Life Cycle Exergy Analysis of Wind Energy Systems

Assessing and improving life cycle analysis methodology

Simon Davidsson
Abstract

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Wind power capacity is currently growing fast around the world. At the same time different forms of life cycle analysis are becoming common for measuring the environmental impact of wind energy systems. This thesis identifies several problems with current methods for assessing the environmental impact of wind energy and suggests improvements that will make these assessments more robust.

The use of the exergy concept combined with life cycle analysis has been proposed by several researchers over the years. One method that has been described theoretically is life cycle exergy analysis (LCEA). In this thesis, the method of LCEA is evaluated and further developed from earlier theoretical definitions. Both benefits and drawbacks with using exergy based life cycle analysis are found. For some applications the use of exergy can solve many of the issues with current life cycle analysis methods, while other problems still remain.

The method of life cycle exergy analysis is used to evaluate the sustainability of an existing wind turbine. The wind turbine assessed appears to be sustainable in the way that it gives back many times more exergy than it uses during the life cycle.

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Sammanfattning (Swedish Summary)


En exergibaserad livscykelanalys kan lösa vissa av problemen med befintliga livscykelanalyser, men många av problemen måste behandlas för alla typer av livscykelanalys. Användandet av exergi för att beskriva naturresurser skulle kunna tillföra en vetenskaplig relevans till livscykelanalys, men samtidigt verkar inte tillämpbarheten av detta helt fastslaget. Mer forskning behövs när det gäller att förbättra livscykelanalysmetoder samt hur exergibegreppet kan och bör användas.
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Abbreviations

CDP  cumulative degree of perfection
CEENE  cumulative exergy extraction from the natural environment
CExC  cumulative exergy consumption
CExD  cumulative exergy demand
ELCA  exergetic life cycle analysis
EPBT  energy payback time
EROI  energy return on investment
ExROI  exergy return on investment
GER  global energy requirement
HAWT  horizontal axis wind turbine
HHV  higher heating value
LCA  life cycle assessment or life cycle analysis
LCEA  life cycle exergy analysis
LCI  life cycle inventory
LCIA  life cycle impact assessment
LHV  lower heating value
PEPBT  primary energy payback time
VAWT  vertical axis wind turbine
Nomenclature

\( A' \)  
\( A \)  
\( CF \)  
\( C_p \)  
\( E \)  
\( E_{ch} \)  
\( E_{chn} \)  
\( E_{chne} \)  
\( E_{in} \)  
\( E_{in}^{\text{tot}} \)  
\( E_{indirect} \)  
\( E_{nu} \)  
\( E_{out} \)  
\( E_{out}^{\text{tot}} \)  
\( E_{ph} \)  
\( E_{pr} \)  
\( E_{tr} \)  
\( E_{waste} \)  
\( I \)  
\( g \)  
\( H \)  
\( k \)  
\( n_e \)  
\( n_i \)  
\( P \)  
\( p_0 \)  
\( P_R \)  
\( P_w \)  
\( r \)  
\( S \)  
\( S^{\text{tot}} \)  
\( S_{eq}^{\text{tot}} \)  
\( T_0 \)  
\( U \)  
\( v \)  
\( W \)  
\( \eta_{ex,1} \)  
\( \eta_{ex,2} \)  
\( \eta_{ex,3} \)  
\( \Delta E \)  
\( \Delta G_f \)  
\( \Delta S^{\text{tot}} \)  
\( \rho \)  
\( \mu_i \)  

Anergy (J) 
area (m²) 
capacity factor of wind turbine 
rotor power coefficient 
exergy (J) 
chemical exergy (J) 
standard chemical exergy of chemical compound (J) 
standard chemical exergy of an element (J) 
exergy input (J) 
total input exergy (J) 
indirect exergy used during life cycle (J) 
nuclear exergy (J) 
exergy output (J) 
total output exergy (J) 
physical exergy (J) 
exergy of product (J) 
transit exergy (J) 
exergy of waste (J) 
information 
the gravitational constant (N²m²/kg²) 
enthalpy (J) 
Boltzmann’s constant 
kmol of element e 
kmol of element i 
power (W) 
pressure of the environment (Pa) 
rated power of wind turbine (W) 
average power actually produced by wind turbine (W) 
radius (m) 
entropy (J/K) 
entropy of the total system, i.e. the system and the environment (J/K) 
entropy of the total system, i.e. the system and the environment, at equilibrium (J/K) 
temperature of the environment (K) 
internal energy (J) 
velocity (m/s) 
energy (J) 
exergy efficiency as exergy output divided by exergy input 
exergy efficiency as useful exergy output divided by exergy input 
exergy efficiency as useful exergy output minus transit exergy divided by exergy input minus transit exergy 
exergy destruction (J) 
formation Gibbs free energy (J) 
total entropy increase (J/K) 
density of air (kg/m³) 
chemical potential of substance i in its environmental state (J/mol)
1. Introduction

Wind energy and other renewable energy resources are often described as being clean or emission free and are automatically assumed to be good for the environment. In reality, all methods for converting energy into a usable form have various environmental impacts. It is important to have methods for evaluating the sustainability of different energy producing processes to be able to compare them to each other and plan an energy system for the future.

Wind energy capacity is growing at a high pace and the global installed capacity roughly doubles every three years (WWF, 2010). This makes wind power a highly important form of renewable energy resource for the future and its environmental impact and sustainability needs to be further evaluated. Different forms of life cycle based analysis are becoming increasingly common as a measure of the environmental impact of products and processes. As wind energy is growing, life cycle analysis is also becoming a common method for evaluating the environmental impact of wind energy. Several life cycle based assessments of wind turbines have been made during the last couple of decades coming both directly from wind turbine producing companies and consultant firms (Vestas, 2006; Vestas, 2011) as well as peer reviewed scientific articles (Schleisner, 2000; White, 2006; Ardent et al., 2008; Crawford, 2009; Martinez et al., 2009a; Martinez et al., 2009b; Tremeac and Menuier 2009; Weinzeettel et al., 2009) and conference papers (Lee et al., 2006).

The concept of exergy has been around for a long time, but is not very commonly used in many applications. Exergy and exergy-related tools can be used to evaluate the sustainability of products and also to design sustainable systems. Exergy-related analytical tools are still evolving and completely applicable methods that connect exergy to criteria for sustainable development in a scientific way have not fully developed. Many researchers have suggested the use of exergy combined with life cycle analysis. One of the methods is life cycle exergy analysis, proposed and theoretically described by Gong and Wall (1997, 2001) and Wall (2002, 2010). The applicability of exergy together with life cycle analysis, and more specifically the method LCEA, is further investigated in this thesis.

1.1. Question at issue

The main question at issue for this master’s thesis is to evaluate, develop and define the method of life cycle exergy analysis (LCEA) and investigate how to use LCEA in practice for evaluating the sustainability of products and processes.

Existing life cycle assessments of wind energy systems are reviewed and potential issues with current methodology, as well as possible improvements that exergy and LCEA could offer, are investigated.

The sustainability of a modern wind turbine is investigated and calculated with the method of LCEA, using an existing life cycle assessment as a base.

1.2. Methodology

In order to answer the questions at issue, the concept of exergy and current life cycle methodology, as well as basic knowledge about how modern wind turbines work needs to be understood. A literature study covering the concept of exergy, different types of life cycle analysis, the use of combining life cycle
methodology with the exergy concept as well as the basic theory of wind power and wind turbine manufacturing is performed and presented in Chapter 2.

While searching for data to base an LCEA of an existing wind turbine on, many existing assessments of wind turbines are reviewed. During this work many possible issues with the way the environmental impact of wind turbines is currently evaluated was found. This is presented in Chapter 3 as a critical review dealing with some questionable methods used in existing assessments.

The method of LCEA is further developed, starting from the existing theoretical description of LCEA. A more detailed description of the method as well as guidelines and thoughts on how the method can and should be used in practice generally, and more specifically on wind power systems, are developed. The method is also applied on a real wind turbine using an existing life cycle assessment of a wind turbine as a base, with several other assumptions and calculations made, attempting to keep the analysis in line with the descriptions of the method of LCEA.

This thesis is divided into seven chapters. In Chapter 2 a literature study covering the theoretical background for the thesis is presented. Chapter 3 contains a critical review of existing life cycle analysis of wind power systems. Chapter 4 builds on the limitations of existing methods and the current definition of life cycle exergy analysis, asking what a proper LCEA would look like. Chapter 5 applies this theoretical model to an actual wind turbine. The results are discussed in Chapter 6 and in Chapter 7 the main conclusions made are presented as well as suggestions on future research on the area.
2. Theoretical background

The concept of exergy is fundamental to this thesis. Gaudreau (2009) describes many different scientific disciplines where exergy has been used before, including ecology and system thinking, resource accounting, life cycle assessments and engineering. Exergy is not something that people, either in the general public or the scientific community, are very familiar with. Energy is sometimes falsely defined as being “the ability to do work” and in everyday language most people refer to exergy when they say energy. The fundamentals of the exergy concept and some of its possible uses are described throughout the rest of this chapter.

2.1. What is exergy?

The difference between exergy and energy is explained clearly by Gong and Wall (1997), see Table 2.1. The first law of thermodynamics concludes that neither energy nor mass can disappear. Energy is defined as motion or ability to produce motion and is a measure of quantity. Energy is always conserved and can neither be produced nor consumed. At the same time only a part of that energy can be converted into work, for most energy carriers. Exergy is defined as work, or the ability to produce work, where work means ordered motion. Exergy is a measure of both quality and quantity and is only conserved in reversible processes. Since real processes are always irreversible, exergy is always lost in real processes.

<table>
<thead>
<tr>
<th>Energy</th>
<th>Exergy</th>
</tr>
</thead>
<tbody>
<tr>
<td>The first law of thermodynamics</td>
<td>The second law of thermodynamics</td>
</tr>
<tr>
<td>Energy is motion or ability to produce motion.</td>
<td>Exergy is work, i.e. ordered motion, or ability to produce work.</td>
</tr>
<tr>
<td>Energy and matter is “the same thing.”</td>
<td>Exergy and information is “the same thing.”</td>
</tr>
<tr>
<td>Energy is always conserved, i.e. in balance; it can neither be produced nor consumed.</td>
<td>Exergy is always conserved in a reversible process, but reduced in an irreversible process, i.e. real processes. Thus, exergy is never in balance for real processes.</td>
</tr>
<tr>
<td>Energy is a measure of quantity.</td>
<td>Exergy is a measure of quantity and quality.</td>
</tr>
</tbody>
</table>

The concept of exergy has its roots in the early classical thermodynamics of the 19th century and the history of the concept is well documented, e.g. by Sciubba and Wall (2007). The word exergy was introduced by Zoran Rant in 1953 as a word for “external work” or “technical working capacity”. Since then several slightly different definitions of exergy have existed. A common modern definition as stated by Wall (1977) is:

“The exergy of a system in a certain environment is the amount of mechanical work that can be maximally extracted from the system in this environment.”

Szargut (1989) defines exergy slightly differently as the reverse process of creating the material from the reference environment:
“...the minimal work necessary to produce a material in its specified state from materials common in the environment in a reversible way, heat being exchanged only with the environment.”

Sciubba and Wall (2007) defines exergy as:

“... the maximum theoretical useful work obtained if a system $S$ is brought into thermodynamic equilibrium with the environment by means of processes in which the $S$ interacts only with this environment.”

Sometimes exergy is defined as the part of energy that can be fully converted into any other kind of energy, which is not fully correct since the exergy results from the possibility to interact with the environment (Szargut, 1988). For instance, the removal of energy from an energy carrier with a temperature lower than the environment will cause an increase of exergy.

To describe the difference between energy and exergy the concept of anergy has been introduced as presented in equation 2.1. (Szargut, 1988).

$$A' = W - E \quad (2.1)$$

Where $A'$ is anergy, $W$ is energy and $E$ is exergy. It is important to notice that anergy may be negative, i.e. when the exergy is larger than the energy, as for cold systems or systems at low pressure. Thus, anergy is not a commonly accepted or needed concept.

Exergy is strongly connected to entropy since the exergy of a system is (Wall 1977):

$$E = T_0(S^\text{tot}_{\text{eq}} - S^\text{tot}) \quad (2.2)$$

Which can be derived using thermodynamic relations into:

$$E = U + p_0 - T_0S - \sum \mu_i n_i \quad (2.3)$$

For a flow the exergy is:

$$E = H - T_0S - \sum \mu_i n_i \quad (2.4)$$

Where $E$ is exergy, $T_0$ is the temperature of the environment, $S$ is entropy, $S^\text{tot}$ is the entropy of the total system, $S^\text{tot}_{\text{eq}}$ is the entropy of the total system at equilibrium, $U$ is internal energy, $p_0$ is the pressure of the environment, $\mu_i$ is the chemical potential of substance $i$ in its environmental state, $n_i$ is kmol of element $i$ and $H$ is enthalpy.

Exergy is not a static attribute, but has to be formulated in respect to a reference environment or reference state. The higher the exergy content, the farther a system is from its reference environment thermodynamically.

Exergy is also sometimes quantified into several different types of exergy, such as: kinetic exergy, potential exergy, physical exergy, chemical exergy and nuclear exergy (Szargut, 2005).
\[
E = \frac{v^2}{2} + gX + E_{ph} + E_{ch} + E_{nu}
\]
(2.5)

Where \( g \) is the gravitational constant, \( v \) is the velocity related to the Earth’s surface, \( X \) is height above the lowest level prevailing near the considered device.

### 2.1.1. Reference environments

Exergy is not a static attribute, but must always be formulated in relation to a reference environment. To make it easier to use exergy, attempts to make it more similar to a static attribute have been made, by formulating standard reference environments, or reference states. Gaudreau (2009) describes three different reference environments formulated by different authors called: process dependent, equilibrium and defined reference states. The Exergoeconomy group calls the different reference environments Szargut’s criterion, Chemical equilibrium and Abundance (Szargut et al. 2005). All three main types of reference environments have received some criticism, for example by Gaudreau (2009) and Gaudreau et al. (2009). Defined reference states based on Szargut’s criterion appears to be most widely used and will be used throughout this thesis. Szargut et al. (2005) propose an agreement on an international reference environment for evaluating exergy resources of the world which would be a Comprehensive Reference Environment based on Szargut’s criterion.

Szargut’s criterion assumes a thermodynamically dead planet where all materials have reacted, dispersed and mixed. There are three different kinds of reference substances that can be accepted: gaseous components of the atmospheric air, solid components of the external layer of the Earth’s crust and ionic or molecular components of seawater. Valero (2008) addresses some drawbacks of the reference environment based on Szargut’s criterion by recommending not seeing it as a dead reference environment, but as a mathematical tool for obtaining standard chemical exergies of the elements. Different reference environments can also be related to global and local standard environments, which is dealt with by Wall (1977).

### 2.1.2. Exergy and information

Since exergy is a measure of how much a system deviates from its equilibrium with the environment the more information is needed to describe it the more it deviates. This creates a strong connection between exergy and information (Wall 1977). The relationship between exergy \( E \) and information \( I \) in binary units (bits) is:

\[
E = k'T_0l
\]
(2.6)

Where \( I \) is information, \( T_0 \) is the temperature of the environment and \( k' = k \ln 2 \approx 1.0 \cdot 10^{-23} \, \text{J/K} \) and \( k \) is Boltzmann’s constant. Thus \( k'T_0 = 2.9\times10^{-21} \, \text{J} \) is the amount of exergy of one bit of information at room temperature.

### 2.1.3. Exergy losses

In a real process there is always a loss of exergy, i.e. the exergy input always exceeds the exergy output due to irreversibilities. This means that exergy is not preserved or balanced in real processes, while energy is always preserved and balanced, which is a fundamental difference. This lost exergy vanishes into nothing and can be called exergy destruction, \( \Delta E \).
Exergy destruction can in literature also be referred to as availability destruction, irreversibility, lost work (Gong and Wall, 1997) and internal exergy loss (Szargut, 1989). At the same time some exergy outflows are not utilized, but emitted to the environment. This exergy can be called $E_{\text{waste}}$ (Gong and Wall, 1997) or external exergy loss (Szargut, 1989). It is important to separate exergy destruction caused by irreversibilities from exergy flow to the environment since the first mentioned by definition has no exergy and therefore no environmental effects, while the latter has exergy and can cause environmental harm (Gong and Wall 1997).

The exergy destruction is related to the entropy generation and can be described by:

$$\Delta E = T_0 \Delta S^{\text{tot}} = E_{\text{in}}^{\text{tot}} - E_{\text{out}}^{\text{tot}} \quad (2.7)$$

where $\Delta E$ is exergy destruction, $\Delta S^{\text{tot}}$ is the total entropy increase, $E_{\text{in}}^{\text{tot}}$ is the total input exergy and $E_{\text{out}}^{\text{tot}}$ is the total output exergy.

### 2.1.4. Exergy efficiency

There are some different ways to define exergy efficiency. Wall (1977) defines it as utilized exergy divided by the exergy which is theoretically possible to utilize. The most common definition is however utilized exergy divided by used exergy. Wall (2002) states the exergy efficiencies as:

$$\eta_{\text{ex},1} = \frac{E_{\text{out}}}{E_{\text{in}}} \quad (2.8)$$

Where $E_{\text{out}}$ is the exergy output and $E_{\text{in}}$ is the exergy input. A part of the output is usually waste:

$$E_{\text{out}} = E_{\text{pr}} - E_{\text{waste}} \quad (2.9)$$

Where $E_{\text{pr}}$ is the exergy of the product and $E_{\text{waste}}$ is the exergy of waste. This creates a new definition of exergy efficiency:

$$\eta_{\text{ex},2} = \frac{E_{\text{out}} - E_{\text{waste}}}{E_{\text{in}}} = \frac{E_{\text{pr}}}{E_{\text{in}}} = \eta_{\text{ex},1} - \frac{E_{\text{waste}}}{E_{\text{in}}} \quad (2.10)$$

It is also possible for some exergy to be transit exergy, $E_{\text{tr}}$, that passes through the system unaffected. The exergy efficiency then becomes:

$$\eta_{\text{ex},3} = \frac{E_{\text{out}} - E_{\text{waste}} - E_{\text{tr}}}{E_{\text{in}} - E_{\text{tr}}} = \frac{E_{\text{pr}} - E_{\text{tr}}}{E_{\text{in}} - E_{\text{tr}}} \quad (2.11)$$

Szargut et al. (1988) calls the exergy of useful products divided by feeding exergy the cumulative degree of perfection (CDP) and defines useful exergetic effect divided by driving exergy as exergetic efficiency.

### 2.1.5. Exergy as a measure of quality

A common way to use exergy in practice is to express the quality of different energy carriers, or how much of the energy can be transformed into useful energy. Wall (1977) presents indexes of exergy quality, see Table 2.2.

**Table 2.2. Exergy quality indexes of different forms of energy. Adapted from Wall (1977).**
Form of energy | Quality index (Percentage of exergy)
---|---
Potential energy | 100
Kinetic energy | 100
Electrical energy | 100
Chemical energy | about 100
Nuclear energy | 95
Sunlight | 93
Hot steam | 60
District heating | 30
Waste heat | 5
Heat radiation from earth | 0

Exergy can also be used as a measure of quality of other resources, like different materials, since the exergy content is dependent on how ordered the elements are in the material.

**Table 2.3. Exergy quality indexes of different materials. Adapted from Wall (1977).**

<table>
<thead>
<tr>
<th>Form of matter</th>
<th>Quality index (Percentage of exergy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matter in an ordered form</td>
<td>100</td>
</tr>
<tr>
<td>Matter as commercial goods</td>
<td>100 almost</td>
</tr>
<tr>
<td>Mixtures of elements</td>
<td>90 approximately</td>
</tr>
<tr>
<td>Rich mineral deposits</td>
<td>50 - 80</td>
</tr>
<tr>
<td>Ore</td>
<td>50 approximately</td>
</tr>
<tr>
<td>Poor mineral deposits</td>
<td>20 - 50</td>
</tr>
<tr>
<td>Mineral dissolved in seawater or soil</td>
<td>0 approximately</td>
</tr>
</tbody>
</table>

### 2.1.6. Exergy and resource accounting

Mass and energy are not good measures for describing resource consumption or depletion since neither energy nor mass can disappear. The exergy concept makes it possible to describe both mass and energy of different resources with a common physical unit that is in fact consumed in real processes, and thus possible to save by improvements or economizing measures. Wall (1977) states that all human utilization of resources and disposal of waste and emissions effects nature and suggest that the effect is strongly related to the exergy of the resource or waste. For those reasons the use of exergy for different kinds of resource accounting has been proposed by many scientists over the last decades (Wall 1977; Szargut, 1988; Cornelissen, 1997; Ayres et al., 1998; Valero 2008). Valero (2008) concludes that exergy analysis of minerals has the possibility to be a universal and transparent method for evaluating degradation of non-renewable resources.

The use of exergy to describe resource consumption has received some critique. Gaudreau et al. (2009) claims that the use of exergy as a measure of resource quality and consumption is not well established
and states that exergy should not be used for this, until some problems and limitations are addressed and solved. At the same time, the use of exergy to describe resource quality and consumption is defined and used by many scientists, and the use is wide spread. Exergy as a measure of resource consumption is a fundamental part of the LCEA method, and is used throughout this thesis. These issues will not be addressed to any great extent in this thesis, but a continued discussion on the matter is encouraged.

2.1.7. Exergy and waste impact

It has also been suggested by several researchers that exergy can be used to measure the potential harm in emissions. Wall (1977) suggests the exergy of waste products is strongly related to the effect it has on nature. Ayres et al. (1998) concludes that there are two different ways to calculate the exergy of wastes, which can preferably both be applied for mutual verification. A waste emission can be in thermal or chemical disequilibrium with the environment which can cause environmental harm.

Several issues with using exergy as a measure of waste impact have been pointed out. First of all there seems to exist a paradox in the way exergy in the environment can be both a resource that have value, as well as an emission that are harmful (Gaudreau et al., 2009). Also, the exergy of waste emission does not seem to necessarily reflect the magnitude of the environmental impact. Ayres et al. (1998) states that exergy embodied in waste streams is not an accurate measure of potential for harm or eco-toxicity, but can be better than the alternatives to use mass and waste heat or other non comparable units. Cornelissen and Hirs (2002) argue that the use of exergy as a measure of waste emissions and potential of causing environmental harm cannot be validated.

It does not seem to be adequately proven that the exergy of emissions reflects the environmental damage and that the use of exergy as a way to describe waste impact is valid. This use of the exergy concept seems to have met more critique than the use of describing resource value. Exergy is not used to describe waste and emission impact in this thesis, but further research and discussion this concerning this use of the exergy concept is encouraged.

2.1.8. Chemical exergy calculation methodology

To express natural resources with the concept of exergy, a method of calculating the exergy of the resource is needed. A comprehensive methodology to calculate exergy of raw materials based on the standard chemical exergy of the chemical elements where first presented by Wall (1977) and later by Szargut et al. (1988). The standard chemical exergy of chemical compounds can be calculated with equation 2.12 (Szargut, 2005):

\[ E_{chn} = \Delta G_f + \sum e n_e E_{chne} \]  \hspace{1cm} (2.12)

Where \( \Delta G_f \) is formation Gibbs energy, \( n_e \) is the amount of kmol of element \( e \) and \( E_{chne} \) is the standard chemical exergy of the element. Standard chemical exergies of chemical elements is presented in Szargut et al. (1988). Later other contributions to new standard chemical exergy of elements have been proposed (de Meester et. al. 2006; Rivero and Garfias 2006; Szargut et al. 2005).

To quickly and easily calculate the exergy of different substances that are not published or if you do not have access to published exergies of different components, the Exergoeckology Group has developed an
online exergy calculator (Exergoeconomy, 2011), see Fig. 2.1. The calculator is based on Szarguts reference environment and the methodology described in Szargut et al. (2005).

![Exergy calculator](http://www.exergoeconomy.com/excalc/)

**Figure. 2.1. The Exergy calculator at** http://www.exergoeconomy.com/excalc/

To use exergy for describing different materials, it is necessary to be able to easily calculate or access the exergy value of the resources used throughout the life cycle, as they appear in nature. Szargut (1988) listed exergy values for resources commonly used in industrial processes. An exact calculation of the chemical exergies of many organic fuels consisting of mixtures and solutions of many different organic compounds is not possible to make, but for energy resources the exergy content is close to the net calorific value (Szargut et al. 1988). Szargut et al. (1988), Finnveden and Östlund (1997) and Szargut (2005) listed relative quantities between the net calorific value and the exergy of different energy resources. These ratios are presented in Table B1, in Appendix B.

Szargut et al. (1988) presents chemical exergies of many other non-energy resources. Finnveden and Östlund (1997) also listed exergy values of different minerals. Throughout this thesis resources that are used as a material (material resources) is often separated from resources that are used to produce energy for the process (fuel resources). Resources that are normally fuel resources, like oil and fossil gas, can in fact sometimes appear as a material resource, for instance when oil is used as a material for polymers. The exergy of fossil fuels used as materials are still calculated with the ratios of their heating values.

**2.1.9. Exergy and sustainability**

The word sustainable and sustainability is commonly used today, often without a real definition of what it means. The most common current definition comes from the World Commission on Environment and Development (1987) and states:

“*Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*.”
What this actually means can be debated and a more scientific description of sustainability can be useful. Wall (1977; 2010) describes that the present use of resources in society is not sustainable as deposits are used and turned into waste, and claims that sustainable engineering needs to be developed instead. By exposing the losses and giving numbers to the flows that needs to be minimized in processes, exergy could be a way to describe the sustainability of processes. Exergy can describe both the use of energy and material resources in society with one common unit. A society that consumes its exergy resources faster than they are renewed can by definition not be sustainable. According to Wall (1977) an energy producing process, like a wind turbine, can be regarded as sustainable if it produces more exergy than it takes from the system.

This is the definition of sustainability that will be used throughout this thesis. The wind turbine assessed in Chapter 5 is therefore considered sustainable if, what can be called the exergy return on investment (ExROI), is over 1.

2.2. Existing methods of environmental impact assessments
Several methods to evaluate energy efficiency and environmental impact of processes and products have evolved over the years. In this chapter the development and basic theory of energy analysis and life cycle assessment is described. Also, the application of exergy in the life cycle perspective is presented.

2.2.1. Energy analysis
After several researchers around the world had begun work on methods similar to energy analysis, the word energy analysis was stated at a conference held by the International Federation of Institutes for Advanced Studies in 1974, where guidelines with conventions for energy analysis were provided (Mortimer, 1991). The guidelines defined the technique, units as well as methods of calculation and reporting of results. Since then, these conventions have changed and different types of energy analysis have evolved. Crawford (2009) describes two different traditional methods of energy analysis, namely process analysis and input-output (I/O) analysis. Process analysis, or process chain analysis, measures materials and energy flows of the processes during the life cycle and tries to translate the material flows into energy using an embodied energy factor to sum up the total energy use. Input-output analysis on the other hand uses a matrix of different parts of an entire economy and uses economic factors to calculate the energy use (White and Kulcinski, 1998).
2.2.2. Exergy analysis

Since energy analysis is based on the first law of thermodynamics it often fails to identify losses of work or effective use of resources. A process based energy analysis could take exergy in account to form an exergy analysis. To estimate the total exergy input in a certain process you need to take every different inflows of exergy into account. Wall (1977) called budgeting of the inflows and outflows of exergy as a way to express the sum of natural resources consumed through a certain process exergy analysis. From this idea several types of exergy based methods have evolved which will be described in segment 2.3.

Figure 2.1. A typical process analysis with up to four levels.

Figure 2.2. Possible system boundaries surrounding the production process of a wind power plant.
2.2.3. Life Cycle Assessment (LCA)

Even though they have evolved more or less separately, life cycle analysis or life cycle assessment (LCA), have many similarities to energy analysis. The main difference is that LCA is not restricted to just energy. In an LCA you try to estimate the environmental burden by identifying, quantifying and assessing the environmental impact of the energy and materials used as well as wastes released to the environment (Finnveden and Östlund, 1997).

Baumann and Tillman (2004) states that there are several guidelines as well as ISO-standards describing how to perform an LCA, but also that there are still many different ways to do this. Many of the guidelines were written before the ISO-standards were issued and are generally more detailed than the standards. Neither the standard nor the guidelines states clear requirements for the procedure of performing the LCA or how the modeling and reporting of the LCA should be undertaken. The European Commission (2010) describes that the even though the ISO standards provide a framework for LCA, the practitioner of the method is still left with a wide range of choices, which can affect the legitimacy of the results.

An LCA generally follow four basic steps, see figure 2.3: 1) definition of the scope and goal of the analysis, 2) inventory analysis, or life cycle inventory (LCI), 3) impact assessment and 4) interpretation and weighing.

**Figure 2.3. The four main steps of a life cycle assessment.**

### 2.2.3.1. Goals and scope

In the goals and scope phase the methods to use and system boundaries are decided. It is also decided which types of environmental impact that are interesting and the level of detail of the study (Baumann and Tillmann, 2004). Starting from the goals and cope, an inventory analysis is built as a model of the system, which should result in a complete mass and energy balance for the system, see Fig 2.4. Choices
made here about system boundaries, cut-off limits or functional units can have large impact on the final results.

![Diagram of mass and energy balance for the complete life cycle.]

**Figure 2.4. The mass and energy balance for the complete life cycle.**

### 2.2.3.2. Life cycle inventory

In the life cycle inventory (LCI) the inputs and outputs throughout the life cycle, within the system boundaries, are decided. There are several different ways to do this, and choices in methodology can have a large impact on the results.

Ekvall and Weidema (2004) describe a way to divide the life cycle inventory into two main methods: attributional and consequential LCI. Baumann and Tillmann (2004) describe the same thing but use the terminology accounting and change-oriented LCA. The traditional attributional LCI describes the physical flows relevant to environmental impact into and out from the life cycle system boundaries, from raw material extraction to waste management. A consequential LCI, on the other hand, is designed to generate information about consequences of actions made by describing how the physical flows relevant to environmental impact will change with certain changes in the life cycle. To do that, marginal data is used to describe the consequence of a decision in a relevant way. Allocation is avoided through system expansion, because multifunctional processes and open-loop recycling (recycling from one product system into another) affect processes outside of the life cycle. For multifunctional processes, all processes that are affected by a change in the use of a product are included. For open-loop recycling the system is expanded to include the unit processes that are affected by an increase or decrease in flow to or from the system. In reality there is not always a clear line between attributional and consequential assessments.

Like with energy analysis, there are also two other main methods to use for the life cycle inventory: process chain analysis and input-output analysis. A process chain analysis, like the ones based on ISO 14040, is generally seen as more accurate and relevant than an input-output analysis. Process chain analysis is, however, accused of missing a great deal of important information that can be taken account for in an input-output analysis. Hybrid methods that could use the advantages of both methods and be more accurate have been suggested. Crawford (2009) claims that the system boundaries for a process analysis can be up to 87% incomplete, and proposes the use of hybrid methods instead.

### 2.2.3.3. Impact assessment and interpretation

The next step in a classical LCA is the impact assessment, where the results from the inventory are converted into environmentally relevant information (Baumann and Tillmann 2004). First, the
parameters from the inventory are classified to different types of environmental impact. Then, the impact is characterized by calculating the relative contributions to the different environmental impacts. According to Jolliet (2003), two basic schools of methodology for life cycle impact assessment (LCIA) have been developed: Classical impact methods (eg. CML and EDIP) and damage oriented methods (eg. Eco-indicator 99, EPS) and propose a new methodology called Impact 2002+. Martínez (2010) compares no less than seven different methods to perform an LCIA.

After the LCIA an attempt is sometimes made to express the impact on a common scale through weighting, or in other ways further evaluate the results from the impact assessment. This can never be based solely on natural science, but subjective values must always be introduced (Baumann and Tillmann, 2004). Either the results of the LCI or characterized results of the LCIA can be presented and interpreted.

This thesis will not go into any further depth of the different methodologies, but it is important to see that there are many different ways to perform an LCA, thus, implying a variety of results to the same object of study.

2.2.4. Natural resources in LCA
Finnveden (2005) points out that the impacts from resource depletion have been included in most LCIA methods and that resource use often is important for the final result in different impact methods. However, methods to quantify resource depletion in LCA have been under debate and no consensus has been reached on which methodology to use. One possible way to go about this could be the use of the exergy concept.

2.3. Life cycle based analysis and exergy
The use of exergy in life cycle assessments has been suggested by many different researchers since the late 1990s (Cornelissen, 1997; Finnveden and Östlund, 1997; Gong and Wall, 1997; Ayres et al., 1998; Dewulf and Van Langenhove, 2002; Bösch et al., 2007) and many benefits of the use of exergy in life cycle analysis have been described. Ayres et al. (1998) point out three benefits of using exergy as a common measure of inputs and outputs: it creates a possibility to immediately estimate the exergetic efficiency of the process and makes it possible to compare different environmental impacts with each other using a single unit, which also creates a possibility to compare environmental performance of larger systems, such as industries or nations, over time.

A few different methods that use exergy in a life cycle perspective have been introduced by different authors. Many similarities exist, but also some important differences. Brief descriptions of a few of the methods are presented as follows.

2.3.1. Cumulative exergy consumption (CExC)
Szargut (1988) presents a method called cumulative exergy consumption (CExC) to express the sum of the exergy of all natural resources consumed in the steps of a production process. Unlike cumulative energy consumption it also takes non-energetic raw materials extracted from the environment into account. A method to calculate the cumulative degree of perfection (CDP) is also proposed that can indicate the deviation from thermodynamic perfection, or the the exergetic efficiency of the process.
CExC does not take into account if the exergy used comes from renewable funds or flows or non-renewable stocks and does not take account for the in- and outflows of exergy over time.

Bösch et al. (2007) attempts to use CExC as an indicator in LCA, and introduces a new notation to Szargut’s CExC method by calling it cumulative exergy demand (CExD), to stress the similarities to cumulative energy demand (CED). CExD is used on resources in the ecoinvent database and the method has now been accepted as one of the impact assessment methodologies to the ecoinvent database.

2.3.2. Exergetic life cycle analysis (ELCA)
Cornelissen (1997) propose a method called exergetic life cycle analysis (ELCA), which can be used together with LCA to determine the consumption and depletion of natural resources by measuring the life cycle irreversibility, i.e. the exergy loss. Cornelissen (1997) also proposes a method called Zero-ELCA which quantifies the exergy of the emissions by looking at the exergy needed for abatement of the emissions. ELCA and Zero-ELCA is seen as an extension of the LCA to take account of the emissions and depletion of natural resources within the LCA. ELCA does not separate abiotic from biotic resources and did not, at first, separate renewable resources from non-renewable. Cornelissen and Hirs (2002) later added a distinction between renewable and non-renewable resources and demonstrated ELCA as a method to quantify depletion of natural resources and to assess the efficiency of natural resource use, within the method of LCA.

2.3.3. Cumulative exergy extraction from the natural environment (CEENE)
CEENE is described by Dewulf et al. (2007) as an impact assessment method. Exergy data on ores, minerals, air, water, land occupation and renewable energy sources has been elaborated to quantify the amount of exergy taken away from the ecosystems. Like Bösch et al. (2007), the data is coupled with the LCI database of ecoinvent, but unlike CExD this method takes account of land use. CEENE is described as a way to solve some of the shortcomings of previous methods by presenting up-to-date thermochemical data and include exergy from land use.

2.3.4. Life cycle exergy analysis (LCEA)
The basics of LCEA have been outlined by Gong and Wall (1997, 2001) and Wall (2002, 2010). In LCEA renewable resources are separated from non-renewable. First of all natural resources are classified as natural flows and stocks. Stocks are then divided into deposits (dead stocks) and funds (living stocks). Natural flows and funds are renewable while deposits are non-renewable. All in- and outflows during the life cycle of production, use and disposal or recycling, are then considered as exergy power over time.

The direct exergy input (e.g. wind) of renewable sources can be disregarded since it is a natural flow and is therefore renewable. If not used natural exergy flows will be wasted and lost. Non-sustainable use of exergy funds, like clearing of forests in a non-sustainable fashion and use of exergy deposits are regarded as non-renewable resources.
The life cycle of a system usually consists of three separate stages with different exergy flows that are analogous to the three steps in the life cycle of a product in an LCA; construction phase, operational phase and clean up phase. During the construction phase, exergy is spent and none is created besides eventual byproducts. The exergy used for construction combined with the exergy used for maintenance and clean up make up the total indirect exergy, $E_{indirect}$. At what moment in time the exergy is used is important.

A power plant using fossil fuels takes the exergy from the fuels used during the operational phase. The exergy of the output electrical energy will always be lower than the exergy of the fuels used during the production. A power plant using fossil fuels can therefore never be sustainable, according to the definition stated in 2.1.9., since it uses more exergy than it generates. The exergy flow over the lifetime of a fossil fuel power plant is illustrated in Figure 2.6.

![Exergy flows in society](image)

**Figure 2.5.** Exergy flows in society.

![Example of exergy flow diagram for LCEA of a power plant using non-renewable fuels](image)

**Figure 2.6.** Example of exergy flow diagram for LCEA of a power plant using non-renewable fuels.
Renewable sources of electrical power, on the other hand, convert the renewable exergy power of a natural flow to a useable form of energy. As an example, a wind turbine produces exergy power in form of electrical power directly from the exergy power in the wind. During the operational phase it will hopefully produce more exergy than the indirect exergy needed during the life cycle. The exergy flow over the life cycle of a wind turbine is illustrated in Figure 2.7. The fact that the exergy utilized during the operational phase of the life cycle comes from a renewable source does however not automatically mean that it is sustainable. Wall (1997) points out that, for instance, a solar panel made from aluminum and glass can actually use more indirect exergy than it will ever generate during its life cycle. LCEA is suggested as a method to investigate this kind of issues.

![Exergy Flow Diagram](image)

Fig. 2.7. Example of exergy flow diagram for LCEA of a wind power plant.

The method of LCEA has so far only been described in these highly theoretical terms and appears to never have been applied on a real case. An important part of this thesis is to evaluate the method and develop guidelines on how an LCEA should be performed in practice by applying it to wind energy systems. A case study where the method is used on an actual wind turbine is presented in Chapter 5.

2.4. Wind energy

When attempting to evaluate the sustainability of wind energy, it is important to understand the theory of harvesting energy from the wind, as well as the basic construction of modern wind turbines.

2.4.1. Main theory of the wind

The exergy power in the wind can be calculated with equation 2.13. (Boyle, 2004):

\[ P = \frac{1}{2} \rho A v^3 \]  

(2.13)

Which can be written as:

\[ P = \frac{1}{2} \rho \pi r^2 v^3 \]  

(2.14)

Where \( P \) is the exergy power, \( \rho \) is the density of the air, \( A \) is the swept area of the wind turbine, \( r \) is the radius of the swept area and \( v \) is the velocity of the wind.

The power from the kinetic energy in the wind depends on the cube of the velocity of the wind and the square of the turbine radius. This means that if the radius is doubled, the power of the wind increase 4
times. This has created a trend towards bigger and bigger swept areas of wind turbines. On the other hand, if the velocity of the wind is doubled, the power in the wind increases 8 times. These physical properties of the wind make it important to have large swept areas, but even more important to place turbines where the wind speeds are high over big parts of the time.

It is not possible to extract all of the power of the wind, mainly because it cannot be stopped to zero velocity. In fact, the maximum power extraction happens when the velocity after the turbine is 1/3 of the velocity before the turbine. From this, the widely famous Betz limit concludes that it is not possible to extract more then 16/27 (about 59 %) of the kinetic energy of the wind (van Kuik, 2007). There are also mechanical and electrical losses in different parts of the turbine, which makes the maximum power possible to extract in reality even lower. The ratio between the rotor power and the power in the wind is expressed with the rotor power coefficient $C_p$.

$$C_p = \frac{\text{Rotor power}}{\text{Power in the wind}} \quad (2.15)$$

Which together with equation 2.13, gives:

$$P = C_p \frac{1}{2} \rho A v^3 \quad (2.16)$$

A wind turbine can only work at certain wind speeds and when the wind speed is under a certain value, called the cut-in wind speed, no power is produced. As the wind speed increases, the power produced increases until it hits the turbines rated power, which is the power production the turbine is designed for. If the wind speed gets too high, the turbine also stops production. The actual average production can be expressed with the very important factor a wind turbine, the capacity factor $CF$. The capacity factor is defined as the ratio between the energy actually produced by the turbine, $P_w$, and the energy possible to produce if it would run at its rated power, $P_R$, all the time.

$$CF = \frac{P_w}{P_R} \quad (2.17)$$

The capacity factor can vary greatly and affects the energy production to a great extent. Lenzen and Munksgaard (2002) reviewed a great number of energy and CO₂ assessments performed since the 1970s, and found capacity factors ranging from 7.9 % to 50.4 %, with modern wind turbines typically ranging between 20-35 %.

2.4.2. Intermittency

The electrical power is not produced evenly over time, which makes wind power a highly intermittent source of energy. This is a big problem with wind power and most other renewable energy sources. The power used on the grid needs to be produced at the same moment it is used, unless it can be stored somehow first.

White and Kulcinski (1998) point out that highly intermittent energy sources like wind can never fully compete with base load technologies without some way to store energy to enable the use of power when it is needed. A large share of wind power on the market might in the future create need for
storage of energy that would cost energy, and perhaps make the energy from wind less favorable from an exergy viewpoint.

2.4.3. Modern wind turbines
This thesis will not describe the design aspects of modern wind turbines very thoroughly, but what a modern wind turbine is needs to be defined. The totally dominant wind turbine design today is three bladed horizontal axis wind turbines (HAWT). Manwell et al. (2009) describes the different parts of the turbine. The wind gets caught by the rotor, consisting of the blades and the supporting hub. The energy is then transferred by the drive train, which includes the rest of the rotating parts of the wind turbine including shafts, a gearbox, couplings, a mechanical brake, and a generator. The nacelle and main frame includes the wind turbine housing, bedplate, and the yaw system. All of this is located on top of the tower resting, on the foundation. Machine controls are also needed to control the turbine and the produced electrical power needs to be balanced and delivered to the grid by the electrical system including cables, switchgear, transformers, and often electronic power converters. Some variations in design exist within the three bladed HAWT as well. For instance you can have fixed or variable rotor speed, gearbox or direct driven generator, synchronous or induction generator, different blade materials and power control systems (Manwell et al. 2009).

Wind turbines are usually built in groups, often referred to as wind farms. This helps getting multiple wind turbines at places with good wind resources and also concentrates repairs and maintenance to fewer locations. The wind turbines are connected electrically as well as by roads. Roads often have a relatively high environmental cost in a wind farm (Manwell et al. 2009).

Quite few different materials make up the greater part of the turbines mass. Steel and concrete makes up the bulk of the mass, while other important materials are copper, aluminum, and composite materials. A common wind turbine consists to a very large extent out of steel. Only counting the actual turbine reviewed in Schleisner (2000), steel consist of about 86 % of the total mass of the turbine. If you also take the foundation into account, concrete will be 79 % of the total mass, while reinforced iron and steel combined accounts for 18 % of the total mass of the turbine. The rest of the materials only make up a couple of percent of the total mass.

2.4.4. Trends in wind turbine construction
Wind energy development is currently growing fast. At the end of 2009 wind energy was generating about 2 % of the world’s total electrical energy production, with an energy production of approximately 340 TWh per year and a growth rate of 31,7 % (WWEA, 2010).

Larger swept area, as well as higher wind speeds, which can be reached with a higher tower, can increase the production of a wind turbine greatly. This have lead to a trend that wind turbines are getting larger at a fast pace. Even though most of the existing wind turbines are actually quite small, the fast increase in size is a reason that the newer bigger turbines at around 1.5 – 5 MW of installed capacity makes up the majority of the production (Manwell et al., 2009).

Another trend is to build offshore wind farms. Some benefits of offshore wind farms compared to onshore wind farms is that there are more area available for siting, it is possible to come closer to load
centers like cities, the wind speed is generally higher, more evenly distributed and there are less turbulence (Manwell et al. 2009). Weinzettel et al. (2008) also claims that the next step could be to move to deeper water, which could demand some kind of floating wind turbines.

Direct driven turbines using large permanent magnet generators avoiding the need for gear boxes are becoming increasingly common. These turbines often use large amounts of rare earth metals like neodymium for the permanent magnets. There are also other types of wind turbines being tried out during history and still under development. Some vertical axis wind turbine (VAWT) designs have existed through the years and some new models are under development. The main benefit of vertical axis wind turbines is that you can have all the heavy mechanical parts, like the generator, on the ground instead of high up in the air, which makes the weight less important and maintenance easier.
3. Critical review of existing LCA of wind power

As different types of life cycle analysis have become increasingly common in recent years, at the same time as wind energy is growing at a high pace, the application of LCA and energy analysis on wind energy systems are also becoming increasingly common. In the last couple of years, several assessments of energy performance and environmental impact over the life cycle of wind power plants have been performed. These different assessments use somewhat different methodology, report different forms of environmental impact, and compare different kinds of turbines of different sizes. This makes it hard to compare and evaluate the result from different studies. It is especially hard to evaluate the actual impact of projected expansion of wind energy systems in the world. During the duration of this thesis, several existing assessments of wind power are reviewed. Questionable aspects of the methodology used are found in many of the assessments that need to be addressed, some of which could be improved or dealt with by using the method of LCEA, or other exergy based methodology.

The different assessments look at slightly different types of turbines. Only a few of them look at more modern multi-megawatt turbines, while other look at smaller turbines. Weinzettel et al. (2008) look at a floating type of offshore wind turbine. Some studies investigate only the net energy return and greenhouse gas emissions (Crawford 2009; Lee et. al. 2006; White, 2006), while others attempt to estimate other environmental impact with different sorts of impact assessments (Ardente et al., 2008; Martinez et al., 2009a; Martinez et al., 2009b; Tremeac and Menuier 2009; Vestas, 2006; Vestas, 2011; Weinzettel et al., 2008). The functional unit chosen when performing life cycle assessment on wind turbines is usually 1 kWh of electrical energy generated and distributed with an expected life of 20 years. The energy use and production is usually presented either as energy payback time (EPBT) or energy return on investment (EROI). The way the energy is compared can be a bit different between different assessments. It is also common to present a CO₂ payback time.

Some critical aspects on the reviewed life cycle assessments are presented in the rest of this chapter. The critique expressed here is not directed towards any specific researcher, the ISO-standards, or existing guidelines for performing LCA. The objective is to highlight issues not addressed or potential problems with current methods used in the actual reviewed assessments of wind turbines, regardless of whether they follow current standards or not. Not all problems described are relevant in all applications and one of the main goals of this thesis is to discuss the applicability of the results in a larger perspective, rather than looking at just one wind turbine or wind farm.

3.1. Energy use and electrical energy conversions

In the majority of assessments reviewed, it is hard to follow which different types of energy carriers that are used and how they are converted into primary energy. How much of the energy used is electrical energy, if it has been converted into primary energy and how this has been done is usually not explained. In fact, not one single of the reviewed assessments present the amount of electric energy compared to direct thermal energy used during the life cycle.

As an example Schleisner (2000) states: “The energy used is divided into fuels used to estimate the emissions through the life cycle”. How the energy is divided into the fuels is not thoroughly explained. How the electrical energy should be converted into primary energy is not obvious and depending on the
generation mix for the electrical energy and the heating values used for the calculations, the results can be significantly different. For instance, emissions from the generation mixes for electrical energy with high emissions can be up to 100 times greater than for generation mixes with low emissions, which can have a large impact on the results of an LCA (Gode et al. 2009).

In assessments that do state what electrical energy generation mix is used, it is common to use a national generation mix. Tremeac and Meunier (2009) use the average generation mix for Finland for a turbine assembled in Finland, while Schleisner (2000) assumes the energy supply system follows Danish conditions. What the Danish conditions look like is not described. It is pointed out that the energy used to produce the energy sources are converted according to Danish conditions, despite the actual origin of the energy source.

The European electrical grid is largely interconnected, and countries export and import electrical energy to and from each other. The use of national electrical energy generation mixes is therefore not obvious. One possible alternative approach is to use an average European mix instead. Another approach is to use marginal electricity, where all electricity is seen as the last producing process taken into use, which can often be approximated as electrical energy from coal fired power plants in the short time perspective (Gode et al. 2009). No matter which electrical energy generation mix is used, a more transparent and consistent treatment of electrical energy could contribute heavily to all life cycle based methodology, especially for electricity intensive processes.

3.2. Electrical energy production and energy payback ratios

The electrical energy produced is often compared to the energy used during the life cycle to express the amount of net energy gained from the wind turbine. Kubiszewski et al. (2010) defines the energy return on investment (EROI) as:

\[
EROI = \frac{\text{cumulative electricity generated}}{\text{cumulative primary energy required}}
\]

The use of EROI can be a fairly good indicator that an energy producing process actually produces more energy than it use during its life cycle. However, some of the LCA reviewed (Ardente et al., 2008; Tremeac and Meunier, 2009) do this in another way by converting the produced electrical energy into primary energy that would be needed to produce the electricity. This electrical energy is then assumed to replace an electrical energy generation mix and the produced electrical energy is therefore given the value of the primary energy needed to produce the electrical energy it replaces. Tremeac and Meunier (2009) argue that this method should be used, citing that it is more consistent and calls it primary energy payback time (PEPBT).

Comparing results from using the ordinary EROI and those converting the produced electrical energy into primary energy is difficult since the return ratio from the latter will be many times greater. As long as different assessments do not use the same method it will add to the difficulties of comparing them with each other. Also, the actual energy savings and environmental benefits of producing 1 kWh of electricity from wind is far from certain, and different methods to do this could add to the confusion.
This is further examined in the discussion in segment 6.1. The use of exergy would solve this problem since the exergy and produced electrical energy by definition are the same.

3.3. Material resource use
The refined materials used are usually presented in the analysis, but only include those that make up a certain part of the turbine. Vestas (2011), for example, has a cut-off criteria where any flow that is under 1% of the cumulative mass of all the inputs and outputs in the LCI model may be excluded if it has no environmental relevance.

These cut-off criteria have the potential to cause highly important materials to be neglected. In Vestas (2011) the two materials with the biggest part of the mass, steel and concrete, make up a total of 95% of the weight of the wind farm, and these figures are generally expected for most wind farms. Many materials that could play an important role in resource use in the future can therefore be missed in the analysis.

The rare earth metal neodymium is one material that is becoming increasingly common in modern wind turbines, since permanent magnets containing neodymium are extremely strong, enabling light and small generators. Some models, especially direct driven turbines, can have a large demand for neodymium in the generators. Neodymium has potential to be a limiting factor to how fast wind energy can be built and can therefore be an important element in resource use in modern wind turbines. None of the reviewed assessments present any use of neodymium in the inventories and it is likely that many of them do not contain any neodymium. However, according to Biggs (2011), the Vestas V112 that is assessed in Vestas (2011) does contain neodymium, which is not accounted for in the assessment. Even if it is just a small part of the material used, it can be an important factor.

3.4. Recycling
The international standards for LCA allow for different ways of dealing with recycling, but states that the approach of inflows and outflows of recycled materials should be consistent (Ekvall and Weidema 2004). Many of the assessments reviewed in this thesis credit the beneficial environmental impact of recycling the materials in the future to the overall environmental impact of the life cycle. For example, Vestas (2006) states: “Without the reutilization scenario, the environmental impacts would be significantly higher”. Martinez et al. (2009b) concludes that “despite the significant amount of material used, its final impact is reduced because of the 90 % material recycling in the phase of dismantling and disposal of the turbine” and the recycling lowers the environmental impact in 9 out of 11 impact categories used. Tremeac and Meunier (2009) state: “The reason why dismantling and removal yields impact reductions is that recycling is used to a high extent”.

This end-of-life approach for recycling is supported by the metals industry (Atherton, 2006). For some materials, which make up large parts of a wind turbine, like metal, copper and aluminum, it is highly likely that the materials will be recycled in the future. However, several reasons why the end-of-life approach for recycling is questionable for evaluating wind turbines, especially for evaluating a growth of wind energy in the energy system, can be mentioned. An example using steel to illustrate this follows.
According to the European Steel Technology Platform (ESTP, 2009), 90% of the steel in Europe is eventually being recycled. Most of this steel has been held up for many years, the average being around 40 years, at the same time as the world steel consumption is projected to keep growing at a high pace. ESTP (2009) projects the global steel consumption to be over 2000 Mtonnes by 2050, compared to just under 1400 Mtonnes in 2010. This growth, and the fact that the recycled steel is often very old, makes the total part of steel production coming from recycled steel only being 45% in Europe (ESTP, 2009). This figure is even lower globally and this is one thing that can make the end-of-life approach problematic. If wind energy capacity is to keep growing greatly, this will still create a demand for the virgin materials and energy today, no matter how much of the resources that will be recycled in 20 years, or more, from now. From a resource perspective, iron ore will still have to be mined, even if the steel can be recycled in the future. Also, there is no guarantee that the materials will in fact be recycled 20 years from now. To speculate in supply and demand, prices and other economical factors concerning steel in 20 years is difficult. It is likely that the recycling of steel will continue at a high rate, but there is no guarantee for it. What we can know is much of the different materials are recycled today.

Another important factor is the moment in time when emissions occur. For instance, wind energy is often proposed as an important feature in stopping global warming. Most climate scientists agree that we need to cut greenhouse gas emissions fast to stop the rise in global average temperature at a reasonable level. Greenhouse gases released today will still affect the climate for the 20 years until the materials can be recycled. This makes the evaluation of CO₂ emissions somewhat dubious if this method is used.

A real example of when this end-of-life approach can go wrong can be showed with Vestas (2011), which is the only assessment reviewed that actually presents a detailed description of the natural resources used. The resources are presented in a table describing different resources used in different stages of the life cycle. However, several resources have negative values of resource use, which can be interpreted as if you actually gain virgin material. The use of iron ore described in Vestas (2011) is presented in Table 4.1.

<table>
<thead>
<tr>
<th>Material resources</th>
<th>Total</th>
<th>Wind-turbine</th>
<th>Foundations</th>
<th>Transformer</th>
<th>Wind plant set up</th>
<th>Site operations</th>
<th>End of life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron ore (56.86%)</td>
<td>-2.68E-04</td>
<td>1.65E-03</td>
<td>1.53E-04</td>
<td>8.06E-06</td>
<td>3.54E-06</td>
<td>1.25E-04</td>
<td>-2.21E-03</td>
</tr>
<tr>
<td>Iron ore (65%)</td>
<td>7.32E-06</td>
<td>-9.39E-07</td>
<td>5.73E-06</td>
<td>-8.97E-10</td>
<td>1.10E-09</td>
<td>-6.28E-08</td>
<td>2.59E-06</td>
</tr>
</tbody>
</table>

If the two different iron ore grades are combined to a total amount of iron ore it adds up to a total of $-2.61 \cdot 10^{-4}$ kg iron ore per kWh of produced electricity. This could be interpreted as if you would actually gain 0.26 grams of iron ore for every kWh produced by the wind turbine, which is nonsense.

The future of main materials, other than metals used for wind turbine construction, like composites for blades, is not as certain as for metals. Tremeac and Meunier (2009) assume that 98% of the blades of the turbine will be recycled. Stiller (1999) states that there is no real recycling technology which allows for re-use of the fiber tissues, though recovery at a reduced quality seems possible. Several different
methods for future recycling of disposed materials are presented in Stiller (1999), none of which allows a full recycling. Many kinds of polymers cannot be turned into their old form and the output glass fibers are of lower quality and should be seen as new products rather then something that can substitute the old fiber (Stiller, 1999).

The potential benefit of the recycling in the future could be allocated to the product using the recycled goods in the future instead. This is supported by for instance Stiller (1999) that states that “...using waste materials is of advantage to the product made out of these secondary materials”.

The importance of time is well described by the LCEA method since it also accounts for the dynamics of the complete life cycle of the process.

3.5. Capacity factors and projected production

One factor that is highly important for the final results of an LCA of a wind turbine is the estimated energy production. The produced electrical energy correlates with the capacity factor $CF$, defined in equation 2.17 as the ratio between the energy actually produced and the energy possible to produce if running at rated power all the time. Most of the assessments reviewed assume a fairly high capacity factor and therefore a high total production of electrical energy, and lower emissions and energy use per produced kWh of electrical energy.

Many LCA relies totally on theoretical numbers on production and ends up with capacity factors that turn out to be too high estimates when they are compared to actually measured numbers. For example, White (2005) compares projected capacity factors for three wind farms with actual capacity factors measured on actual use, which were significantly lower than the projected. The projected capacity factors were 0.33, 0.35 and 0.31, when the actual capacity factors were 0.256, 0.286 and 0.199 respectively. For all three wind farms the capacity factors were greatly over estimated, which makes the estimate of produced power, and therefore energy payback ratio and similar measurements, highly inaccurate if the projected number is used. Ardente et al. (2008) finds the actual capacity factor measured over a year to be 0.19 compared to the design capacity factor of 0.3.

Depending on which capacity factor is used, large differences in results of produced electricity will occur. Since the results of the assessments is often presented in energy input or emissions per kWh of produced electrical energy, the capacity factor chosen can have great impact on the result. Communicating emissions and energy use as a fixed value per kWh of produced electrical energy can be problematic considering the vast differences of the result depending on the production. The production is often hard to estimate, and the uncertainty of this should be communicated.

3.6. Variation in results

For several reasons, some of which are mentioned in this chapter, there is a wide spread in results from different assessments. Lenzen and Munksgaard (2002) reviewed existing energy and CO$_2$ life cycle analyses of wind turbines and found large variations in results. The energy intensity varied from 0.014-1.016 kWh$_{in}$/kWh$_{el}$ and the CO$_2$ intensity varied from 7.9 – 123.7 g/ kWh$_{el}$. Kubiszewski et al. (2010) describes another review looking at energy return on investment (EROI) and CO$_2$-emissions and
presents EROI ranging from 1.0 to 125.8. The average EROI was approximately 18. These numbers reviewed range from the early 1970s, and a lot has happened in the wind energy industry since then, so this could explain some of the variation.

Different assessments come to vastly different conclusions about the environmental impact depending on the different methods used. One thing that can create greatly different results is if input-output analysis or process analysis is used for the inventory. White (2005) uses input/output analysis for assessing energy use of the operations and maintenance phase and comes to the conclusion that it uses about 34% of the total energy use of a wind farm. Other assessments use much lower numbers than this. For example, Ardente et al. (2008) states that energy usage for operations and maintenance is 6.5% of the total energy. It is not likely that the energy use for operations and maintenance for two different wind farms varies from 6.5% to 34% of the total energy use. The methods of expressing the impact also vary. Some only express CO₂ emissions and energy use while some express different forms of other environmental impact with different units. All of this makes it hard to compare different assessments and use them in a larger context to evaluate what a continued growth of wind energy would mean.
4. Refining of LCEA Methodology

The method of life cycle exergy analysis (LCEA) was theoretically outlined by Gong and Wall (1997, 2001) and Wall (2002, 2010), and the basic theory is presented in Chapter 2.3.4. For attempting to use the method in practice, more specific guidelines have to be developed. In this chapter, more practical applications of LCEA and some general guidelines on how an LCEA should be used is presented.

LCEA has many similarities to classical life cycle assessment methods and can to some extent be seen as an attempt to address and improve some of the limitations facing existing LCA methods. The idea is to make it possible to evaluate and express the sustainability of both products and larger systems with one common physical unit, namely exergy. The first two steps of LCA, goals and scope and life cycle inventory (LCI), are very similar between the methods, although slightly different information is needed for the LCI.

4.1. Phase 1: Goals and scope
As with classical life cycle analysis, the first step in a life cycle exergy analysis is to determine what the goals of the assessment are. System boundaries, cut-off limits, functional unit and which processes that are realistic and relevant to include in the inventory to reach the goals need to be decided. What is needed and feasible can vary greatly between different products and processes.

4.2. Phase 2: Life cycle inventory
The next step in a life cycle exergy analysis is to perform the actual inventory of inputs and outputs of mass and energy, i.e. exergy, throughout the life cycle. Relevant data of the materials and processes related to the process needs to be found and accessed. An LCI can be performed in several different ways and traditional LCA methods can vary greatly in what kind of processes and what kind of information is viewed as important.

Wall (1977) emphasized the importance of utilizing common units when comparing different commodities. Energy resources are usually measured in energy units while other raw materials are measured in many different units, for example different mass and volume units. The only common measure to compare different commodities statistically is economic measures, i.e. currency. This will vary with many different variables such as cost of production, subsidies, taxes as well as supply and demand. One way to avoid the problem of the value of a commodity changing without the physical properties having changed would be to choose a physical unit, like exergy, instead. Input-output and hybrid methods used for traditional energy analysis and LCA depend on economic values of processes and commodities. The use of this type of inventory methods are not recommended for LCEA since one of the basic ideas behind the method is that it should stand on a strictly scientific base. To follow the basic idea of LCEA, process chain analysis should be used to describe material and energy inputs and outputs throughout the life cycle.

In segment 2.2.3.2., two other ways to perform an LCA is described, that needs totally different information for the LCI, namely attributional and consequential LCA. A consequential LCA describes the consequences of actions made as the relevant physical flows changes in the life cycle, instead of describing the relevant physical flows into and out from the life cycle system boundaries, as for an
attributional LCA. Data from a consequential LCI does not go along with the definition of the method of LCEA and should not be used. However, some aspects of it could be used, for example marginal data for electrical energy generation, which is further discussed in Chapter 6.

4.3. Phase 3: Calculation of exergy
The next step is to calculate the exergy of the in- and out-flows of resources during the life cycle. The result will be expressed as exergy over time, and no further impact assessment or weighing, as is common in other life cycle assessments, is necessary.

Once the raw materials and energy resources that have been used are known, the exergy of the resources is calculated, as they are found in the environment. The input of the system can be for example metal ores or fuels. The raw materials can be used as material exergy and fuel exergy. As pointed out by Finnveden and Östlund (1997) it is necessary to know the composition of the resource extracted to calculate the exergy.

4.3.1. Material exergy
The exergy of material resources, as they are found in the environment, have to be calculated. The chemical exergy of the resources can be calculated according to the method described in Szargut (2005). To get information about what the raw materials consists of and calculate the exergy can be time consuming and complicated. If possible, standard values can be used to make the method easier to use. Finnveden and Östlund (1997) and Szargut et al. (1988) present material exergy inputs required to produce certain materials calculated with regard to Szargut’s reference state (Szargut et al. 1988). Finnveden and Östlund (1997) point out that some of the exergy values are somewhat different than the values presented by Szargut et al. (1988) and concludes that it is important to describe the system boundaries used and justify choices made.

Some materials, especially metals, can be produced by recycled materials that usually have a lower demand of fuel exergy input. However, the material exergy input of the recycled material is usually higher than the raw materials needed, and that material exergy should also be included as an input.

4.3.2. Fuel exergy
The fuel exergy inflow will consist basically out of two different types of energy: electrical energy and thermal energy from combusting fuels. The electrical energy is made from different types of electricity producing processes, and the exergy of the input of resources must be quantified. The exergy of the energy resources used is calculated with the ratios presented in Table B.1., found in Appendix B.

It is not obvious which electrical energy generation mix that should be used for calculating the input exergy to produce the electrical energy. It is important to always describe which choices are made and why. Which generation mix that is used for the calculations can have quite large effects on the results, and can create rather subjective results.

It is common to see electrical energy as an average mix of the electrical energy produced in a certain area, sometimes within a country or a larger area. If an average generation mix is used, a mix covering an entire interlinked grid should be used. The European countries electrical power grids are
interconnected to varying extent and it is recommended to use average European generation mix for products made in Europe, rather than the generation mix for the specific country. It could be argued that a marginal electrical energy generation mix should be used, which is further discussed in Chapter 6.1.

4.4. Important aspects of LCEA

4.4.1. Renewable exergy
Kinetic exergy (e.g. wind or water streams), potential exergy (e.g. water in dams used for hydropower) and radiation exergy (from solar radiation) does not need be calculated, since they are renewable energy sources and are counted as “free”, according to the description of the method of LCEA. Geothermal exergy is usually seen as a renewable energy source as well. Even if these exergy forms themselves can be counted as free, they do have an exergy demand for making extraction of the exergy possible. One example is wind turbines that produce electrical power from the wind, but still have a demand of exergy during the life cycle. If possible, this exergy could be included as an input in an LCI. It is likely that this is negligible since renewable energy producing processes generally generates substantially more energy than they use, at the same time as renewable energy is still is a quite small part of the generation mix, but this could be further investigated. Geothermal, solar, wind, combustible renewables and waste make up 2.8 % of the electrical energy production in the world and hydropower 15.9 % (IEA, 2010).

4.4.2. The importance of time
It can be important to consider at what moment in time the exergy is used and produced. For most renewable energy producing systems, like wind turbines, most of the exergy inflow happens during the manufacturing phase and will therefore induce an increased demand for exergy during that time. The produced electricity will occur at another moment in time and will not change the fact that exergy was used during production. The materials made from the raw materials used for the manufacturing of the turbine will be put into the turbine and most of them will remain there during the entire life cycle of the turbine, which is usually estimated as 20 years. The metals and other recyclable materials are not lost but are taken out of the system for a long time.

The definition of LCEA, which is described in Chapter 2.3.4., gives a possibility to account for exergy flows at different moments in time, and expressing them as exergy power over time.

4.4.3. Presentation of results
It is possible to present the results from an LCEA in total exergy input and output during the lifecycle. For an exergy producing product, like wind turbines, a ratio between exergy input and produced exergy over the life cycle can be calculated. This ratio can be called exergy return on investment (ExROI). ExROI could be a good indicator of the sustainability of a process, especially for comparing different systems to each other.

Another possibility is to present the amount of exergy being used at different periods of time as exergy for a certain phase of the life cycle. This can also be presented in exergy flow diagrams to give a graphical presentation of the inputs and outputs of exergy power, over time.
It is also possible to present more detail about what types of exergy are being used over the life cycle. Energy and materials resources are not interchangeable with each other and sometimes it can be interesting to know how much of the exergy used is fuel exergy and material exergy respectively.
5. Case study of a wind turbine
Out of the assessments reviewed, none is considered able to give adequate information to translate the results straight into an LCEA, according to the definition of the method and the guidelines stated in Chapter 4. However, Ardente et al. (2008) express the most detailed information about the different processes in the life cycle, and is therefore used as a base for making the case study of a wind turbine presented in this chapter.

Ardente et al. (2008) present an LCA of an Italian wind farm that assesses the eco-profile of the electrical energy produced by an 11 turbine wind farm, each with a nominal power of 660 kW. The production and deliverance of electrical power and energy use for raw materials, components manufacturing, transports, installation, maintenance, disassembly and disposal have been analyzed, with some focus on parts often neglected in typical LCA including installation, civil works and maintenance. The energy usage for the different processes is presented in a highly detailed manner, which is why this LCA is chosen as a base for the case study. In this chapter, an LCEA is presented, according to the description of the method in Chapter 4, using interpretations of Ardente et al. (2008) as a base.

5.1. Phase 1: Goals and scope
The main goal of this case study is to evaluate and develop the method of LCEA, by applying it on a wind turbine. The exergy return on investment will also be investigated and discussed. The case study is based on the LCA in Ardente et al. (2008), and therefore mainly uses the system boundaries and assumptions made there. For the exergy use for the materials production, other sources and system boundaries are used, but for the rest of the life cycle fuel exergy figures are mainly adapted from Ardente et al. (2008).

This case study will not take into account the exergy of emissions and waste throughout the life cycle, but the scope covers only exergy use and production. Within the given system boundaries the total exergy use and exergy production is estimated and expressed as a ratio between the two, exergy return on investment (ExROI), as an indicator of sustainability. The functional unit is one wind turbine, so the exergy use and production of one turbine is investigated, where 1/11 of the exergy use for building works is allocated one of the 11 turbines.

One important thing that should be pointed out is that the system boundaries in Ardente et al. (2008) are somewhat different than in most other reviewed LCA of wind farms. The system boundaries are relatively large when it comes to which processes in the installation and building works are included. For building works the flattened surfaces (lay bays) under the foundation, electric cables, cable trenches, paths and roads and transformer room are included. This turns out to include large amounts of rocks, sand, soil and different polymers, that are not included in most other assessments.

5.2. Phase 2: Life cycle inventory
The second step of the LCEA is to decide how much different energy and material resources are used. Ardente et al. (2008) present masses of refined material, from which the raw materials used, as they appear in nature, can be estimated. The total energy used is calculated and presented in Ardente et al. (2008), called global energy requirement (GER), and is 45.4 TJ of primary energy for the entire wind farm.
of 11 turbines. It is however not explained what kind of energy this is, which is needed to translate it in to fuel exergy according to the description of LCEA from Chapter 4. Instead a new inventory is done covering the materials production, while the fuel exergy of the rest of the life cycle is estimated from the GER in Ardente et al. (2008).

5.2.1. Materials production

Ardente et al. (2008) present the amount of refined materials used for the wind farm, but do not describe what resources are used for making the refined materials. Therefore, the exergy use for producing 1 kg the most important materials were calculated independently, as described in Appendix A and B., and applied to the masses from Ardente et al. (2008), presented in Table 5.1. and 5.2.

**Table 5.1.** Materials used for construction of one wind turbine. Adapted from Ardente et al (2008).

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>66 434</td>
<td>kg</td>
</tr>
<tr>
<td>Cast Iron</td>
<td>6 001</td>
<td>kg</td>
</tr>
<tr>
<td>Glass reinforced plastic</td>
<td>4 950</td>
<td>kg</td>
</tr>
<tr>
<td>Copper</td>
<td>924</td>
<td>kg</td>
</tr>
<tr>
<td>Paints</td>
<td>389</td>
<td>kg</td>
</tr>
<tr>
<td>Lubricant oils</td>
<td>111.2</td>
<td>kg</td>
</tr>
<tr>
<td>Aluminum</td>
<td>85</td>
<td>kg</td>
</tr>
<tr>
<td>PVC</td>
<td>65.2</td>
<td>kg</td>
</tr>
<tr>
<td>Bronze</td>
<td>5</td>
<td>kg</td>
</tr>
</tbody>
</table>

The description of materials for building works is very detailed in Ardente et al. (2008), and has been directly monitored during the building process. Lay-bays, foundations, electric cables, cable trenches, paths and roads as well as the transformer room are included in the assessment.

**Table 5.2.** Materials used for building works for a wind farm containing 11 wind turbines. Adapted from Ardente et al. (2008).

<table>
<thead>
<tr>
<th>Materials used for building works for the wind farm</th>
<th>Mass</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate quarrying</td>
<td>21 708 000</td>
<td>kg</td>
</tr>
<tr>
<td>Local soil and stones</td>
<td>10 333 494</td>
<td>kg</td>
</tr>
<tr>
<td>Steel</td>
<td>122 527</td>
<td>kg</td>
</tr>
<tr>
<td>Polypropene</td>
<td>115</td>
<td>kg</td>
</tr>
<tr>
<td>HDPE</td>
<td>11 383</td>
<td>kg</td>
</tr>
<tr>
<td>Polybutadiene</td>
<td>5 141</td>
<td>kg</td>
</tr>
<tr>
<td>Aluminum</td>
<td>8 289</td>
<td>kg</td>
</tr>
<tr>
<td>Copper</td>
<td>2 893</td>
<td>kg</td>
</tr>
<tr>
<td>PVC</td>
<td>18 932</td>
<td>kg</td>
</tr>
<tr>
<td>Sand</td>
<td>2 802 279</td>
<td>kg</td>
</tr>
<tr>
<td>Concrete</td>
<td>4 097 280</td>
<td>kg</td>
</tr>
</tbody>
</table>
As described in Chapter 4, recycling should be included as an input of recycled material instead of a credit for later possible benefit, to be consistent with the definitions of the method LCEA. No information on how much, if any, of the materials used for the turbine in question comes from recycled materials are available. Therefore, average values for production from recycled materials were used. In the main case the steel is considered to be made out of 45 % recycled steel, which is the average value in Europe (ESTP, 2009) and the aluminum out of 30 % recycled aluminum, which is the average value in the world (Stiller, 1999). All other materials are assumed to come from virgin materials.

### 5.2.2. The rest of the life cycle

Ardente et al. (2008) present the energy consumption of the different parts of the life cycle as percentages of the total global energy requirement, where the fuel consumption of the installation of the wind turbines is measured directly during the building phase. The operational phase is assumed to be 20 years long. The percentage of the global energy use in the life cycle stages is taken from Ardente et al. (2008) and presented in table 5.3. The total primary energy use is 45.4 TJ for the wind farm (Ardente et al., 2008), or 4.1 TJ for one wind turbine. The energy use of the different stages for one turbine is calculated with the percentages of the total energy, and is presented in table 5.3.

<table>
<thead>
<tr>
<th>Component</th>
<th>Transports</th>
<th>On Site Installation</th>
<th>Operation and Maintenance</th>
<th>End of Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of total energy</td>
<td>16.4%</td>
<td>6.5%</td>
<td>0.2%</td>
<td>6.4%</td>
</tr>
<tr>
<td>Energy (GJ)</td>
<td>678</td>
<td>247</td>
<td>6.9</td>
<td>264</td>
</tr>
</tbody>
</table>

The energy use in component manufacture is approximated as electrical energy, while transports, on-site installation, operation & maintenance and end of life are approximated as diesel. Data on the raw material used during these stages is not available and is neglected.

### 5.3. Phase 3. Exergy calculation

Some approximations and interpretations of the masses in Table 5.1. and Table 5.2. have to be done to retrieve the masses used in the analysis, as presented in Table 5.4. and Table 5.5. The masses for building works is divided with 11 to allocate the materials to one turbine. Paints and bronze are neglected and not included in the analysis. All different polymers (polypropylene, HDPE, polybutadiene and PVC) are approximated as epoxy resin. A small part of the iron material in the turbine is cast iron, while most of it is steel. The cast iron is approximated as steel and added to the steel mass in the analysis. Aggregate for concrete, local soils and stones are approximated as sand and aggregate quarrying is approximated as rock when calculating material exergy for these materials. Material exergy for sand and rock is taken from Finnveden and Östlund (1997).
The resources from the materials used was turned into exergy by using the exergy inputs for different materials calculated and presented in Appendix A and B and applied to the masses of materials.

5.3.1. Exergy inputs
The exergy inputs from the materials of the wind turbine for the standard case is calculated and presented in Table 5.4. The fuel exergy needed for the lubricant oil is neglected, while the material exergy is approximated as crude oil. The exergy of the other materials is calculated, as described in Appendix A and B.

Table 5.4. Exergy of the different materials of one wind turbine. Masses presented Table 5.1. and approximations is adapted to these masses as described in section 5.3. The exergy is calculated according to these masses and exergy values from Appendix A and Appendix B.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>72435</td>
<td>263229</td>
<td>1027709</td>
<td>1290938</td>
</tr>
<tr>
<td>Glass fiber</td>
<td>3911</td>
<td>391</td>
<td>83912</td>
<td>84303</td>
</tr>
<tr>
<td>Epoxy resin</td>
<td>1040</td>
<td>54269</td>
<td>1257</td>
<td>55526</td>
</tr>
<tr>
<td>Copper</td>
<td>924</td>
<td>120120</td>
<td>74517</td>
<td>194637</td>
</tr>
<tr>
<td>Aluminum</td>
<td>85</td>
<td>1307</td>
<td>9156</td>
<td>10463</td>
</tr>
<tr>
<td>Lubricant oils</td>
<td>111</td>
<td>5081</td>
<td>-</td>
<td>5081</td>
</tr>
<tr>
<td>Total</td>
<td>78505</td>
<td>444396</td>
<td>1196551</td>
<td>1640947</td>
</tr>
</tbody>
</table>

The exergy of the different materials for the building works is presented in Table 6.5. Fuel exergy for rocks and sand is neglected while the rest of the exergies are calculated as explained in Appendix A and B.

Table 5.5. Exergy of the different materials of building works allocated to one wind turbine. Masses presented Table 5.2. and approximations is adapted to these masses as described in section 5.3. The exergy is calculated according to these masses and exergy values from Appendix A and Appendix B.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>42 835</td>
<td>14 992</td>
<td>172 680</td>
<td>187 673</td>
</tr>
<tr>
<td>Steel</td>
<td>11 139</td>
<td>40 478</td>
<td>158 038</td>
<td>198 516</td>
</tr>
<tr>
<td>Aluminum</td>
<td>754</td>
<td>11 589</td>
<td>81 170</td>
<td>92 759</td>
</tr>
<tr>
<td>Copper</td>
<td>263</td>
<td>34 190</td>
<td>21 210</td>
<td>55 400</td>
</tr>
<tr>
<td>Polymers</td>
<td>3 234</td>
<td>168 822</td>
<td>3 911</td>
<td>172 732</td>
</tr>
<tr>
<td>Rock</td>
<td>1 973 455</td>
<td>631 505</td>
<td>-</td>
<td>631 505</td>
</tr>
<tr>
<td>Sand</td>
<td>1 236 996</td>
<td>39 584</td>
<td>-</td>
<td>39 584</td>
</tr>
<tr>
<td>Total</td>
<td>3 268 675</td>
<td>941 161</td>
<td>437 009</td>
<td>1 378 169</td>
</tr>
</tbody>
</table>

The exergy for the rest of the life cycle is estimated from the global energy requirement presented in Ardente et al. (2008). The energy used is calculated and presented in Table 5.3. The issue that comes up
is how this primary energy should be translated into exergy. Transports, on site installation, operation & maintenance and end of life is already valued as primary energy, why the energy approximated as diesel can just be converted into exergy with the exergy-heating value ratio described in Appendix B. For the component manufacture, this is approximated as electrical energy, which makes it more complicated. Since the electrical energy is already valued as primary energy, converting it to exergy with the electricity-exergy ratio described in Appendix D, would be a way of double counting the primary energy or exergy needed to produce the electricity. An approximation is made that the exergy of the electrical energy used is equal to the electrical energy.

After deciding the exergy inputs in the different phases of the life cycle, the exergy use can be presented. There is no need for any impact assessments or weighing. The fuel exergy and material exergy in-flows are presented in table 5.6.

### 5.3.2. Exergy outputs

The average measured capacity factor is 0.19, which gives an annual electrical energy production of 12106 MWh for the entire wind farm (Ardente et al., 2008). This is equal to a production of 79.2 TJ of electrical energy produced by one wind turbine in 20 years. Since the exergy content in 1 kWh of electrical energy is 1 kJ, this means that the exergy production during the life cycle is 79.2 TJ.

At the end of the life cycle the materials of the wind turbine needs to be taken care of. Some of the materials, such as metals, will be possible to recycle and could therefore be seen as an exergy output as well. However, this is not dealt with in this case study. The same accounts for wastes and emissions produced over the life cycle. This is further discussed in the discussion in Chapter 6.

### 5.4. Results case study

The fuel exergy and material exergy, as well as total exergy in-flows at the different phases of the life cycle are presented in table 5.6.

<table>
<thead>
<tr>
<th>Table 5.6. Exergy inputs over the life cycle for one wind turbine.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials production for wind turbine</td>
</tr>
<tr>
<td>Components Manufacture</td>
</tr>
<tr>
<td>Transports</td>
</tr>
<tr>
<td>Building works</td>
</tr>
<tr>
<td>On Site Installation</td>
</tr>
<tr>
<td>Operation and Maintenance</td>
</tr>
<tr>
<td>End of life</td>
</tr>
<tr>
<td>Total exergy use</td>
</tr>
</tbody>
</table>

The total exergy use over the life cycle of one wind turbine is 4.3 TJ. 32 % of the exergy comes from material exergy, while 68 % comes from fuel exergy.

The total electrical energy production of one wind turbine is 79.2 TJ. According to the definition of exergy, that means that the exergy output is 79.2 TJ, spread out over the 20 years of production.
The total exergy power flow over the life cycle can be expressed in an exergy flow diagram. The result of the case study is presented in Figure 5.1.

![Exergy flow diagram over the life cycle of the wind turbine.](image)

The main case study indicates that the exergy return on investment would be 18.3, which means that about 18 times more exergy is produced over the life cycle than what is used. This indicates that the wind turbine is a sustainable way to produce exergy. This result can vary greatly with some factors, which is investigated in a sensitivity analysis in the following segment, 5.5. This could also be put in a bigger perspective and be used to evaluate the impact of a continued growth of wind power capacity in the energy system.

### 5.5. Sensitivity analysis

As with classical life cycle assessments, it is a good idea to do a sensitivity analysis of the results of an LCEA. Some parts of the analysis withhold quite large parts of the total exergy, and changes in these factors can have a huge impact on the final results.

#### 5.5.1. Recycling

For the main analysis, the input for steel production used is 45 % from steel scrap and 55 % from iron ore. This is based on an average European production. A more accurate number would perhaps be to use the actual used amount of recycled steel. Otherwise a world average could have been used, since the steel market is a very global market.

It could be argued that all the steel should be seen as coming from raw materials, but it can also be argued that 90 % should be seen as recycled steel since it is likely that 90 % will be recycled in the future. A test is made to try the total exergy inputs when the recycling rates of aluminum and steel is changed to 0 % and 90 %. Changing the recycling rate to 0 % changes the ExROI to 16.8 and 90 % to 20.3. It appears like changing the recycling rates can change the result with about 10 %.
5.5.2. Energy use for materials
Some other sources present higher estimates of energy use for steel production from iron ore than is used in this analysis. Finnveden and Östlund (1997) for instance estimate the fuel exergy requirements for 1 kg of steel as around 30-40 MJ and Szargut et al. (1988) the fuel exergy requirement for pig iron from iron ore as 27.53 MJ / kg, compared to the calculations described in appendix B, where the result is 21.2 MJ / kg. Using a higher exergy demand for the production of steel could also greatly affect the results.

Considering the total global exergy requirement in Ardente et al. (2008) is described as 45.4 TJ of primary energy (4.1 TJ per turbine) should mean that estimating the total fuel exergy demand as the same value should be a fairly good estimation, since the exergy values are close to the heating values of the fuels. To make this estimation instead of the calculations used in the main case would mean that the fuel exergy use would increase from 2.9 to 4.1 TJ and the total exergy use from 4.3 to 5.5 TJ per turbine, which means that the ExROI would decrease from 18.3 to 14.3.

5.5.3. Produced electrical energy
The electrical energy production over the life time can have a huge impact on the final result. If the capacity factor is assumed to be twice as high, 0.4 instead of 0.2, the produced electrical energy and the exergy return on investment will also double.

The measured capacity factor that is used in the standard case is 0.19 which gives an ExROI of 18. If the capacity factor is changed to the design value of the turbine, a capacity factor of 0.3, the ExROI will be 29. If the capacity factor is changed to 0.1, which would be a really low number, the ExROI would become lower than 10.

5.5.4. Electrical energy generation mix
In the main case a European average electrical energy generation mix is used that have an exergy demand of 2.24 MJ per MJ electricity. For evaluating wind energy in a larger perspective, the use of a marginal generation mix could be argued for, that would have an exergy demand of 3.1 MJ per MJ of electrical energy. The calculations of exergy demand for electrical energy are presented in Appendix D.

When applying marginal generation mix instead of average European generation mix the ExROI decreases from 18.3 to 17.5.

5.5.5. Material vs. fuel exergy
It can be added that the material exergy makes up 32 % of the total exergy used. This exergy would be unaccounted for in a normal LCA, and it could therefore be interesting to see what the ExROI for only the fuel exergy would be. The ratio between the exergy produced and the fuel exergy used, or the fuel exergy return on investment, is 27.
6. Discussion

6.1. Problems with current LCA of wind energy

Life cycle based tools can be very useful for evaluating the sustainability and environmental impact of products and processes. These methods are getting increasingly common, but can also be regarded as overly complex or arbitrary for several reasons. In Chapter 3 several issues with current assessments of wind energy systems are described. In this chapter the issues are discussed in further detail. The critique is not necessarily directed towards life cycle analysis methods in general, the specific authors or the ISO-standards, but the intention is to start a discussion on how sustainability of wind energy systems and other renewable energy sources should be assessed. Some of the issues brought up might not be of any immediate concern when looking at just one turbine or one wind farm, but can have strong implications when applied to the role of wind energy in the overall energy system.

In Chapter 3, several potential issues with the way LCA is performed on wind energy systems were mentioned. The first issue is the way different energy carriers are treated and presented. Electrical energy is converted into primary energy, usually without explaining how this is done. It is not obvious which electrical energy generation mixes should be used. Some of the reviewed assessments use national generation mixes of European countries, whereas others use an average European mix. Considering that the electrical grids of most European countries are linked together, the use of a European average mix is more likely to reflect reality. Taking the time aspect in consideration of a growth of wind energy, it can also be argued that the electrical energy used should be seen as marginal electrical energy. The construction of a wind turbine cause an increased energy use before it starts to produce electrical energy, which would create a demand for more electrical energy production during its construction phase. This new production of electrical energy could be seen as marginal electrical energy. Better justification and agreement on which electrical energy generation mixes should be used when assessing energy producing systems like wind turbines are needed.

Another issue with previous life cycle assessments is that the produced electrical energy is not treated consistently from study to study. In some assessments, the produced electrical energy is assumed to replace a generation mix and is therefore given many times better energy return on investment than would otherwise be achieved. This way of thinking can potentially be interesting, but also has some problems. If 1 kWh of electricity is produced by a wind turbine, it is hard to know what implications that will have for the energy system. The electrical energy produced will probably lead to a decrease in production somewhere else, but this is not certain and it is hard to say which other producers will decrease their production. This makes the environmental benefit of the produced electrical energy hard to estimate. A better consensus on how to present produced electrical energy and how to estimate the environmental benefit should be aimed for.

Most assessments explain that different cut-off criteria have been used, where materials under a certain percentage of the mass is neglected. This has the potential to make highly important materials, which only constitute a small part of the total mass to be neglected. The wind industry’s interest in direct drive turbines, and making generators smaller and lighter, has led to a dependence on rare earth metals. Even if the materials can weigh a negligible amount compared to the entire machine, they can still have large...
geopolitical (most rare earth mines are currently in China) and environmental implications. This is likely not a big issue when assessing one specific turbine, but for evaluating a large growth of wind energy in the world, a small amount of a rare resource in each wind turbine can end up being important.

Some issues with how recycling is treated were found in the assessments. The end-of-life approach, which is very commonly used in the assessments, has its benefits, but also some problems. One benefit is that it can encourage construction of turbines with highly recyclable parts. It does have some limitations as it accounts for possible environmental benefits that might occur several decades from now, which make the environmental impact until then hard to estimate. Also, if the end-of-life approach is to be used, the way it is done as well as the implications it has on the result need to be clearly explained, which is often hard to follow in current assessments. In general, the lack of a time dynamic can be a setback for classical LCA methods, and the end-of-life approach can make the environmental impact appear smaller than it is. Building new wind turbines will cause a demand of resources for construction, regardless of how much is recycled more than 20 years from now. If the implications of a continued large growth of wind energy are to be assessed, this way to treat recycling appears inaccurate.

The turbine or wind farm assessed is generally given a certain capacity factor and therefore a projected production of electrical energy. When evaluating a certain wind farm based on actual measured data, it could be valid to give a certain value of an emission or energy use per produced kWh, but especially for assessments using theoretical values of a certain turbine type, this becomes problematic. The capacity factor is not a fixed feature of a type of wind turbine, but can vary greatly depending on many different factors. It is important to be cautious about communicating emissions or energy use per produced kWh as a fixed feature of a wind turbine. The assessments reviewed that give both theoretical and real measured capacity factors generally had overestimated the theoretical values greatly, which creates better environmental results. It is hard to estimate the energy production theoretically, but when this is done it is important to be clear about the uncertainty of the estimation.

Life cycle assessment is standardized in ISO-standards, but as described in this thesis, there is still a great span in methodology used when performing life cycle assessments on wind turbines. The assessments use different methods, developed by different organizations, using different data and report the environmental harm and energy payback in different ways. To be able to truly distinguish the environmental benefits and harm of wind energy and compare it to other ways to generate electrical energy, the methods to evaluate the environmental impacts can be further developed and need to be more scientifically consistent and transparent.

6.2. The usefulness of the exergy concept and LCEA

The exergy concept has been around for a long time, but has not had a big breakthrough. The concept of exergy can be difficult to understand and this means that results expressed in exergy can be hard to communicate to others. This could make exergy based life cycle analysis seem arbitrary to a lot of people. Also, the use of exergy for describing resource consumption and waste impact, as well as the actual definitions of the exergy concept, has met some critique. Gaudreau et al. (2009) states that exergy is not a static thermodynamic property, and should not be treated like one. The use of exergy for
Life cycle applications come with a need to treat the exergy content of a resource as a static thermodynamic property, in order to be easy to use. A continued discussion and evaluation of the use of exergy for the mentioned applications is welcomed. Despite the fact that the use of exergy in life cycle based analysis has been proposed by many researchers over the last 15 years, it appears like the best way to do it, or even if it should be done, is undetermined. The different methodologies that combine exergy with some kind of life cycle perspective have many similarities to each other as well as to classical life cycle assessments. Many aspects of LCEA and similar methods can offer improvements to life cycle assessment methods.

The method of LCEA has many similarities with already established methods of process chain energy analysis and life cycle assessments as well as exergy based life cycle analysis methods, even though important differences to other methods that combines exergy with a life cycle perspective exist. The main differences are the time perspective and the way renewable energy is treated. For evaluating energy producing technologies with a growing installation rate, the time aspect becomes very important. As the fraction of renewable energy grows in the energy system, the way to treat this added exergy demand needs to be addressed as well. A new method should preferably be easier and more applicable than already established methods, and the method of LCEA needs to become easy to use in practice. Some exergy based life cycle analysis methods is coupled with a preexisting LCA database, which is one method for making exergy based methods easier to use in practice. At the same time, many of the problems with classical LCA methodology will remain the same even with the exergy concept. Classical LCA methodology can be more appropriate for many applications, but the issues with current methods discussed in this thesis should be further evaluated. The exergy concept can also be used as an indicator for resource depletion within classical LCA methodology.

Life cycle exergy analysis, as defined in this thesis, cannot describe the specific environmental impact of a product or process, but can be good for describing the sustainability of larger systems and for comparisons between different systems. It can indicate that a wind turbine is sustainable, but is more useful evaluating the implications of developing large quantities of wind turbines. The big strength of the exergy concept for describing natural resources with one common unit also has the possibility to be a big weakness. The exergy return on investment can be a good indicator if a wind turbine is sustainable, but does not say much about the actual resources used. No matter how much electrical energy is produced by a wind turbine, it will never be possible to produce iron ore or neodymium from it, and for some applications it can be important to look at which specific resources that are used. Some resources like land use and fresh water use might become important for designing a future energy system are not included in this thesis, but could perhaps be quantified with exergy and also included in the method.

In the theoretical description of life cycle exergy analysis it is said to describe all in- and outflows during the lifecycle as exergy power over time. However, outputs in form of emissions and wastes have not been included in the method described in Chapter 4. The relevance of using exergy for describing the impact of emissions and wastes appears to be debated and is not used in this thesis. Using exergy could still be a method to express total waste and emissions with a single unit, and could be useful as a quantitative measure, but this needs to be further investigated.
6.3. The case study

In Chapter 5 a case study attempting to use LCEA in practice is described. Many assumptions and system boundaries are taken straight from the assessment presented in Ardente et al. (2008), which might not have been accurately interpreted. The part that includes the exergy of materials production is based on the masses of Ardente et al. (2008), but is mainly based on other sources and assumptions. The rest of the life cycle is interpreted straight from Ardente et al. (2008) and translated to exergy. Both parts have some features and approximations that make the reliability and accuracy of the result uncertain. One very important factor concerning the results is the calculations on steel, since it makes up a big part of the mass as well as the fuel exergy use over the life cycle. The calculated fuel exergy use for steel from raw materials is quite low compared to other sources, as described in Table E.1 in Appendix E. The energy use and recycling rate used comes from European numbers for steel from ESTP (2009). European steel production has decreased its energy use with 50 % over the last 40 years and maybe that adds to the fairly low energy use. Steel is a highly global commodity and average global numbers could have been used instead which could have increased the fuel exergy use. The recycling rate of 45 % used is for Europe, which is higher than the global average that could have been used. The impact of approximating cast iron as steel is unclear, but also adds to the uncertainty of the case study. The material exergy for all materials but the polymers where taken from other sources. However, for epoxy resin the material exergy was calculated, as explained in Appendix A, whereas the calculations rely on several assumptions. The validity of this calculation is uncertain but should be an acceptable estimation. Also, all polymers are approximated as having the same exergy demand as epoxy resin, which is an approximation that adds to the uncertainty. Considering most of the exergy comes from the oil products used as material in the epoxy resin, the approximation as all polymers as epoxy resin appears valid.

To assume that the fuel exergy use would be the same as the global energy requirement 45.4 TJ would probably have been a fairly good estimate of the fuel exergy use, since it is presented as primary energy, and the exergy ratios, presented in Appendix B, is very close to the heating values. To do that would have been inconsistent with the definition of LCEA, since it would have been impossible to describe the actual flows of exergy. One of the main reasons for doing the case study was to develop the method of LCEA, and the inventory of the materials’ production added a lot to the understanding of what an LCEA should be.

The most unexpected thing about the results of the analysis in Chapter 5 is that the material exergy ends up being such a large part of the results at 32 % of the total exergy demand. In a non exergy based assessment this exergy would be completely unaccounted for. The material exergy of rocks makes up 17 % of the overall exergy, which gives both an interesting dimension to this study, but also gives doubts to its relevance. The material exergy of the polymers also holds a great deal of material exergy, which in fact ends up being almost as much as the total exergy of cement and steel respectively. It is also obvious that the materials production and the building works accounts for the biggest part of the exergy use at a total of 82.6 %.

The total exergy return on investment seems to be well within the magnitude of the energy payback ratios commonly presented in life cycle assessments. The resulting exergy payback ratios also indicate that a wind turbine has a net exergy output to the system and is sustainable from that point of view. In
the standard case the exergy return on investment is around 18. This result depends on several factors, some of which are tested in a sensitivity analysis. Changing the estimated production of electrical energy will change the result the most, but none of these factors change the exergy return on investment enough to make the result show that the wind turbine is not sustainable. The capacity factor and production used is measured at a specific location, but building this turbine at another location, with other conditions, would change this.

6.4. Sustainability of wind energy
The reviewed assessments indicate good energy return on investment for the wind turbines, as well as low environmental impacts. As discussed in Chapter 6.1., it is very likely that this is the fact, but there are also some issues with using these methods for drawing conclusions about the sustainability of wind energy. Many of the questionable methods used appear to underestimate the overall environmental impact. It is very likely that the environmental impact would be low without these methods that make wind energy look more environmentally beneficial. In the long run, a continued growth of wind energy systems would benefit from more accurate, open assessments and reflections over how sustainability of wind energy systems should be evaluated.

Users of LCA methodology need to further discuss when different methods and views are appropriate. For many uses, including the assessment of only one wind turbine or wind farm, current methodologies can be sufficient. However, a wind turbine will be a part of an electrical energy system for more than 20 years and other issues, like the time aspect, will be important. Also, the produced electrical energy will most likely substitute other electrical energy producing facilities, which could maybe also be included when evaluating sustainability of wind energy. Even though the environmental impact of this is hard to estimate, it is very likely that a wind turbine will make the environmental impact of produced electrical energy lower. For evaluating the impacts of a large expansion of wind energy, emissions per produced kWh of electrical energy might not always be the most useful information. Resource use and energy (exergy) return on investment are probably more interesting.
7. Conclusions

7.1. Main conclusions
During the review of existing life cycle analysis of wind turbines, several questionable methodologies and weaknesses were found. The critique expressed in this thesis is not directed towards the existing ISO-standards concerning LCA and does not question whether or not the reviewed assessments follow these standards. It is not directed towards the specific assessments or authors, but this thesis addresses a need for discussion on how sustainability of renewable energy resources should be assessed.

There are numerous weaknesses in the way life cycle assessments have been and are currently performed on wind turbines, which need to be addressed. The variation in methodologies within the concept of life cycle assessments produces a great variation in results and makes results from different assessments hard to compare to each other. Different energy carriers are treated inconsistently and without proper explanation and motivation. The produced electrical energy is viewed in different ways, sometimes making the energy return on investment seem many times better. Materials under a certain mass percentage are often neglected, enabling the assessment to miss important materials, such as rare earth metals. Possible environmental benefits of recycling of materials in the future are credited the turbines today, creating a lower apparent environmental impact until then. Capacity factors are often communicated as a fixed feature of a wind turbine and are often overestimated, lowering the apparent environmental impact. These issues do not necessarily mean that the current assessments are not valid, but a further discussion on how sustainability of wind energy should be assessed is welcomed.

The use of exergy for life cycle based analysis methods have been suggested by several researchers over the last couple of decades. This could be a way to give more scientific significance to life cycle based analysis and to deal with some of the problems earlier mentioned. Life cycle exergy analysis (LCEA), or similar methods, can be of importance when evaluating the world’s future energy systems in making sure that we are supplying as much net exergy as possible to society, creating a more sustainable energy production. The use of exergy would standardize some of the inconsistencies in current assessments, while other problems needs to be addressed for all life cycle based methods. Exergy could also be used as an indicator of natural resource depletion within existing LCA methodology. However, how and if exergy should be used for resource accounting and life cycle analysis applications, appears not to be fully concluded.

The result of the case study indicates that the wind turbine assessed gives back more exergy than it uses during the life cycle, and is therefore sustainable according to the definition presented in the thesis. In the main case the wind turbine produces about 18 times more exergy than what is used during the life cycle, at a capacity factor of production at 0.19. This result can vary greatly with some factors, especially assumed production.

7.2. Future research
Life cycle based analysis methods are going to be needed in the future as well, but what methodologies that are appropriate, seems not to be settled. Several different methodologies to perform both life cycle inventories and impact assessments exist and results from different assessments vary greatly. The
potential issues with LCA which are highlighted in this thesis needs to be further addressed, investigated and debated. This thesis only reviews assessments made on wind energy production processes and similar critical reviews should be made on assessments of other energy producing processes as well.

The use of exergy within life cycle analysis has been proposed by many researchers over the last couple of decades and exergy could have a lot to offer the life cycle based methodologies. The exergy concept could play role in solving some of the issues pointed out in this thesis but if, how and to what extent it should be done and the absolute benefits of this are not settled. The validity of the use of exergy for measuring natural resources as well as the basic assumptions regarding exergy reference environments have recently received some critique, and there are issues with the very fundamentals of the exergy concept that also needs to be addressed. Exergy could add a scientific relevance to LCA and make it easier to evaluate the sustainability of growth of renewable energy, but the applicability and use needs to be further evaluated.

If exergy based life cycle analysis, like LCEA, were to be more commonly used, data collection would have to be made easier. One important thing could be to establish some kind of life cycle inventory database containing information relevant to exergy calculations, or standardized exergy values of different materials and processes. It is impossible to point to a perfect way to evaluate sustainability of wind turbines and other energy processes, or predict exactly how this should be done in the future. More work on this need to be done and better methods can be developed.
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Special thanks to Dr. Scott White for taking time to gather his old data and sending it to me.

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Finally I would like to thank all my friends, family, classmates and everyone else who have supported or helped me in any way during my five years of university studies.

Simon Davidsson, 2011-07-04
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Appendix A Material exergy for materials used in case study

For most materials used to build a wind farm, the exergy content of the raw materials have already been calculated by earlier studies (Finnveden and Östlund, 1997; Szargut et al., 1988). Sometimes the results can differ between different sources, but the values used in this case study are presented in Table A.1.

<table>
<thead>
<tr>
<th>Material exgeries</th>
<th>Exergy</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron Ore¹</td>
<td>0.88</td>
<td>MJ / kg steel</td>
</tr>
<tr>
<td>Glass²</td>
<td>0.10</td>
<td>MJ / kg glass fiber</td>
</tr>
<tr>
<td>Copper ore¹</td>
<td>130.00</td>
<td>MJ / kg copper</td>
</tr>
<tr>
<td>Bauxite¹</td>
<td>0.88</td>
<td>MJ / kg aluminum</td>
</tr>
<tr>
<td>Cement²</td>
<td>0.35</td>
<td>MJ / kg cement</td>
</tr>
<tr>
<td>Rock²</td>
<td>0.32</td>
<td>MJ / kg rock</td>
</tr>
<tr>
<td>Sand¹</td>
<td>0.03</td>
<td>MJ / kg sand</td>
</tr>
</tbody>
</table>

¹ Source: Finnveden and Östlund (1997)  
² Source: Szargut et al. (1988)

For some materials the listings of exergy content can vary greatly between different sources. The exergy content of copper ore is somewhat difficult to determine. The mining, concentration and smelting/refining processes of copper mining are quite diverse and there are quite large differences in grade and concentration of the ores containing copper in different regions. 90-95% of the copper ores used are sulfides and the sulfur in the ores makes them high in exergy compared to many other ores (Ayres et al., 2002). Different sources give quite different values on the exergy of copper ore needed to produce 1 kg of copper. Ayres et al. (2002) names a value of 61.6 MJ / kg of copper while Finnveden and Östlund (1997) presents two different values for two different ores at 130 and 990 MJ / kg of copper. Szargut et al. (1988) presents a value of exergy from raw materials as low as 7.5 MJ / kg of copper. In this thesis the exergy value of 130 MJ / kg was chosen.

No sources for material exergy content of polymers in general, and more specifically epoxy resin were found. The material exergy of epoxy resin was instead estimated and calculated based on its components. According to Stiller (1999) epoxy resin for composites is made from benzene, propylene and chlorine. The production of 1000 kg of epoxy resin needs inputs of 230 kg benzene, 792 kg propylene and 1210 kg chlorine.

<table>
<thead>
<tr>
<th>Epoxy Consists of</th>
<th>Mass</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorine</td>
<td>1.21</td>
<td>kg / kg epoxy</td>
</tr>
<tr>
<td>Benzene</td>
<td>0.23</td>
<td>kg / kg epoxy</td>
</tr>
<tr>
<td>Propylene</td>
<td>0.792</td>
<td>kg / kg epoxy</td>
</tr>
</tbody>
</table>

These materials are not found like this in the environment, but are produced from other raw materials. Data on production of benzene, propylene and chlorine was taken from NREL (2011) and the main resources needed as raw material were estimated.
Table A.3. *Materials needed to produce 1 kg of chlorine. Adapted from NREL (2011).*

<table>
<thead>
<tr>
<th>Material</th>
<th>Raw materials</th>
<th>Amount</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorine</td>
<td>Sodium Chloride</td>
<td>0.89</td>
<td>kg / kg chlorine</td>
</tr>
<tr>
<td>Benzene</td>
<td>Pyrolysis gasoline</td>
<td>0.35</td>
<td>kg / kg benzene</td>
</tr>
<tr>
<td></td>
<td>Pet. refining co-product</td>
<td>0.67</td>
<td>kg / kg benzene</td>
</tr>
<tr>
<td>Propylene</td>
<td>Pet. refining co-product</td>
<td>0.31</td>
<td>kg / kg propylene</td>
</tr>
<tr>
<td></td>
<td>Natural gas</td>
<td>0.97</td>
<td>m3 / kg propylene</td>
</tr>
</tbody>
</table>

Pyrolysis gasoline and petroleum refining co-products are estimated as crude oil. This might not be a perfect estimate, but it appears to be the best approximation available. Since more or less all fractions of crude oil re used for something, the pyrolysis gasoline and petroleum refining co-products would most likely have been used for something else that can be made from crude oil. To approximate the “petroleum refining co-product” as having the same exergy as crude oil should be acceptable.

Table A.4. *Total energy resource use for 1 kg of epoxy, translated into exergy.*

<table>
<thead>
<tr>
<th></th>
<th>Mass</th>
<th>Unit</th>
<th>Exergy</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium Chloride</td>
<td>1.08</td>
<td>kg / kg epoxy</td>
<td>0.098</td>
<td>kJ / kg epoxy</td>
</tr>
<tr>
<td>Crude oil</td>
<td>0.48</td>
<td>kg / kg epoxy</td>
<td>21.9</td>
<td>kJ / kg epoxy</td>
</tr>
<tr>
<td>Natural gas</td>
<td>0.62</td>
<td>kg / kg epoxy</td>
<td>30.2</td>
<td>kJ / kg epoxy</td>
</tr>
<tr>
<td>Total Exergy</td>
<td></td>
<td></td>
<td>52.2</td>
<td>kJ / kg epoxy</td>
</tr>
</tbody>
</table>

According to these calculations the chemical exergy in 1 kg of epoxy is 52 MJ. Some fairly large approximations and interpretations of numbers have been made, but it appears to be a reasonable value.
Appendix B Calculation of fuel exergy for materials used in case study

The exergy of different fuels can be calculated in relation to their heating values as shown in Table B.1. In the calculations of fuel exergy the lower heating value is used.

Table B.1. Ratios between exergy content and lower heating value (LHV) and higher heating value (HHV) of fuels. Adapted from Szargut (2005).

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Exergy / LHV</th>
<th>Exergy / HHV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard coal</td>
<td>1.09</td>
<td>1.03</td>
</tr>
<tr>
<td>Lignite</td>
<td>1.17</td>
<td>1.04</td>
</tr>
<tr>
<td>Coke</td>
<td>1.06</td>
<td>1.04</td>
</tr>
<tr>
<td>Wood</td>
<td>1.15</td>
<td>1.05</td>
</tr>
<tr>
<td>Liquid HC-fuels</td>
<td>1.07</td>
<td>0.99</td>
</tr>
<tr>
<td>Natural gas (high CH4)</td>
<td>1.04</td>
<td>0.94</td>
</tr>
</tbody>
</table>

To quantify the fuel exergy use of the production of the materials used for the case study according to the definition of LCEA, resources used for the most important materials were calculated. Many assumptions are made about exergy inflow to the materials production phase and the best data needed is not always found. The estimations of fuel exergy used for the materials production is further explained in this Appendix.

Steel

According to ESTP (2009), steel made from recycled steel scrap requires about 2.5 GJ of energy, most of which are electrical energy, to produce one ton of new steel. All of that energy is approximated as electrical energy. The calculation of exergy needed to produce the electrical energy is explained in Appendix D.


<table>
<thead>
<tr>
<th>Energy input per kg steel produced</th>
<th>Exergy Fuels</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical energy</td>
<td>2.5 MJ / kg steel</td>
<td>5.6 MJ</td>
</tr>
</tbody>
</table>

To produce 1 kg of steel made from iron ore requires a total of 18 GJ, where 83% comes from coke, 10% from electrical energy and the last 7% from other energy sources (ESTP, 2009). It is not clear what “other energy sources” is, but it is approximated as crude oil. This is numbers for European steel production, which in fact has decreased its energy use with 50% over the past 40 years. It is not certain that the rest of the world has gone through the same energy efficiency improvements and the global average is most certainly higher which might affect the results to be quite low.

<table>
<thead>
<tr>
<th></th>
<th>Energy input per kg steel</th>
<th>Unit</th>
<th>Exergy Fuels</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical energy</td>
<td>1.8</td>
<td>MJ</td>
<td>4.3</td>
<td>MJ</td>
</tr>
<tr>
<td>Coke</td>
<td>14.9</td>
<td>MJ</td>
<td>15.8</td>
<td>MJ</td>
</tr>
<tr>
<td>Oil</td>
<td>1.3</td>
<td>MJ</td>
<td>1.3</td>
<td>MJ</td>
</tr>
<tr>
<td>Total fuel exergy</td>
<td></td>
<td></td>
<td>21.2</td>
<td>MJ</td>
</tr>
</tbody>
</table>

Steel in Europe is produced from 45 % scrap steel and 55 % steel from iron ore (ESTP 2009). The author has not been able to find a reliable global number on this, but it is most likely lower. With 45 % of the steel being made from recycled steel scrap the total exergy inputs per kg steel is:

Table B.4. Exergy use for producing 1 kg of steel with 45 % coming from steel scrap.

<table>
<thead>
<tr>
<th>From raw materials</th>
<th>Unit</th>
<th>From scrap</th>
<th>Unit</th>
<th>Total exergy</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel exergy</td>
<td>12</td>
<td>MJ / kg steel</td>
<td>2.5</td>
<td>MJ / kg steel</td>
<td>14</td>
</tr>
<tr>
<td>Material exergy</td>
<td>0.48</td>
<td>MJ / kg steel</td>
<td>3.2</td>
<td>MJ / kg steel</td>
<td>3.6</td>
</tr>
<tr>
<td>Total</td>
<td>284</td>
<td>MJ / kg steel</td>
<td>5.7</td>
<td>MJ / kg steel</td>
<td>17.8</td>
</tr>
</tbody>
</table>

Copper

A wind turbine contains quite a bit of copper, although it is not one of the bigger parts of the turbine. Copper can be produced with several different methods. The three most common methods are flash smelter, reverberatory smelter and heap leach. Flash smelter is the by far most common process and the energy demand for that is used to calculate the fuel exergy use for copper production (Giurco et al. 2006). For production of 1 ton of copper using a flash smelter 6000 kWh of electrical energy, 0.15 tonnes of fuel oil and 0.46 tonnes of diesel is used (Giurco et al. 2006).

Table B.5. Fuel inputs and fuel exergy for production of 1 kg of copper from copper ore. Source, energy input: Giurco et al. (2006).

<table>
<thead>
<tr>
<th></th>
<th>Energy input</th>
<th>Unit</th>
<th>Exergy fuels</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical energy</td>
<td>6.0</td>
<td>kWh</td>
<td>56.2</td>
<td>MJ</td>
</tr>
<tr>
<td>Fuel oil</td>
<td>0.15</td>
<td>kg</td>
<td>6.9</td>
<td>MJ</td>
</tr>
<tr>
<td>Diesel</td>
<td>0.46</td>
<td>kg</td>
<td>21.1</td>
<td>MJ</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>84.1</td>
<td>MJ</td>
</tr>
</tbody>
</table>

Copper is highly recyclable, but is at the same time often used in long lived applications. In the year 2000 copper made from recycled copper scrap only constituted 13 % of the global copper production, and this number is in fact decreasing (Ayres et al., 2002). In the case study the copper recycling was neglected and all copper is seen as coming from raw materials.
**Aluminum**

Aluminum does not make up that big part of wind turbines, but is a highly interesting material due to its high energy demand for production from raw materials.

**Table B.6. Energy use for 1 kg of aluminum produced from raw materials. Energy input source, IAI (2007).**

<table>
<thead>
<tr>
<th>Energy input per kg aluminum</th>
<th>Unit</th>
<th>Fuel Exergy</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>0.173 kg</td>
<td>4.3 MJ</td>
<td></td>
</tr>
<tr>
<td>Diesel</td>
<td>0.0097 kg</td>
<td>0.4 MJ</td>
<td></td>
</tr>
<tr>
<td>Heavy oil</td>
<td>0.207 kg</td>
<td>9.5 MJ</td>
<td></td>
</tr>
<tr>
<td>Natural gas</td>
<td>0.277 m3</td>
<td>10.9 MJ</td>
<td></td>
</tr>
<tr>
<td>Electrical energy</td>
<td>15.68 kWh</td>
<td>126.4 MJ</td>
<td></td>
</tr>
<tr>
<td>Total fuel exergy</td>
<td></td>
<td>151.5 MJ</td>
<td></td>
</tr>
</tbody>
</table>

**Table B.7. Energy use for 1 kg of aluminum produced from recycled aluminum scrap. Source energy input EAA (2008).**

<table>
<thead>
<tr>
<th>Energy input per kg aluminum</th>
<th>Unit</th>
<th>Fuel Exergy</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical energy</td>
<td>0.133 kWh</td>
<td>1.1 MJ</td>
<td></td>
</tr>
<tr>
<td>Heavy oil</td>
<td>0.028 kg</td>
<td>1.3 MJ</td>
<td></td>
</tr>
<tr>
<td>Natural gas</td>
<td>0.068 kg</td>
<td>3.3 MJ</td>
<td></td>
</tr>
<tr>
<td>Total fuel exergy</td>
<td></td>
<td>5.7 MJ</td>
<td></td>
</tr>
</tbody>
</table>

30% of the aluminum produced in the world is made from recycled aluminum scrap, and it is quite obvious from table B.5. and table B.6. that there is a quite big difference in fuel exergy use between the two. In Table B.8 the total exergy use for producing aluminum with 30% coming from recycled aluminum is presented.

**Table B.8. Exergy input per kg aluminum with 30% coming from recycled material.**

<table>
<thead>
<tr>
<th>From raw materials</th>
<th>Unit</th>
<th>From scrap</th>
<th>Unit</th>
<th>Total exergy</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel exergy</td>
<td>106.0</td>
<td>1.7</td>
<td>107.7</td>
<td>MJ/kg aluminum</td>
<td></td>
</tr>
<tr>
<td>Material exergy</td>
<td>5.5</td>
<td>9.9</td>
<td>15.4</td>
<td>MJ/kg aluminum</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>111.5</td>
<td>11.6</td>
<td>123.1</td>
<td>MJ/kg aluminum</td>
<td></td>
</tr>
</tbody>
</table>

**Concrete**

Concrete consists of cement, often portland cement, mixed with aggregates like sand, gravel, crushed stone or other granular materials. According to NREL (2011) cement makes up 8 – 15% of the concrete.
The amount of cement in the concrete is approximated with the number in the middle of the span, e.g. 11.5 % cement.

**Cement**
The energy used during production is taken from *Portland Cement* in the LCA database of NREL (2011) and was converted to exergy.

**Table B.9. Fuels exergy inputs per kg of Portland cement produced. Energy input adapted from NREL (2011).**

<table>
<thead>
<tr>
<th>Energy input</th>
<th>Unit</th>
<th>Exergy Fuels</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bituminous coal</td>
<td>1.07E-01 kg</td>
<td>2.65 MJ</td>
<td></td>
</tr>
<tr>
<td>Gasoline</td>
<td>1.33E-04 liters</td>
<td>0.0046 MJ</td>
<td></td>
</tr>
<tr>
<td>Natural gas</td>
<td>5.57E-03 m³</td>
<td>0.22 MJ</td>
<td></td>
</tr>
<tr>
<td>Electrical energy</td>
<td>1.44E-01 kWh</td>
<td>1.16 MJ</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>4.03</strong> MJ</td>
<td></td>
</tr>
</tbody>
</table>

**Aggregates**
The fuel exergy used for the aggregates are neglected due to lack of data. The cement constitutes 94 % of the total energy used during concrete production (Horvath 2004), so it should not change the result much and be an acceptable approximation. The material exergy of the aggregates are however taken into account and approximated as sand. Since 11.5 % of the concrete is said to be cement, 88.5 % of the mass of concrete is approximated as sand.

**Composite materials**
The blades on modern wind turbines are usually made mostly out of composite materials consisting of glass fibers and a polymer resin. The polymer used is often epoxy resin.

**Glass fiber**
According to Stiller (1999) the glass used to make fiberglass uses 1.27 kWh electrical energy and 0.38 kg natural gas per kg glass which is translated into exergy. The total fuel exergy demand per kg of glass is 21.5 MJ.

**Polymers**
A very common polymer used in wind turbines is epoxy resin. The energy demand for production of 1 kg of epoxy resin is 0.15 kWh of electrical energy (Stiller 1999). According Appendix D the fuel exergy ends up being 1.21 MJ / kg epoxy.
Appendix C Heating values

The following heating values have been used for the calculations. For the fuel exergy calculations the lower heating values have been multiplied with the fuel exergy ratios presented in Table B.1. in Appendix B.

Table C.1. Lower heating values (LHV) of different fuels used. Adapted from Essom (2011).

<table>
<thead>
<tr>
<th>Fuel</th>
<th>LHV</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bitomnius coal</td>
<td>26</td>
<td>MJ/kg</td>
</tr>
<tr>
<td>Coal</td>
<td>22.7</td>
<td>MJ/kg</td>
</tr>
<tr>
<td>Crude Oil</td>
<td>42.7</td>
<td>MJ/kg</td>
</tr>
<tr>
<td>Coke</td>
<td>28.6</td>
<td>MJ/kg</td>
</tr>
<tr>
<td>Natural gas</td>
<td>47.1</td>
<td>MJ/kg</td>
</tr>
<tr>
<td>Diesel</td>
<td>42.8</td>
<td>MJ/kg</td>
</tr>
<tr>
<td>Gasoline</td>
<td>43.4</td>
<td>MJ/kg</td>
</tr>
</tbody>
</table>
Appendix D Electrical energy

The electrical energy generation mix used for the electricity used in the case study is presented in Table D.1. Renewable energy is seen as “free” within the method of LCEA, and gets the exergy value of zero. The exergy of coal, oil and gas is calculated with their heating values, a common efficiency and the exergy ratio. Nuclear energy has an exergy quality of almost 1, and the uranium used for the nuclear energy is assumed to have the same exergy content and an efficiency of 0.3.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total renewable²</td>
<td>0.219</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Coal</td>
<td>0.258</td>
<td>0.35</td>
<td>0.74</td>
<td>0.80</td>
</tr>
<tr>
<td>Oil</td>
<td>0.029</td>
<td>0.35</td>
<td>0.08</td>
<td>0.09</td>
</tr>
<tr>
<td>Gas</td>
<td>0.240</td>
<td>0.5</td>
<td>0.48</td>
<td>0.50</td>
</tr>
<tr>
<td>Nuclear</td>
<td>0.255</td>
<td>0.3</td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td>Total</td>
<td>2.15</td>
<td></td>
<td>2.24</td>
<td></td>
</tr>
</tbody>
</table>

¹Source: IEA(2008)
²Includes biomass, waste, hydro, geothermal, solar PV, solar thermal, wind, tide, other

If marginal generation mix is used, it can be approximated as coal in the short term (Gode et al., 2009), and is approximated as coal fired power plants with an efficiency of 0.35. The exergy demand of the marginal electrical energy mix is then 3.1 MJ exergy / MJ electrical energy.
Appendix E Comparisons

The results from the calculations of fuel exergy demand for materials production was somewhat different than estimates from other sources. Generally the results from Appendix B were quite low in comparison.

Table E.1. Fuel exergy demand from the results presented in Appendix B compared to Szargut (1988) and Finnveden and Östlund (1997).

<table>
<thead>
<tr>
<th>Fuel Exergy demand</th>
<th>Appendix B (MJ/kg)</th>
<th>Szargut, 1988 (MJ/kg)</th>
<th>Finnveden and Östlund, 1997 (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel from scrap</td>
<td>9.1</td>
<td>14.94</td>
<td>-</td>
</tr>
<tr>
<td>Steel from iron ore</td>
<td>21.5</td>
<td>27.53¹</td>
<td>30-40</td>
</tr>
<tr>
<td>Aluminum</td>
<td>159.8</td>
<td>244.69</td>
<td>300</td>
</tr>
<tr>
<td>Copper</td>
<td>84.1</td>
<td>139.88</td>
<td>100</td>
</tr>
<tr>
<td>Glass</td>
<td>21.6</td>
<td>33.3</td>
<td>-</td>
</tr>
<tr>
<td>Cement</td>
<td>4.1</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>Epoxy</td>
<td>0.4</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

¹Listed as Pig Iron