and similar results were obtained, even if they are not reported here. The conclusion is that the transoceanic transport of panels does not contribute significantly to the final score.

Also the environmental impact related to the production of 1 m^2 of photovoltaic panels was investigated for the two alternatives. The unit process used is the same for German and

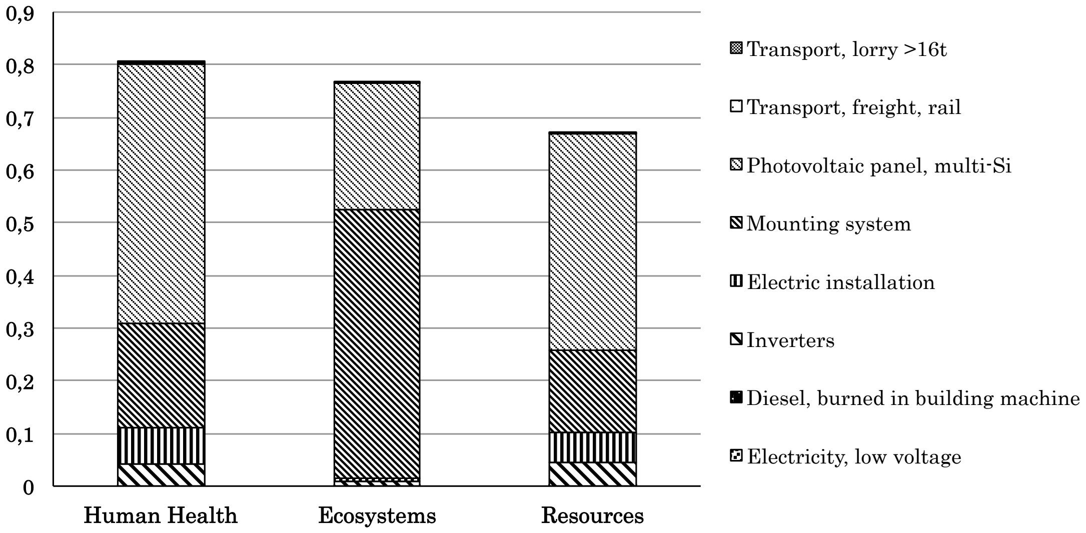

Figure 6.3: Contribution of processes to the ReCiPe Endpoint indicators of the Photovoltaic Park (German panels).

Canadian panels, i.e. *"Photovoltaic panel, multi-Si, at plant/RER/I U"*, with the exception of the electricity mix used along the supply chain. The Ecoinvent datasets of the electricity mix refer to data from 2008 to 2014, considering electricity production from different resources and import from other countries; with this data, panels produced using the German electricity mix presents an highest environmental impact.

6.2.2 Economic assessment

The NPV and the PWR of the photovoltaic park were calculated with and without considering subsidies, in the same way as done for the other systems. Table **??** presents yearly cash flows obtained considering subsidies, that lead to a NPV of 155.6 million euros and a PWR of 1.36. Without considering subsidies the NPV and the PWR result in -15.4 million euros and -0.13, i.e. the investment is not profitable. Results are presented in Table 6.5.

Table 6.5: Results of the economic assessment of the Photovoltaic Park.

	With subsidies	**Without subsidies**
NPV[10^6 €]	155.6	-15.4
PWR [-]	1.36	-0.13

6.2.3 Exergetic assessment

Table 6.6 presents the results of the exergetic assessment of the two alternatives analysed. As obtained for the environmental assessment, the photovoltaic park equipped with panels produced in Germany presents an higher Total Cumulative Exergy Loss. The TCExL of the photovoltaic parks are not significantly different from one another. For both systems the internal exergy loss, obtained subtracting the exergy value of outputs from the Cumulative Exergy Demand, is the component that contributes most to the final score, while the exergy loss caused by land use is the lowest component.

Table 6.6: Total Cumulative Exergy Loss caused by the Photovoltaic Park.

	Canada [PJ]	**Germany** [PJ]
CExD	1.3706	1.3740
Ex_products	1	1
Ex_emissions	0.0798	0.0827
Ex_loss,internal	0.2908	0.2913
Ex_loss,landuse	0.0018	0.0024
Ex_loss,abatement	0.0792	0.0874
TCExL	0.3700	0.3812

Chapter 7

Biomass-fired power plant

Biomass is fuel originated from organic matter produced by photosynthesis, which can be used to generate heat and electricity. Biomass includes for example trees, municipal solid waste, animal wastes, forestry and agricultural residues. The use of biomass presents several advantages: it is widely available, can help in reducing wastes and it can be used for electricity generation in the same power plants that are now burning fossil fuels [68]. In addition, the use of biomass makes the country more independent from countries that produce oil and gas and less dependent on fossil fuels in general. However, biomass firing is not always considered as a good solution from the environmental point of view because its advantages are accompanied with negative aspects such as the fact that its direct combustion can be harmful to the environment, since it is accompanied with carbon dioxide and others pollutant emissions and also because the use of wood biomass can lead to deforestation [68].

Biomass is mainly used in the Netherlands in co-fired power plants to replace in part fossil resources, enabling a sensible reduction of fossil carbon dioxide emissions related to power generation. The Dutch market for electricity derived from biomass resources is well-developed and the Netherlands are the second largest wood pellet importer in the world [69]. Between the co-fired power plants located in the Netherlands, the Amer Power Plant is one of the largest electricity producers of the country. The Amer Power Plant is located in Geertruidenberg and comprises 2 units with a total power generating capacity of 1245 MW and a heat production capacity of 600 MW. The primary fuel is coal, but also natural gas, wood gas and biomass such as wood pellets are used [70].

Recently, CE Delft [71] has conducted a study concerning alternatives for co-firing biomass in coal plants, reaching the conclusion that the maximum contribution to the 14% renewable energy target of this kind of energy production is 25 PJ per year. Two possible scenarios for the replacement of this 25 PJ energy production were analysed; the first scenario implies the use of four different renewable energy sources (wind and solar energy, industrial bio-steam and biomass for district heating) while the second alternative involves the conversion of Unit 8 of the Amer Power Plant to be 100% biomass-fired. It was decided to analyse a biomass-fired power plant based on the CE Delft study, as last system of the case study of this research.

7.1 General description of the biomass-fired power plant

Since the subject of this research will be Unit 8 of the Amer Power Plant, this section deals with information about its characteristics and the modifications that would be made for its conversion to burn only biomass. Considering the co-fired power plant, Unit 8 has a capacity of 645 MW_e and 250 MW_th and it has been used from 1980 to the 1st of January 2016, when it was taken out of operation for the four-yearly complete revision. Figure 7.1 shows the main components of the power plant: the fuel is used to generate steam in a boiler, afterwards sent to a turbine connected to a generator; the steam is cooled using a condenser and a cooling tower. Part of the steam is taken from the turbine and delivered to houses, commercial buildings and greenhouses. The power plant is equipped with several end of pipe devices, such as electrostatic precipitators which ensure that almost 100% of the fly ashes is filtered out of the flue gases, a desulfurization unit and a DeNOx unit that remove more than 85% of sulfur dioxide and 80% of nitrogen oxides from the flue gases, respectively [70].

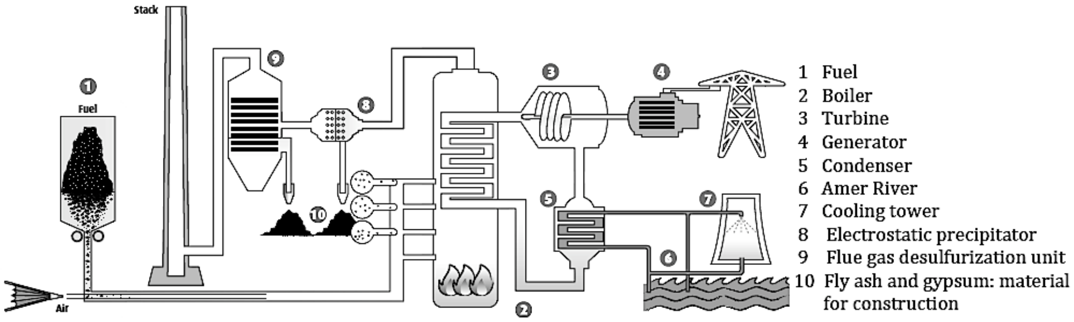

Figure 7.1: Schematic representation of Unit 8 of Amer Power Plant [70].

The conversion to burn only biomass implies several modifications to the power plant:

- installation of facilities for storage and handling of wood pellets;
- installation of hammer mills to grind the biomass or adaptation of the existing coal mills;
- installation of specific biomass burners or adjustments to the current burners to burn wood pellets;

Data concerning the expected performances of Unit 8 can be found in the CE Delft report [71]. The power plant would be characterised by an electrical efficiency of 39%, which is lower than the current efficiency, and an electricity production of 17 PJ accompanied with a heat production of 8 PJ (i.e. 0,47 PJ_{th} per PJ_e).

7.2 Biomass-fired power plant in the Ecoinvent process

A co-fired power plant based on the Amer Power Plant has already been studied by Stougie in the "Fossil versus renewable energy sources for power generation" case study [1]. Therefore data related to the wood pellets supply chain that were used in this research, refer to that previous case study. The system analysed is shown in Figure 7.2. Similarly as done for the other systems, each phase of the supply chain of the electricity generation from wood pellets is taken into account.

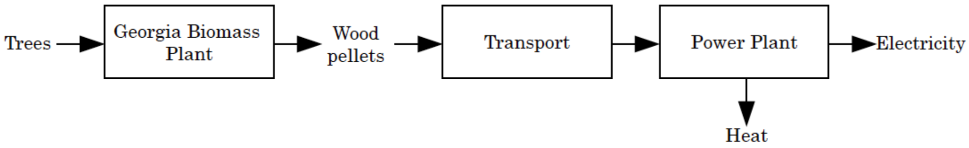

Figure 7.2: Firing of wood pellets.

7.2.1 Wood pellets supply chain

Most of the wood pellets fired in the power plant are produced and imported from the Georgia Biomass plant, located in Waycross, Georgia (USA). This plant has a capacity of 750000 tons of wood pellets per year and was commissioned by the owner of the Amer Power Plant.

The wood pellet supply chain has been modeled by Stougie [1] and consists of the following unit processes that are modifications of Ecoinvent unit processes:

- **Wood pellet at Savannah harbor**: based on the Ecoinvent unit process *"Wood pellets, u=10%, at storehouse/RER U"* , 1.285 m^3 of *"Georgia wood from planing, kiln dried"* is needed;
- **Georgia wood from planing, kiln dried**: based on the Ecoinvent unit process *"Industrial residue wood, from planing, softwood, kiln dried, u=10%, at plant/RER U"* , 1 m^3 of *"Georgia sawn timber, kiln dried"* is needed;
- **Georgia sawn timber, kiln dried**: based on the Ecoinvent unit process *"Sawn timber,*

softwood, raw, kiln dried, u=10%, at plant/RER U" , 1.001 m^3 of *"Georgia sawn timber, forest-debarked"* and 958 MJ of *"Georgia wood chips,burned in furnace"* are needed;

- **Georgia sawn timber, forest-debarked**: based on the Ecoinvent unit process *"Sawn timber, softwood, raw, forest-debarked, u=70%, at plant/RER U"*, 0.9996 m^3 of *"Georgia wood, debarked, at forest road"* is needed;
- **Georgia wood, debarked, at forest road**: based on the Ecoinvent unit process *"Round wood, softwood, debarked, u=70% at forest road/RER U"*, 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**: 1 m^3 of this consists 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 of *"Residual wood, softwood, under bark, u=140%, at forest road/RER U"*;
- **Georgia wood chips, burned in furnace**: based on the Ecoinvent unit process *"Wood chips, from industry, softwood, burned in furnace 300kW/CH U"*, 0.000328 m^3 of *"Georgia bark"* is used as a fuel;

It was assumed that all the biomass burned in the power plant would be wood pellet imported from Georgia. Other data used in this research are a lower heating value of wood pellet of 17 GJ/ton and a volumetric bulk density (weight per unit of volume) of 650 kg/m^3 [72], used to calculate the volumetric wood pellet consumption. With this data we can calculate the amount of wood pellets required for the production of 1 PJ of electricity, which equals 232046 m^3.

7.2.2 Emissions from wood pellet combustion

When considering wood pellet combustion, it is important to point out the composition of the flue gases generated, because emissions have to be evaluated and taken into account. The composition of the flue gasses is related to the chemical composition of wood pellet and it is carried out with an element-analysis. Results of an element-analysis of wood pellet are shown in Table 7.1 [73].

Table 7.1: Example of chemical composition of wood pellets.

Element	**Share [%]**
Hydrogen (H_2)	5.8
Carbon (C)	46.5
Oxygen (O_2)	39.5
Ash	0.9
Sulphur (S)	0.05
Nitrogen (N_2)	0.28
Water (H_2 O)	7

Flue gases are composed of elements and substances whose emission do not lead to environmental impact, such as nitrogen, water, oxygen and argon, but also of other gases and matter that are not desirable under the environmental and health point of view, i.e. carbon dioxide, sulphur dioxide, carbon monoxide, nitrogen oxides, polycyclic aromatic hydrocarbons (PAH), total organic compounds (TOC) and particulate matter.

Emission values for delivered energy are presented in Table 7.2 [73], [74]. These values were used to model the Biomass-fired Power Plant in the Ecoinvent process.

Table 7.2: Emissions derived from wood pellet combustion.

Emission	**[mg/MJ]**
Carbon dioxide	108
Sulphur dioxide	0
Carbon monoxide	50-3000
Nitrogen oxide	130-300
TOC	10
PM	30

7.2.3 Electricity and heat generation in the Ecoinvent process

The Ecoinvent process *“Electricity-wood pellet”* is based on the unit process *“Hard coal, burned in power plant/MJ/NL”*, found in the Ecoinvent database. Anyway, this process was completely modified using data found in the CE Delft report [71], and neglecting several emissions to air, since wood pellets combustion is accompanied with less emissions than hard coal combustion.

The process was modeled considering an electricity production of 1 PJ, i.e. the functional unit, accompanied with an heat generation of 0.47 PJ. The power plant itself is based on the Ecoinvent unit process *“Hard coal power plant/RER/I U”*, because it was not possible to find a process suitable for this case study in the Ecoinvent database and anyway the Amer Power Plant would be based on an hard coal power plant, even if subjected to the modifications needed for the conversion to burn only biomass . Since that the Amer Power Plant is equipped with both condenser and cooling tower, it is assumed that 25% of the plant is river cooled and the other 75% uses the cooling tower, referring to Ecoinvent guidelines [75]. Emissions are related to Table 7.2 and the amount of slags and ashes generated, that is not combustible, is assumed to be 1 % of the burned mass of wood pellet [73]. For the transport of wood pellets from Georgia to the power plant site, it was assumed a distance of 7200 km by transoceanic ship and 50 km by barge.

An overview of products, material/fuels and emissions related to the production of 1 PJ of electricity is given in Appendix B, and Figure 7.3 shows a schematic representation of the main unit process, *"Electricity-wood pellet"*. Unlike what done for the Offshore Wind Farm, the reference process is not shown in Figure 7.3, since it is significantly different.

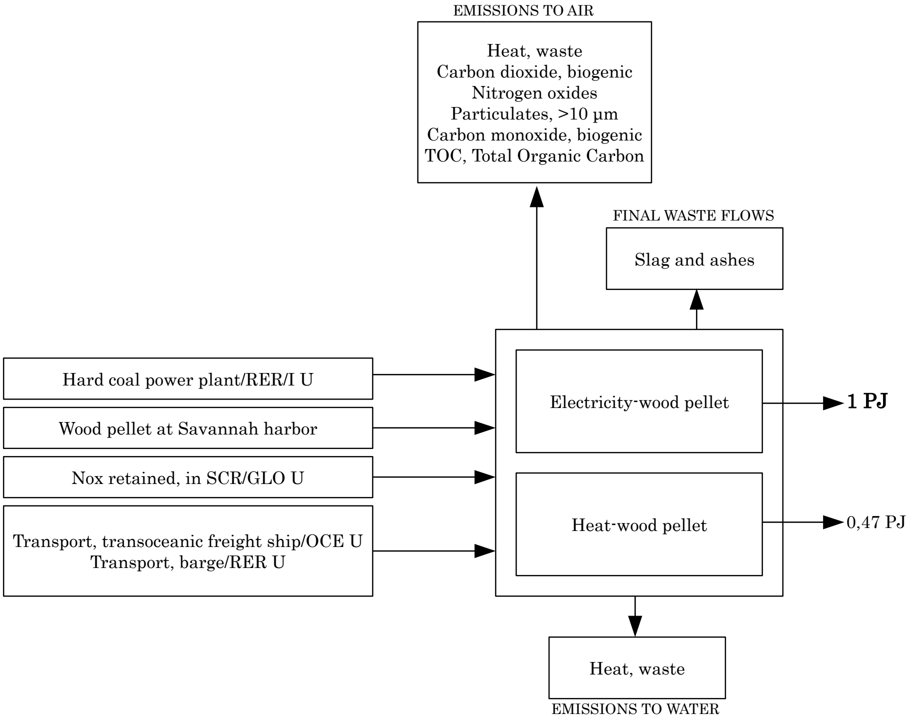

Figure 7.3: Ecoinvent unit process of the Biomass-fired Power Plant, modeled in the case study.

7.2.4 Economic data

Table 7.3 presents the economic data used for the calculation of the NPV and the PWR of the Biomass-fired Power Plant, related to the production of 1 PJ of electricity. The considered costs are investment costs of the wood pellet power plant and the hard coal power plant, the estimated conversion cost, wood pellet cost and O&M costs. The considered incomes are subsidies and electricity revenues.

The total investment costs of the wood pellet and coal power plant are 137 million euros and 550 million euros (i.e. half of the investment cost of the Amer Power Plant, that includes Unit 8 and 9), respectively [1]. The estimated conversion costs were found in the CE Delft report (450 €/kW$_e$) [71], the selling price of wood pellet considered is 120 €/ton [76] and, as already mentioned, operation and maintenance costs are 4% of the initial investment cost. Yearly subsidies were calculated from data found in the CE Delft report [71].

Table 7.3: Economic data of the Biomass-fired Power Plant related to the production of 1 PJ of electricity.

Economic data	
Investment and conversion costs [10^6 €]	77
Operation and maintenance costs [10^6 €/year]	2.4
Revenues of electricity [10^6 €/year]	16.6
Wood pellet cost [10^6 €/year]	18.1
Subsidy [10^6 €/year]	35.3

7.3 Results

This section provides a review of the results of the environmental, economic and exergetic assessment of the Biomass-fired Power Plant, referring to the electricity generation on 1 PJ.

7.3.1 Environmental assessment

Table 7.4 presents the ReCiPe Midpoint indicators while 7.5 presents the Endpoint indicators, after normalization and weighting as well.

Table 7.4: ReCiPe Midpoint indicators derived from the LCA of the Biomass-fired Power Plant.

Impact category	**Unit**	**Score**
Climate change	[$\mathrm{kg_{CO2,eq}}$]	$4.37 \cdot 10^7$
Ozone depletion	[$\mathrm{kg_{CFC\text{-}11,eq}}$]	$3.34 \cdot 10^0$
Terrestrial acidification	[$\mathrm{kg_{SO2,eq}}$]	$6.09 \cdot 10^5$
Freshwater eutrophication	[$\mathrm{kg_{P,eq}}$]	$2.92 \cdot 10^4$
Marine eutrophication	[$\mathrm{kg_{N,eq}}$]	$3.42 \cdot 10^4$
Human toxicity	[$\mathrm{kg_{1,4\text{-}DB,eq}}$]	$2.18 \cdot 10^7$
Photochemical oxidant formation	[$\mathrm{kg_{NMVOC}}$]	$8.05 \cdot 10^5$
Particulate matter formation	[$\mathrm{kg_{PM10,eq}}$]	$2.29 \cdot 10^5$
Terrestrial ecotoxicity	[$\mathrm{kg_{1,4\text{-}DB,eq}}$]	$2.72 \cdot 10^3$
Freshwater ecotoxicity	[$\mathrm{kg_{1,4\text{-}DB,eq}}$]	$5.09 \cdot 10^5$
Marine ecotoxicity	[$\mathrm{kg_{1,4\text{-}DB,eq}}$]	$5.29 \cdot 10^5$
Ionising radiation	[$\mathrm{kBq_{U235,eq}}$]	$2.33 \cdot 10^7$
Agricultural land occupation	[$\mathrm{m^2a}$]	$2.57 \cdot 10^8$
Urban land occupation	[$\mathrm{m^2a}$]	$3.22 \cdot 10^6$
Natural land transformation	[$\mathrm{m^2}$]	$3.55 \cdot 10^4$
Water depletion	[$\mathrm{m^3}$]	$1.20 \cdot 10^6$
Metal depletion	[$\mathrm{kg_{Fe,eq}}$]	$2.02 \cdot 10^6$
Fossil depletion	[$\mathrm{kg_{oil,eq}}$]	$1.28 \cdot 10^7$

Impact categories of climate change, human toxicity and land occupation present quite high scores. Concerning land occupation it was investigated which processes contribute more to the score and clearly the wood pellet supply chain gives the largest contribution.

The Endpoint indicator related to ‘damage to ecosystems’ is significantly higher than the other indicators, followed by ‘damage to human health’ and ‘damage to resources’. The total ReCiPe score results in 12.2 MPt.

Table 7.5: ReCiPe Endpoint indicators derived from the LCA of the Biomass -fired Power Plant.

Damage category	**Unit**	**Score**
Human Health	[DALY]	138
Ecosystems	[species.yr]	3.6
Resources	[$]	2283395
Human Health	[/]	6832.7
Ecosystems	[/]	19976.4
Resources	[/]	7398.2
Human Health	[MPt]	2.7
Ecosystems	[MPt]	8
Resources	[MPt]	1.5
Total	[MPt]	12.2

Figure 7.3 shows the contribution of each process to the final scores. It is evident that the process that has the highest impact on each endpoint indicator is *"Wood pellets at Savannah harbor"*, that include all the processes related to the wood pellet supply chain. The second process that contribute most on the damage categories is the transoceanic transport of wood pellet from Georgia (US) to the Netherlands. Investigating which processes contribute most to the overall ReCiPe score, it is pointed out that *"Softwood, standing, under bark, in forest/RER U"* contributes for almost 57 %.

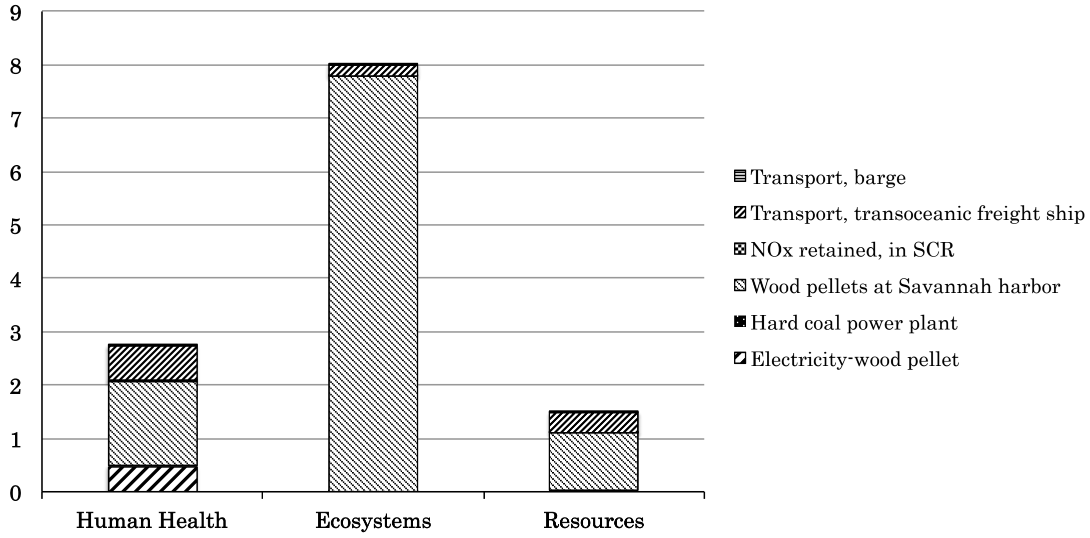

Figure 7.4: Contribution of the Ecoinvent processes to the ReCiPe Endpoint indicators of the Biomass-fired Power Plant.

7.3.2 Economic assessment

As done for the other two systems, the Net Present Value and the Present Worth Ratio were calculated with and without considering subsidies, with a discount rate of 8%. The results of the economic assessment are shown in Table 7.6. The alternative with subsidies is profitable, resulting in a NPV of 148.2 million euros and a PWR of 2.1, while the scores have negative values without considering subsidies, i.e. the investment is not convenient, as expected and obtained also for the two other systems of the case study.

Table 7.6: Results of the economic assessment of the Biomass-fired Power Plant.

	With subsidies	**Without subsidies**
NPV [10^6 €]	148.2	-110.9
PWR	2.1	-1.5

7.3.3 Exergetic assessment

The results of the exergetic assessment of the Biomass-fired Power Plant are presented in Table 7.7. Similarly to the other two systems, the Total Cumulative Exergy loss is mainly due to the internal exergy loss, while the other components, i.e. exergy loss caused by land use and abatement exergy loss are quite small. The exergy loss caused by the system to generate 1 PJ of electricity is about 3 PJ.

Table 7.7: Total Cumulative Exergy Loss caused by the Biomass-fired Power Plant

	[PJ]
CExD	3.9573
$\mathbf{Ex_{products}}$	1.0000
$\mathbf{Ex_{emissions}}$	0.4161
$\mathbf{Ex_{loss,internal}}$	2.5412
$\mathbf{Ex_{loss,land\ use}}$	0.0175
$\mathbf{Ex_{loss,abatement}}$	0.4149
TCExL	2.9735

Chapter 8

Comparison of the results

In the previous chapters, the Offshore Wind Farm (OWF), the Photovoltaic Park (PP) and the Biomass-fired Power Plant (BPP) were discussed and analysed. Once the environmental, economic and exergetic assessments of the three systems have been conducted, the results are compared to understand which system is preferred from each point of view. After the presentation of the results, the reasons that make one system preferred over the others are discussed. For simplicity, just one of the photovoltaic park will be compared with the other two systems, i.e. the one equipped with panels produced in Germany, as already explained in Section 6.2. In sections 8.1, 8.2 and 8.3 the results of the environmental, economic and exergetic assessment are compared separately while in Section 8.4 all results are presented together, followed by considerations about the consequences of choosing the system that is preferred from the exergetic point of view, in regard to the other aspects of sustainability.

8.1 Results of the environmental sustainability assessment

The results of the environmental sustainability assessment of the three systems are presented in Table 8.1, both before and after weighting. The preferred system is the Offshore Wind Farm, that present a significantly lower overall ReCiPe score, with the Photovoltaic Park following in second position. It is very interesting to notice that after normalization and weighting, each system is characterised by a different rank of the scores related to the three damage category, e.g. for the wind farm the highest score is the one related to resources, for the photovoltaic park the one related to human health and for the biomass power plant the one related to ecosystems.

It can be noticed that in some cases, even if the normalized score of a damage category is higher than the others, the Endpoint indicator in MPt is lower, because the three damage categories are weighted in a different way, i.e. damage to resources contributes only for 20% to the final score while the other two categories for 40%, according to the weighting set chosen for the case study.

The ReCiPe scores were calculated also excluding infrastructure processes to investigate how much the impact of each system depends on the construction of infrastructure. Clearly all ReCiPe scores decrease, resulting in 0.0058, 0.839 and 11.4 for the Offshore Wind Farm, Photovoltaic Park and Biomass-fired Power Plant respectively. Therefore, especially for the first two systems, infrastructure contribute significantly to the total ReCiPe score.

Table 8.1: Comparison of the ReCiPe Endpoint indicators of the three systems.

Damage category	**Unit**	**OWF**	**PP**	**BPP**
Human Health	[/]	475.2	2012	6755.1
Ecosystems	[/]	175.4	1912.8	19749.4
Resources	[/]	1245.8	3350.7	7314.1
Human Health	[MPt]	0.19	0.80	2.7
Ecosystems	[MPt]	0.07	0.76	7.9
Resources	[MPt]	0.25	0.67	1.5
Total	**[MPt]**	**0.51**	**2.24**	**12.1**

It was also investigated the contribution of processes to the total ReCiPe scores. A detailed overview of processes of the whole supply chain which contribute at least for 80% to the scores of the systems is presented in Appendix C. Figure 8.1 presents the processes with at least a contribution of 2.5 %.

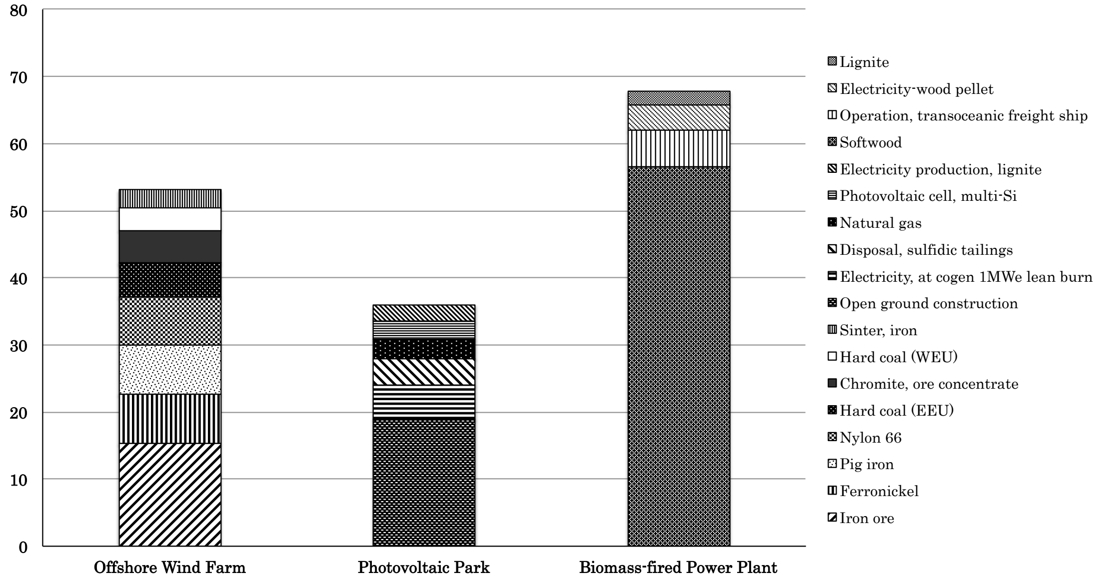

Figure 8.1: Contributions to the ReCiPe scores of the three systems.

Some interesting considerations can be pointed out, concerning aspects that influence the environmental impact of electricity generation from wind, solar and biomass energy, also referring to the Midpoint indicators presented together in Table 8.2 .

Table 8.2: Comparison of the ReCiPe Midpoint indicators of the three systems.

Impact category	**OWF**	**PP**	**BPP**
Climate change [$kg_{CO2,eq}$]	$3.64 \cdot 10^6$	$1.63 \cdot 10^7$	$4.37 \cdot 10^7$
Ozone depletion [$kg_{CFC\text{-}11,eq}$]	$2.00 \cdot 10^1$	$3.46 \cdot 10^0$	$3.34 \cdot 10^0$
Terrestrial acidification [$kg_{SO2,eq}$]	$1.30 \cdot 10^4$	$5.84 \cdot 10^4$	$6.09 \cdot 10^5$
Freshwater eutrophication [$kg_{P,eq}$]	$1.96 \cdot 10^3$	$1.09 \cdot 10^4$	$2.92 \cdot 10^4$
Marine eutrophication [$kg_{N,eq}$]	$1.02 \cdot 10^3$	$5.98 \cdot 10^4$	$3.42 \cdot 10^4$
Human toxicity [$kg_{1,4\text{-}DB,eq}$]	$2.61 \cdot 10^6$	$1.62 \cdot 10^7$	$2.18 \cdot 10^7$
Photochemical oxidant formation [kg_{NMVOC}]	$1.22 \cdot 10^4$	$5.45 \cdot 10^4$	$8.05 \cdot 10^5$
Particulate matter formation [$kg_{PM10,eq}$]	$1.03 \cdot 10^4$	$2.47 \cdot 10^4$	$2.29 \cdot 10^5$
Terrestrial ecotoxicity [$kg_{1,4\text{-}DB,eq}$]	$3.43 \cdot 10^2$	$3.31 \cdot 10^4$	$2.72 \cdot 10^3$
Freshwater ecotoxicity [$kg_{1,4\text{-}DB,eq}$]	$8.46 \cdot 10^4$	$3.32 \cdot 10^5$	$5.09 \cdot 10^5$
Marine ecotoxicity [$kg_{1,4\text{-}DB,eq}$]	$8.61 \cdot 10^4$	$3.87 \cdot 10^5$	$5.29 \cdot 10^5$
Ionising radiation [$kBq_{U235,eq}$]	$5.80 \cdot 10^5$	$3.35 \cdot 10^6$	$2.33 \cdot 10^7$
Agricultural land occupation [m^2a]	$7.68 \cdot 10^4$	$7.86 \cdot 10^5$	$2.57 \cdot 10^8$
Urban land occupation [m^2a]	$3.48 \cdot 10^4$	$9.35 \cdot 10^6$	$3.22 \cdot 10^6$
Natural land transformation [m^2]	$7.68 \cdot 10^2$	$3.06 \cdot 10^3$	$3.55 \cdot 10^4$
Water depletion [m^3]	$1.01 \cdot 10^5$	$1.59 \cdot 10^6$	$1.20 \cdot 10^6$
Metal depletion [$kg_{Fe,eq}$]	$2.90 \cdot 10^6$	$3.88 \cdot 10^6$	$2.02 \cdot 10^6$
Fossil depletion [$kg_{oil,eq}$]	$1.07 \cdot 10^6$	$4.58 \cdot 10^6$	$1.28 \cdot 10^7$

Human health and environmental issues

Concerning the impact on human health and on ecosystems, the first aspect to highlight is that both wind farm and photovoltaic park do not generate any pollution or greenhouse gases emission during the operational phase, unlike the biomass power plant, since wood pellet combustion is accompanied with several emissions. Anyway, the LCA analyzed every process along the supply chain, therefore emissions that accompanied manufacturing, transport and other phases are taken into account as well. For example, photovoltaic panel manufacturing requires a high electricity consumption, which can be higher than the one related to wind turbines manufacturing, therefore pollution and emissions associated with this electricity generation can be relevant.

Other impacts on human health related to photovoltaic energy production have to be considered as well, such as the use of hazardous materials (e.g. hydrochloric, nitric and sulfuric acid, acetone, hydrogen fluoride) to purify and clean cell surfaces, which generates toxic fumes and substances that can be easily inhaled by workers. Furthermore wafer slicing and other processes during the production of panels generate a large amount of liquid and solid wastes, which would have an high environmental impact if rejected in the environment, and that have to be properly disposed.

Analysing the Midpoint indicators it can be noticed that the biomass power plant presents higher values of ecotoxicity over the other systems, except for the terrestrial ecotoxicity score, which is significantly higher for the photovoltaic park. Investigating which processes and substances contribute more to this score, it is pointed out that silver, mainly used in photovoltaic cell production, gives an important contribution to this score.

Land occupation and degradation

As shown by the Midpoint indicators, from a life cycle point of view, generating 1 PJ of electricity with the wind farm requires less space than electricity generation from the wood pellet power plant or the photovoltaic system. The land occupation scores obtained from the LCA, are not only related to the installation itself but also to infrastructure and equipment and land use in each process along the whole supply chain.

Land use, especially for large open-ground solar facilities, raises concern about land degradation, while impacts of wind farms on the natural environment are more related to changes in air pressure caused by turbines, that can lead to birds death, or impacts on fish life and marine ecosystem. Nevertheless, we should remember that only land occupation is taken into account when conducting an LCA with SimaPro, while environmental implications of height, volume or noises are not considered because of the lack of data.

Use of resources

The highest Endpoint indicator related to the damage to resources is the one of the Biomass-fired Power Plant, but the photovoltaic system presents higher values for both the impact categories of metal and water depletion. Concerning the consumption of water along the supply chain of electricity produced by photovoltaic panels, the main contribution is given by processes for the production of silicon and also the use of water to clean panels during installation and operation. For the biomass power plant the use of water is mainly associated with fossil fuels (e.g. hard coal and lignite) burned in power plants or electricity generated from nuclear power plants. Anyway so far no models are available to express the damage of water use on the endpoint level, therefore this values are not taken into account when calculating the Endpoint indicators [24].

8.2 Results of the economic assessment

Table 8.3 presents the comparison of the results of the economic assessment, with and without considering subsidies.

Comparing the PWR of the three systems, the preferred one is the Biomass-fired Power Plant, followed by the Photovoltaic Park. The less profitable system is the Offshore Wind Farm. All the system are subsidized for 15 years, but the power plant presents an higher yearly subsidy that takes into account also the conversion cost. Therefore, even if the conversion cost is considered in the calculation and the power plant is the only system which use a fuel that has a cost, i.e. wood pellet has to be imported from United States while wind and sun energy are free, the third system is characterized by the higher PWR. This is also due to lower investment costs, related to the generation of 1 PJ of electricity.

Table 8.3: Results of the economic assessment of the three systems considering subsidies.

	Offshore Wind Farm	**Photovoltaic Park**	**Biomass-fired Power Plant**
With subsidies			
NPV [10^6 €]	91	156	148.2
PWR	0.6	1.4	2.1
Without subsidies			
NPV [10^6 €]	-83.6	-15.4	-110.9
PWR	-0.55	-0.13	-1.5

The wind farm has the lowest PWR because the investment for the construction of the installation, and consequently operation and maintenance costs, are the highest. The photovoltaic park presents an higher NPV than the biomass power plant, but since the investment cost is higher, the PWR results in a lower score.

Without subsidies none of the system is profitable under the economic point of view. In this case the biomass power plant is the last-preferred system, having a PWR significantly lower than zero, while the other two systems have a PWR just slightly lower than zero. Anyway it was already clarified that each system would be subsidized by the Dutch government.

Figure 8.2 shows the contribution of the investment costs and yearly costs and revenues from electricity and subsidies to the PWR, for the three systems.

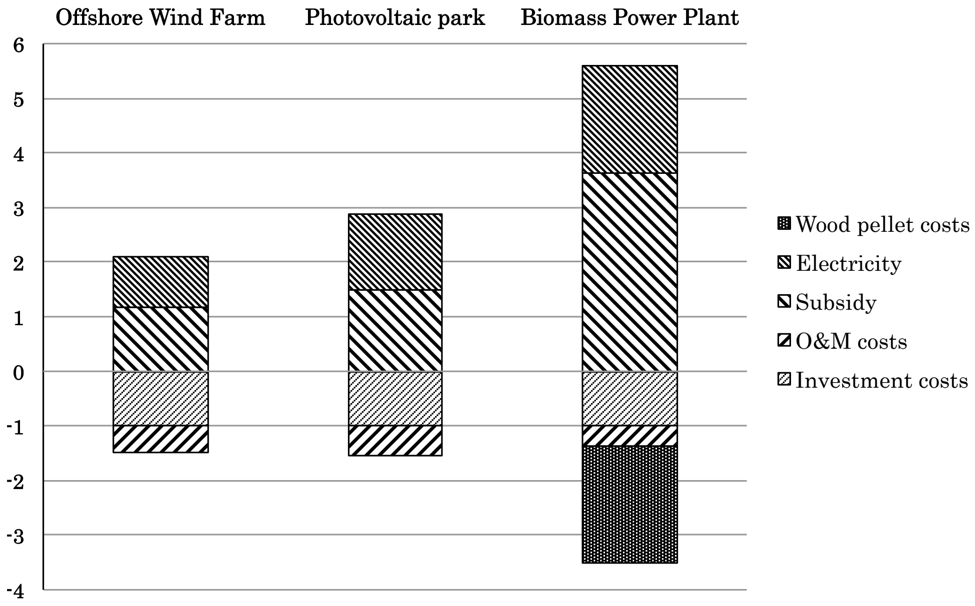

Figure 8.2: Contributions to the PWR scores of the three systems.

Anyway, it is important to point out that even if the amount of subsidies given to each system was calculated from data found in the SDE+2016, it is not the real amount of subsidies, since the systems are not in operation yet. Furthermore, it was also taken into account the subsidy of a certain phase of tendering, but in the reality it could be different. Also other simplification were made, i.e. research and development cost (R&D) and decommissioning cost were neglected, because usually lower than the others.

8.3 Results of the exergetic assessment

The results of the exergetic assessment are presented in Table 8.4, which shows all the components of the Total Cumulative Exergy Loss: the internal exergy loss, the exergy loss caused by land use and the abatement exergy loss.

The exergetic assessment is linked with the environmental LCA, and many of the data reported by SimaPro were used to calculate the components of the TCExL. The CExD was calculated with SimaPro, and the exergy losses of emissions were calculated multiplying the amount of emissions of each substance, reported in the Inventory, by the standard exergy values of emissions, that can be found in Appendix A. The exergy loss caused by land use is obtained making use of data related to land occupation, reported in the Inventory as well. Finally, the amount of carbon dioxide, sulphur dioxide, nitrogen oxides and phosphate emitted to air were multiplied by the exergy loss caused by the abatement of these substances. A limitation in the calculation

Table 8.4: Results of the exergetic assessment of the three systems.

	Offshore Wind Farm [PJ]	**Photovoltaic Park [PJ]**	**Biomass-fired Power Plant [PJ]**
CExD	1.1446	1.3740	3.9573
$\mathbf{Ex_{products}}$	1	1	1
$\mathbf{Ex_{emissions}}$	0.0168	0.0827	0.4161
$\mathbf{Ex_{loss,internal}}$	0.1278	0.2913	2.5412
$\mathbf{Ex_{loss,landuse}}$	0.0006	0.0024	0.0175
$\mathbf{Ex_{loss,abatement}}$	0.0206	0.0874	0.4149
TCExL	0.1490	0.3812	2.9735

of the abatement exergy loss is that only the abatement exergy values of few emissions could be found in literature, therefore the TCExL results in a lower score.

The preferred system is the Offshore Wind Farm and the second-best system is the Photovoltaic Park, which results in a TCExL just slightly higher than the first one. The Biomass-fired Power Plant presents a TCExL substantially higher than the other two systems.

For each system the largest contribution to the TCExL is given by the internal exergy loss. The exergy loss caused by land use is quite small for all the systems, especially for the wind farm and the same is also for the abatement exergy loss.

The Offshore Wind Farm and the Photovoltaic Park do not present really different results. The higher scores of the photovoltaic system are also related to the use of scarcer materials in the construction of photovoltaic panels, that result in higher exergy losses during their extraction. The Biomass-fired Power Plant presents higher scores for each component of the TCExL, but especially the internal exergy loss is significantly higher than the others. The internal exergy loss is given by the difference between the CExD and the exergy of outputs (products and emissions). The CExD of the Biomass-fired Power Plant is more than three times bigger than the ones of the other systems, i.e. the total exergy removal from nature to provide 1 PJ of electricity from wood pellet combustion is higher. This is also related to the fact that the combustion process, as every chemical process, is accompanied with internal exergy losses that can have a significant value. It can be noticed that the exergy value of emissions is higher than the ones associated with the other systems, also because combustion of wood pellet itself is accompanied with emissions while the other two systems do not present emissions during operation. Anyway, the exergy value of emissions is not a measure of the impact these substances have on the environment, that is taken into account through the abatement exergy loss. Logically, since the exergy value of emissions of the Biomass-fired Power Plant is the highest, also its abatement exergy value is the highest.

8.4 Overall comparison of the results

The results of the environmental (ReCiPe), economic (PWR) and exergetic (TCExL) sustainability assessments are presented in Table 8.5. In order to compare the results and understand if exergy analysis can be used in sustainability assessment of technological systems, Table 8.5 presents also a grading of the three systems, besides the absolute scores obtained from the assessments. If also the social sustainability assessment was conducted, another possible way to compare the results of the regular methods with the TCExL would have been to combine the scores in an overall indicator. Anyway, since weighting of results is subjective, it is preferable to compare the separate results of the sustainability assessments with each other.

Table 8.5: Overview of the assessment results of the three systems.

	OWF		**PP**		**BPP**	
	absolute	ranking	absolute	ranking	absolute	ranking
ReCiPe [MPt]	**0.51**	1	2.24	2	12.1	3
PWR [-]	0.6	3	1.4	2	**2.1**	1
TCExL [PJ]	**0.15**	1	0.38	2	3.0	3

The Offshore Wind Farm is the preferred system from both the environmental and exergetic point of view, while the Biomass-fired Power Plant is preferred from the economic point of view. The Photovoltaic Park is the second best system, using every method.

In this specific case, choosing the system which is the best from the exergetic point of view, i.e. the wind farm, has not consequences for the environmental sustainability, but its economic sustainability is the lowest of the three systems. Anyway, as explained in Section 8.3, assumption were made in the calculation of subsidies, therefore the results are purely indicative.

In accordance with what done by Stougie [1] during the previous case studies, the environmental and economic sustainability of the three systems are presented versus the TCExL caused by each system, in Figure 8.3 . It was needed to get a dimensionless indicator for the environmental sustainability, which increases with the sustainability itself. This was done by multiplying the inverse of the ReCiPe score of each system with the one of the Offshore Wind Farm, that present the highest environmental sustainability. Figure 8.3 shows that the environmental sustainability is higher for lower exergy losses, while the economic sustainability increases with increasing exergy losses. This is in line with what expected from the relationship between economic sustainability and exergy losses, i.e. higher investment costs lead to lower economic sustainability but also lower exergy losses, as explained in Section 2.4.1. Therefore the fact that the wind farm has the lowest economic sustainability but also the lowest exergy losses could have been guessed.

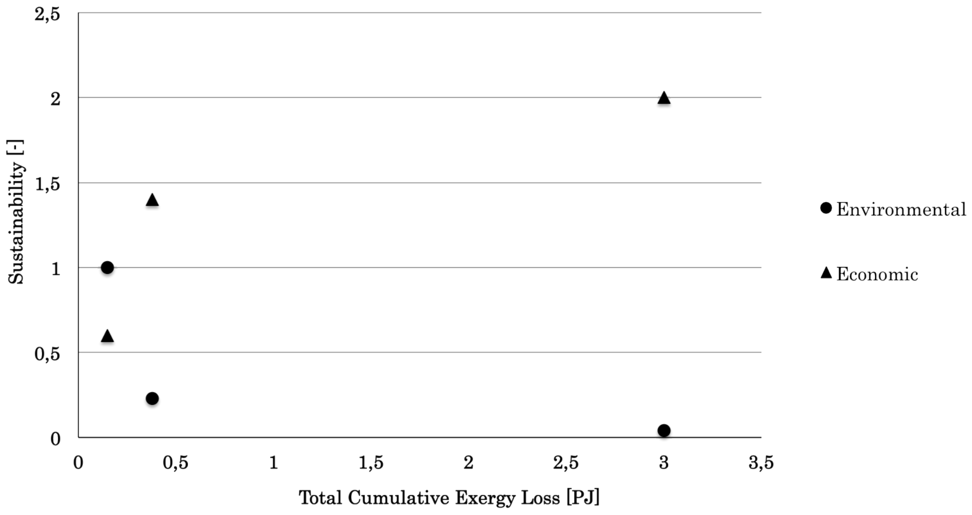

Figure 8.3: The environmental and economic sustainability of the systems versus the TCExL caused by these systems.

Anyway it cannot be exactly deducted which is the relationship between exergy losses and economic sustainability, because the wind farm (and also the photovoltaic system) presents important technological differences with the biomass power plant. For example, the fact that the wind farm presents an lower economic sustainability could be linked to higher prices of materials used for its construction. Furthermore, the relationship between exergy losses and costs previously described, is usually true when comparing two systems that use the same technology but that have different sizes, e.g. heat exchangers. Maybe comparing similar systems would lead to more interesting results in regard to the link between economic aspects and exergy losses.

Conclusions

Our planet is constantly changing, in parallel with our technological development, and it is undeniable that we are part of the problem. The first step was to become aware of the environmental impact that every process, used to produce things we need, has. Now we are also trying to be part of the solution, shifting to a more sustainable behavior, in order to guarantee the same opportunities to the future generations. The need to be more respectful towards the natural environment rests with the individual but it is also influencing industries and governments in their decisions.

This awareness of environmental issues is reflected in an increasing number of sustainability assessments of technological processes and systems. A regular method, i.e. the environmental Life Cycle Assessment, is commonly applied, but sometimes results are conditioned by subjective choices, such as weighting factors of damage categories. Furthermore, also economic and social aspects should be considered to get a complete idea of the sustainability of a process, and this can be done only using other methods in parallel with the environmental assessment, since an overall sustainability method has not been completely developed yet. Another approach to assess the sustainability makes use of exergy analysis, that implies the calculation of exergy losses or exergy efficiencies. Not all the exergetic methods are suitable for sustainability assessment , but the Total Cumulative Exergy Loss method was developed to be an improvement over the other methods and to take into account as many of the components of sustainability as possible. At least theoretically, when calculating exergy losses, the three aspects of sustainability can be evaluated. A relationship between exergy losses and economic and social aspects was pointed out by researchers in this field, but anyway these aspects can be taken into account only indirectly, and the same applies for depletion and scarcity of resources.

The case study of this research included the environmental and economic sustainability assessments of three power generation systems, to compare with their exergetic assessment, i.e. the calculation of the total cumulative exergy loss. The choice of the systems relates with the aim to analyse technologies that use renewable sources and that are currently under construction in the Netherlands, to help achieving the target to generate 14 % renewable energy by 2020. It was assessed the impact of 1 PJ of electricity, considering all the processes needed for its generation, but neglecting transport, distribution, use and storage, since all the systems are located in the Netherlands and the results would be the same, i.e. the grading of the systems would not change taking into account these processes. Anyway this does not mean that they do not have an important role when assessing the impact of generating electricity from a life cycle point of view. The environmental and economic assessment were conducted calculating the ReCiPe Midpoint and Endpoint indicators, and the Net Present Value and the Present Worth Ratio of each system, respectively. The exergetic analysis consisted in the calculation of the Total Cumulative Exergy Loss. Results were compared and some conclusions were pointed out.

The Offshore Wind Farm is the preferred system from the environmental and exergetic point of view, while the Biomass-fired Power Plant is preferred from the economic point of view. The Photovoltaic Park is the second-best system, according to all the methods. Therefore the three methods do not agree in the choice of the most sustainable system. The fact that the preferred system from the environmental point of view is also the one which presents lower exergy losses is consistent with what expected from the relationship between environmental sustainability and exergy losses. Concerning the economic sustainability, the wind farm results in the lower PWR, i.e. it is the less profitable system. This is mainly due to the high construction costs and the fact that the system with the lowest exergy loss is in also the one with the highest investment costs is line with considerations previously made, even if it is usually true for systems that use the same technology. Therefore, from this case study it is pointed out that the economic sustainability has not a predictable relationship with the TCExL, because the three systems use technologies really different from one another and different inputs to the processes.

Anyway this research presents several limitations and neglects some aspects that should be considered when assessing the sustainability of systems or processes. First of all it is important to remember that since a lot of information about the systems are not known yet, assumptions about the type of wind turbines and photovoltaic panels were made, therefore the systems are only based on the real plants taken as reference. The first shortcoming of this research is that the social sustainability of the three systems was not assessed, because of the lack of data, therefore one of the ‘pillars’ is missing and cannot be compared to the others. It is alway recommended to assess also the social component to get an overall view of the sustainability of the system. Another limit is related to the calculation of the abatement exergy loss, that considers only few emissions, whose abatement exergy values could be found in literature. Therefore the TCExL results in a lower score and it would be better, in order to get more complete results, calculate the abatement exergy values of other emissions. Furthermore, fluctuating wind speed and solar irradiance were not considered, therefore the emissions due to backup systems operation or a lower solar irradiation are not taken into account. Concerning economic data, assumptions and simplifications were made, especially about subsidies, therefore the economic indicator should be calculated more accurately once specific information will be available.

Concluding, it was pointed out that regular methods and the TCExL method do not agree in the choice of the more sustainable system, but also that exergy analysis, and in this specific case the TCExL method, can be used in sustainability assessment to get interesting results and compare alternatives, especially with regard to environmental aspects. Since the relationship between exergy losses and economic aspects is not always easy to point out, when comparing systems that differ too much from a technological point of view, it is preferable to conduct a separate economic analysis. It would be interesting to compare systems that use the same technology but that have different sizes and capacities. Conducting other case studies, applying the TCExL method in parallel with regular methods, could be a way to understand better if economic and social aspects can be related to exergy losses in a more consistent way.

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Appendix A

Tables in this appendix present the standard chemical exergy values of emissions and waste flows, reported by Stougie [1]. This data originate from and/or are calculated from thermodynamic data reported in literature [6], [50], [77], [78].

Table A1: Standard chemical exergy values of emissions to air.

Emission to air	**MJ/kg**	**Emission to air**	**MJ/kg**
1,4-Butanediol	29	Boron trifluoride	3
1-Butanol	37	Bromine	0.67
1-Pentanol	38	Butadiene	47
1-Pentene	48	Butane	48
1-Propanol	34	Butene	47
2-Butene, 2-methyl-	47	Calcium	21
2-Methyl-1-propanol	37	Carbon dioxide, biogenic	0.45
2-Nitrobenzoic acid	20	Carbon dioxide, fossil	0.45
2-Propanol	33	Carbon dioxide, land transformation	0.45
Acenaphthene	42	Carbon disulfide	22
Acetaldehyde	26	Carbon monoxide, biogenic	10
Acetic acid	15	Carbon monoxide, fossil	10
Acetone	31	Chlorine	1.7
Acetonitrile	29	Chloroacetic acid	10
Aluminium	40	Chlorosilane, trimethyl-	27
Ammonia	20	Chromium	18
Aniline	35	Chromium VI	18
Anthracene	41	Chrysene	41
Antimony	5.4	Cobalt	12
Arsenic	10	Copper	6,8
Arsine	12	Cumene	45
Barium	6.7	Cyanide	24
Benzaldehyde	34	Cyclohexane	47
Benzene	42	Diethanolamine	27
Benzene, 1,3,5-trimethyl-	44	Diethylamine	43
Benzene, ethyl-	43	Dinitrogen monoxide	2.4
Benzene, hexachloro-	10	Ethane	50
Benzo(b)fluoranthene	40	Ethanol	30
Benzo(ghi)perylene	40	Ethene	49
Beryllium	99	Ethene, chloro-	21

[1] MJ/MJ

Table A2: Standard chemical exergy values of emissions to air-Continued.

Emission to air	[MJ/kg]	**Emission to air**	[MJ/kg]
Ethene, tetrachloro-	7.3	Nitric oxide	3
Ethylamine	37	Nitrobenzene	27
Ethylene oxide	29	Nitrogen	0.026
Ethyne	49	Nitrogen oxides	1.9
Fluorine	12	Octane	47
Formaldehyde	18	Oxygen	0.12
Formic acid	6.5	Ozone	3.5
Furan	31	Palladium	4.5
Heat, waste [1]	0.22	Pentane	48
Helium	7.6	Phenanthrene	41
Heptane	48	Phenol	34
Hexane	48	Phosphorus	37
Hydrogen	117	Platinum	3.4
Hydrogen bromide	1.4	Propanal	31
Hydrogen chloride	2.3	Propane	49
Hydrogen cyanide	24	Propene	49
Hydrogen fluoride	4	Propylamine	39
Hydrogen iodide	1.6	Rhodium	6.7
Hydrogen peroxide	4	Scandium	28
Hydrogen sulfide	24	Silicon	45
Iodine	1.5	Silver	3.2
Isocyanic acid	13	Sodium	18
Isopropylamine	39	Sodium chlorate	1.3
Magnesium	31	Sodium formate	14
Mercury	0.7	Sodium hydroxide	1.9
Methane	52	Strontium	10
Methane, biogenic	52	Styrene	44
Methane, bromo-, Halon 1001	8.3	Sulfur dioxide	4.9
Methane, bromochlorodifluoro-, Halon 1211	6.1	Sulfur hexafluoride	8.8
Methane, bromotrifluoro-, Halon 1301	4.2	Sulfur oxides	3.9
Methane, chlorodifluoro-, HCFC-22	7	Sulfur trioxide	3.1
Methane, chlorotrifluoro-, CFC-13	5.7	Sulfuric acid	10
Methane, dichloro-, HCC-30	8.3	t-Butyl methyl ether	39
Methane, dichlorodifluoro-, CFC-12	4.6	t-Butylamine	42
Methane, dichlorofluoro-, HCFC-21	10	Tellurium	3.8
Methane, fossil	52	Thallium	1.7
Methane, monochloro-, R-40	15	Thorium	7.6
Methane, tetrachloro-, CFC-10	4.5	Tin oxide	2.2
Methane, tetrafluoro-, CFC-14	5.2	Toluene	43
Methane, trichlorofluoro-, CFC-11	4.3	Toluene, 2-chloro-	31
Methane, trifluoro-, HFC-23	8.1	Trimethylamine	40
Methanol	23	Uranium	7.1
Methyl acetate	22	Used air	0
Methyl acrylate	26	Water	1.9
Methyl amine	33	Xylene	43
Methyl formate	17	Zinc	6.7
Monoethanolamine	30	Zinc oxide	0.28
m-Xylene	44	Zirconium	18
Nickel	11		

[1] MJ/MJ

Table A3: Standard chemical exergy values of emissions to water.

Emission to water	**[MJ/kg]**	**Emission to water**	**[MJ/kg]**
1,4-Butanediol	28	Heat, waste [1]	0.016
1-Butanol	36	Hexane	48
1-Pentanol	38	Hydrogen chloride	6.4
1-Pentene	47	Hydrogen fluoride	2.5
2-Methyl-1-propanol	36	Hydrogen peroxide	3.5
2-Methyl-2-butene	47	Iodide	0.92
2-Propanol	33	Iron, ion	8.4
Acenaphthene	42	Isopropylamine	39
Acenaphthylene	39	Magnesium	26
Acetaldehyde	26	Manganese	8.78
Acetic acid	15	Mercury	0.54
Acetone	31	Methane, dibromo-	4.3
Acetonitrile	29	Methane, dichloro-, HCC-30	8.2
Acetyl chloride	13	Methane, monochloro-, R-40	18
Aluminium	29	Methanol	22
Ammonia	22	Methyl acetate	23
Aniline	37	Methyl acrylate	24
Anthracene	40	Methyl amine	33
Antimony	3.6	Methyl formate	18
Barium	5.6	m-Xylene	43
Benzene	42	Naphthalene	41
Benzene, ethyl-	43	Nickel	4
Beryllium	67	Nitrobenzene	26
Bromate	1	o-Xylene	43
Bromine	0.63	Phenol	33
Butene	47	Phosphate	1.5
Butyl acetate	31	Phosphorus	28
Butyrolactone	25	Potassium, ion	0.32
Calcium, ion	0.84	Propanal	32
Carbon disulfide	22	Propane, 1,2-dichloro-	18
Cesium	3	Propanol	33
Chloride	0.067	Propene	49
Chlorine	1.8	Propylamine	40
Chloroacetyl chloride	9.2	Rubidium	4.5
Chromium	11	Scandium	21
Chromium VI	11	Selenium	4.4
Chrysene	40	Silicon	30
COD, Chemical Oxygen Demand	0	Sodium formate	4
Copper	2.1	Sodium, ion	0.16
Copper, ion	1.4	Strontium	8.6
Cresol	35	Sulfate	0.17
Cumene	44	Sulfide	22
Cyanide	24	Sulfur	19
Decane	47	t-Butyl methyl ether	38
Diethylamine	42	t-Butylamine	42
Dimethylamine	38	Toluene	43
Ethanol	29	Toluene, 2-chloro-	31
Ethene, chloro-	22	Triethylene glycol	25
Ethyl acetate	26	Trimethylamine	41
Ethylamine	37	Tungsten	4.5
Ethylene oxide	29	Urea	11
Fluoride	0.56	Xylene	43
Formate	4	Zinc	5.2
Formic acid	6.3		

[1] MJ/MJ

Table A4: Standard chemical exergy values of emissions to soil and final waste.

Emission to soil	**[MJ/kg]**	**Emission to soil**	**[MJ/kg]**
Aluminium	33	Mercury	0.54
Ammonia	20	Molybdenum	7.6
Antimony	3.6	Nickel	4
Arsenic	6.6	Phosphorus	28
Barium	5.4	Potassium	9.4
Boron	58	Silicon	30
Bromide	0.37	Sodium	15
Cadmium	2.6	Strontium	8.6
Calcium	18	Sulfate	0.058
Carbon	34	Sulfide	12
Chromium	10	Sulfur	19
Chromium VI	11	Sulfuric acid	1.7
Cobalt	4.5	Tin	4.6
Copper	2.1	Titanium	19
Fluoride	0.56	Vanadium	14
Heat, waste [1]	0.016	Zinc	5.2
Iron	6.7	**Final waste**	**[MJ/kg]**
Lead	1.1	Calcium fluoride waste	0.15
Magnesium	26	Mineral waste, from mining	0
Manganese	8.8	Slags and ashes	0

[1] MJ/MJ

Appendix B

Tables B1 and B2 present an overview of materials, fuels, emissions and waste to treatment related to the construction of fixed and moving parts of the 4 MW wind turbine of the Offshore Wind Farm and of the Photovoltaic Park, respectively. Table B3 presents the final Ecoinvent process for electricity and heat generation from the Biomass-fired Power Plant.

Table B1: Overview of materials/fuel and waste to treatment related to the construction and installation of the moving parts of the 4 MW wind turbine.

Materials/fuels	
Electricity, medium voltage, production UCTE, at grid/UCTE U [*kWh*]	122000
Aluminium, primary, at plant/RER U [*kg*]	1433
Cast iron, at plant/RER U [*kg*]	46466
Chromium steel 18/8, at plant/RER U [*kg*]	89962
Copper, at regional storage/RER U [*kg*]	2271
Glass fibre reinforced plastic, polyamide, injection moulding, at plant/RER U [*kg*]	76029
Lead, at regional storage/RER U [*kg*]	1
Lubricating oil, at plant/RER U [*kg*]	1254
Polyethylene, HDPE, granulate, at plant/RER U [*kg*]	45
Polypropylene, granulate, at plant/RER U [*kg*]	0
Polyvinylchloride, bulk polymerised, at plant/RER U [*kg*]	10
Steel, low-alloyed, at plant/RER U [*kg*]	26315
Synthetic rubber, at plant/RER U [*kg*]	169
Tin, at regional storage/RER U [*kg*]	1
Section bar rolling, steel/RER U [*kg*]	72781
Sheet rolling, aluminium/RER U [*kg*]	1433
Sheet rolling, chromium steel/RER U [*kg*]	89962
Wire drawing, copper/RER U [*kg*]	2271
Transport, lorry >16t, fleet average/RER U [*tkm*]	25093
Transport, freight, rail/RER U [*tkm*]	218412
Transport, barge/RER U [*tkm*]	10921
Waste to treatment	
Disposal, plastics, mixture, 15.3% water, to municipal incineration/CH U [*kg*]	26834
Disposal, glass, 0% water, to municipal incineration/CH U [*kg*]	49419
Disposal, used mineral oil, 10% water, to hazardous waste incineration/CH U [*kg*]	1254
Disposal, polyethylene, 0.4% water, to municipal incineration/CH U [*kg*]	45
Disposal, polypropylene, 15.9% water, to municipal incineration/CH U [*kg*]	0
Disposal, polyvinylchloride, 0.2% water, to municipal incineration/CH U [*kg*]	10

Table B2: Overview of resources, materials/fuel and waste to treatment related to the construction and installation of the moving parts of the 4 MW wind turbine.

Resources	
Transformation, from sea and ocean [m^2]	380
Transformation, to industrial area, benthos [m^2]	380
Occupation, industrial area, benthos [m^2a]	7600
Materials/fuels	
Concrete, normal, at plant/CH U [m^3]	1118
Copper, at regional storage/RER U [kg]	3900
Diesel, burned in building machine/GLO U [MJ]	4321
Epoxy resin, liquid, at plant/RER U [kg]	848
Excavation, hydraulic digger/RER U [m^3]	77000
Gravel, unspecified, at mine/CH U [kg]	300000
Lead, at regional storage/RER U [kg]	7575
Polyvinylchloride, bulk polymerised, at plant/RER U [kg]	3500
Reinforcing steel, at plant/RER U [kg]	1640000
Steel, low-alloyed, at plant/RER U [kg]	184242
Sheet rolling, steel/RER U [kg]	184242
Welding, arc, steel/RER U [m]	353
Wire drawing, copper/RER U [kg]	3900
Transport, lorry >16t, fleet average/RER U [tkm]	308418
Transport, freight, rail/RER U [tkm]	14245
Transport, barge/RER U [tkm]	198712
Waste to treatment	
Disposal, polyvinylchloride, 0.2% water, to municipal incineration/CH U [kg]	3500

Table B3: Inputs and emissions related to the construction of the Photovoltaic Park.

Materials/fuels	**Canada**	**Germany**
Electricity, low voltage, at grid/NL U [kWh]	1895	1895
Diesel, burned in building machine/GLO U [MJ]	403425	403425
Inverter, 500kW, at plant/RER/I U [p]	100	100
Electric installation, photovoltaic plant 1.3 MWp, at plant [p]	23	23
Open ground construction, on open ground [m^2]	182096	185186
Photovoltaic panel, muti-Si, at plant/RER/I U[m^2]	187559	190714
Transport, transoceanic freight ship/OCE U [tkm]	18469774	0
Transport, freight, rail/RER U [tkm]	0	1878332
Transport, lorry >16t, fleet average/RER U [tkm]	1237096	534418
Emissions to air		
Heat, waste [MJ]	1440	1440

Table B4: Electricity and heat generation from wood pellet combustion in the Ecoinvent process.

Products	
Electricity [PJ]	1
Heat [PJ]	0.47
Materials/fuels	
Hard coal power plant/RER/I U [p]	0.00294
Wood pellets at Savannah harbor [m^3]	232045.5
NOx retained, in SCR/GLO U [ton]	373.4
Transport, transoceanic freight ship/OCE U [tkm]	1085972851
Transport, barge/RER U [tkm]	7541478
Emissions to air	
Heat, waste [PJ]	0.645
Carbon dioxide, biogenic [ton]	252
Nitrogen oxides [ton]	466.7
Particulates, >10 um [ton]	35
Carbon monoxide, biogenic [kton]	1.17
TOC, Total Organic Carbon [ton]	11.7
Emissions to water	
Heat, waste [PJ]	0.215
Final waste flows	
Slags and ashes [kton]	1.5

Appendix C

Tables in this appendix present the processes that give the most important contribution to the Total ReCiPe scores of the three systems.

Table C1: Processes which contribute most to the total ReCiPe score of the Offshore Wind Farm.

Compared to the total ReCiPe score	[%]
Iron ore, 46% Fe, at mine/GLO U	15.27
Ferronickel, 25% Ni, at plant/GLO U	7.36
Pig iron, at plant/GLO U	7.31
Nylon 66, glass-filled, at plant/RER U	7.21
Hard coal, at mine/EEU U	5.04
Chromite, ore concentrate, at beneficiation/GLO U	4.89
Hard coal, at mine/WEU U	3.35
Sinter, iron, at plant/GLO U	2.67
Clinker, at plant/CH U	2.14
Natural gas, burned in industrial furnace >100kW/RER U	2.00
Steel, electric, un- and low-alloyed, at plant/RER U	1.99
Hard coal, burned in industrial furnace 1-10MW/RER U	1.74
Manganese concentrate, at beneficiation/GLO U	1.62
Disposal, sulfidic tailings, off-site/GLO U	1.46
Natural gas, at production onshore/RU U	1.32
Hard coal, at mine/ZA U	1.26
Disposal, spoil from coal mining, in surface landfill/GLO U	1.21
Lignite, at mine/RER U	1.20
Operation, transoceanic freight ship/OCE U	1.10
Quicklime, in pieces, loose, at plant/CH U	1.08
Disposal, spoil from lignite mining, in surface landfill/GLO U	0.90
Ferrochromium, high-carbon, 68% Cr, at plant/GLO U	0.88
Lignite, burned in power plant/DE U	0.86
Copper concentrate, at beneficiation/RER U	0.83
Crude oil, at production onshore/RME U	0.82
Hard coal, at mine/AU U	0.76
Hard coal, at mine/RNA U	0.75
Crude oil, at production onshore/RAF U	0.70
Hard coal coke, at plant/RER U	0.69
Steel, converter, unalloyed, at plant/RER U	0.68
Natural gas, at production onshore/DZ U	0.67
Crude oil, at production offshore/NO U	0.65
Total	80.38

Table C2: Processes which contribute most to the total ReCiPe score of the Photovoltaic Park.

Compared to the total ReCiPe score	[%]
Open ground construction, on open ground	18.91
Electricity, at cogen 1MWe lean burn, allocation exergy/RER U	5.07
Disposal, sulfidic tailings, off-site/GLO U	4.00
Natural gas, at production onshore/RU U	2.92
(PPP)Photovoltaic cell, multi-Si, at plant/DE U	2.58
Electricity, high voltage {DE}, lignite [1]	2.50
Aluminium, primary, liquid, at plant/RER U	2.43
Copper concentrate, at beneficiation/RER U	2.13
Iron ore, 46% Fe, at mine/GLO U	1.70
Electricity, high voltage {DE}, hard coal [2]	1.60
Copper concentrate, at beneficiation/RLA U	1.55
Lignite {RER}— mine operation — Alloc Def, U	1.42
Hard coal {WEU}— mine operation — Alloc Def, U	1.41
Flat glass, uncoated, at plant/RER U	1.38
Natural gas, at production onshore/DZ U	1.35
Hard coal, at mine/WEU U	1.33
Natural gas, at production offshore/NO U	1.28
Natural gas, at production onshore/NL U	1.23
Hard coal, burned in power plant/DE U	1.18
Hard coal, at mine/EEU U	1.10
Spoil from lignite mining {GLO}, treatment [3]	1.07
Crude oil, at production onshore/RME U	1.02
Lignite, at mine/RER U	1.01
MG-silicon, at plant/NO U	0.85
Copper, primary, at refinery/RLA U	0.84
Crude oil, at production offshore/NO U	0.83

[1] Electricity, high voltage {DE}|electricity production, lignite|Alloc Def, U

[2] Electricity, high voltage {DE}|electricity production, hard coal|Alloc Def, U

[3] Spoil from lignite mining {GLO}|treatment of, in surface landfill|Alloc Def, U

Table C3: Processes which contribute most to the total ReCiPe score of the Photovoltaic Park-Continued.

Compared to the total ReCiPe score	[%]
Pig iron, at plant/GLO U	0.81
Lignite, burned in power plant/DE U	0.81
Ethylene, average, at plant/RER U	0.79
Disposal, spoil from lignite mining, in surface landfill/GLO U	0.76
Light fuel oil, burned in industrial furnace 1MW, non-modulating/CH U	0.74
Heat, at cogen 1MWe lean burn, allocation exergy/RER U	0.73
Magnesium, at plant/RER U	0.72
Manganese concentrate, at beneficiation/GLO U	0.71
Ferronickel, 25% Ni, at plant/GLO U	0.71
Crude oil, at production onshore/RU U	0.69
Crude oil, at production offshore/GB U	0.68
Crude oil, at production onshore/RAF U	0.68
Hard coal, burned in power plant/ES U	0.65
Natural gas, burned in industrial furnace >100kW/RER U	0.64
Operation, transoceanic freight ship/OCE U	0.61
Disposal, plastics, mixture, 15.3% water, to municipal incineration/CH U	0.57
Electricity, high voltage {DE}, natural gas [1]	0.52
Natural gas, at production offshore/NL U	0.51
Chromite, ore concentrate, at beneficiation/GLO U	0.50
Bauxite, at mine/GLO U	0.49
Hard coal, at mine/ZA U	0.47
Operation, lorry >16t, fleet average/RER U	0.47
Heavy fuel oil, burned in power plant/IT U	0.45
Hard coal, burned in industrial furnace 1-10MW/RER U	0.44
Natural gas, at production onshore/DE U	0.43
Natural gas, burned in gas turbine, for compressor station/RU U	0.42
Nylon 66, glass-filled, at plant/RER U	0.42
Disposal, spoil from coal mining, in surface landfill/GLO U	0.42
Copper concentrate, at beneficiation/ID U	0.40
Polyethylene, HDPE, granulate, at plant/RER U	0.40
Total	80.30

[1] Electricity, high voltage {DE}|electricity production, natural gas, at conventional power plant| Alloc Def, U

Table C4: Processes which contribute most to the total ReCiPe score of the Biomass-fired Power Plant.

Compared to the total ReCiPe score	[%]
Softwood, standing, under bark, in forest/RER U	56.49
Operation, transoceanic freight ship/OCE U	5.44
Electricity-wood pellet	3.84
Lignite, at mine/RER U	2.06
Softwood, stand establishment/tending/site development, under bark/RER U	1.71
Disposal, spoil from lignite mining, in surface landfill/GLO U	1.55
Lignite, burned in power plant/DE U	1.48
Diesel, burned in building machine/GLO U	1.29
Crude oil, at production onshore/RME U	1.14
Hard coal, burned in power plant/DE U	1.06
Crude oil, at production offshore/NO U	0.95
Hard coal, at mine/EEU U	0.91
Hard coal, at mine/WEU U	0.87
(wpsc)Georgia wood chips, burned in furnace	0.85
Hard coal, burned in power plant/PL U	0.81
Total	80.46