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Investigation of the Energy Payback of the Mervento 3.6-118 Wind Turbine

Linn Wilhelmsson

Bachelor's Thesis

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BACHELOR'S THESIS

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Summary

This thesis is done as an energy-payback investigation on a wind turbine of the prototype Mervento 3.6-118. The energy payback shows how long it will take until the wind turbine has produced the same amount of energy that was needed for the manufacture, transport and erection of the turbine. The study was done as a part of Mervento's environmental management system while the company was getting certified according to ISO 14000. Information concerning components, materials and transport distances was collected via discussions with Mervento's personnel, reviews of design documents and literary studies. The collected data was handled with the lifecycle assessment software SimaPro, and general background data concerning transports, materials and industrial processes from SimaPro's database was utilized. The results from the calculation show that the energy payback for the prototype (125 meters high) is 10.76 months and the energy payback for the shorter tower option (90 meters high) is 9.69 months. This is slightly higher than average, but can be explained by the fact that recycling of the steel tower is not included in the calculation. However, the results should not be used in direct comparison to other studies, since the system boundaries vary between studies. The results further show that the major part of the energy consumption stems from the steel tower, but the manufacture of glass fibre in the blades and the copper in the generator also consume a lot of energy.

Language: English Key words: energy payback, LCA, Mervento, windpower

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EXAMENSARBETE

Författare: Linn Wilhelmsson
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Handledare: Nina Åkerback

Titel: *Utredning om Energibalansen för Vindkraftverket Mervento 3.6-118*

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Sammanfattning

Detta examensarbete är en energibalanskalkyl gjord på ett vindkraftverk av prototypen Mervento 3.6-118. Energibalansen berättar hur länge det tar innan vindkraftverket har producerat lika mycket energi som krävdes vid tillverkningen, transporten och resningen av turbinen. Studien gjordes som en del av Merventos miljöledningssystem i samband med att företaget certifierade sig enligt ISO 14000. Information om komponenter, material och transportsträckor samlades ihop med hjälp diskussioner med Merventos personal, genomgång av designdokument och litteraturstudier. Den insamlade datan behandlades med livscykelanalys-mjukvaran SimaPro och generell bakgrundsdata om transporter, material och industriella processer från SimaPros databas utnyttjades. Resultatet från kalkylen visar att energibalansen för prototypen (125 m högt) är 10,76 månader och energibalansen för det kortare tornalternativet (90 m högt) är 9,69 månader. Detta är aningen högre än genomsnittet, men kan bero på att återvinningen av ståltornet inte är inkluderat i beräkningen. Resultaten bör dock inte användas i direkta jämförelser med andra studier eftersom systemgränserna varierar mellan studier. Resultaten visar också att största delen av energikonsumtionen beror på ståltornet, men också glasfibervingarna och kopparn i generatorn kräver mycket energi.

Språk: Engelska Nyckelord: energibalans, LCA, Mervento, vindkraft

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Tillgängligt: Examensarbetet finns tillgängligt i webbiblioteket Theseus.fi.

OPINNÄYTETYÖ

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Tiivistelmä

Tämä opinnäytetyö on energiataselaskelma joka on tehty Mervento 3.6-118-tuulivoimalalla. Energiatase kertoo, kuinka kauan kestää ennen kuin tuulivoimala on tuotannut yhtä paljon energiaa kuin sen valmistus, kuljetus ja pystytys kuluttavat. Tutkimus tehtiin osana Merventon ympäristöjärjestelmää samassa yhteydessä kuin yritys haki ISO 14000-sertifiointia. Tietoa komponenteista, materiaaleista ja kuljetusmatkoista kerättiin muotoilu-dokumenteista, keskustelemalla henkilökunnan kanssa sekä kirjallisuustutkimuksen avulla. Kerätty tieto käsiteltiin elinkaariarviointiohjelmisto SimaPron avulla ja yleiset taustatiedot kuljetuksista, materiaaleista ja teollisista prosesseista haettiin SimaPron tietokannasta. Tulokset näyttävät, että korkeamman tornin (125 m) energiatase on 10,76 kuukautta ja matalamman vaihtoehdon energiatase on 9,69 kuukautta. Tämän on hieman keskiarvon yläpuolella ja se voi johtua siitä että laskelma ei sisällä terästornin kierrätystä. Tuloksia ei kuitenkaan saisi käyttää suorassa vertailussa, koska järjestelmärajat vaihtelevat tutkimuksesta toiseen. Tulokset kertovat myös että suurin osa kulutuksesta johtuu terästornista mutta myös lapojen lasikuitu ja generaattorin kuparin valmistus kuluttavat paljon energiaa.

Kieli: englanti Avainsanat: energiatase-laskelma, elinkaarearviointi, Mervento, tuulivoima

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Foreword

I would like to thank the environmental coordinator, Camilla Österberg-Mattila, for all her help and guidance, and the rest of the staff at Mervento for putting up with all the questions I bothered them with during my time there. Thanks also go out to Nina Åkerback, head of the environmental engineering programme at Novia University of Applied Sciences, and to environmental engineering student and classmate Andreas Forsman, with whom I have had a lot of cooperation during my time at Mervento.

Explanation of Terminology and Abbreviations

Allocation	A term used in the LCI for dividing the environmental cost of a process so that it complies with the practical use of the process.
B.C.E.	Before Christian Era (same meaning as B.C, Before Christ)
EDIP	Environmental Design of Industrial Products; a commonly used LCA software.
EMAS	Eco Management and Audit Scheme, a European standard for EMS.
EMS	Environmental Management System; a structured way of assessing and controlling the environmental performance of a company.
HAWT	Horizontal-axis wind turbine
IA	Impact Assessment; the third phase of an LCA, where the environmental impact is analyzed with the help of an impact assessment method (sometimes abbreviated IAM).
ISO	International Organization of Standardization; mostly used in the context of a specific standard, e.g. ISO 14001. A standard can be seen as an officially published guide on how to perform a task.
LCA	Life Cycle Assessment; or Life Cycle Analysis. A tool for assessing the environmental impact, or specific parts of the impact, of a product or a service.
LCI	Life Cycle Inventory; the second phase in an LCA, where the data concerning the product or service is collected.
SimaPro	The LCA software that was used for calculating the energy balance.
VAWT	Vertical-axis wind turbine

List of Appendices

1 Introduction

This thesis is the practical result of my bachelor’s degree in environmental engineering, and of my work at Mervento. It is presented in a (hopefully) reader-friendly manner, and will focus on explaining the different choices I have made during the process of reaching those results. It will give a brief insight into the background of my work, explain the methodology behind the work, and finally present the results.

A separate report was written exclusively for Mervento's management group, with approximately the same contents as this thesis. For practical reasons though, and because of time limits, I chose not to include the theoretical parts of the thesis in the report. In a similar manner some details or paragraphs have been written out of the thesis because of confidential content, mostly concerning the inventory.

1.1 Background

The energy payback, also called an energy balance, was done as a part of Mervento's management system, more specifically the environmental management system (EMS). See figure 1 below. In short, an EMS is based on identifying significant environmental aspects (such as "transports"), which are used together with legal requirements to form environmental objectives (such as "lessen the transports with 10 %"). These objectives shall correspond to the company's environmental policy, and specific targets are worked out that shall be followed and supervised to make sure that the objective is reached. More on EMS can be found in chapter 2.2.

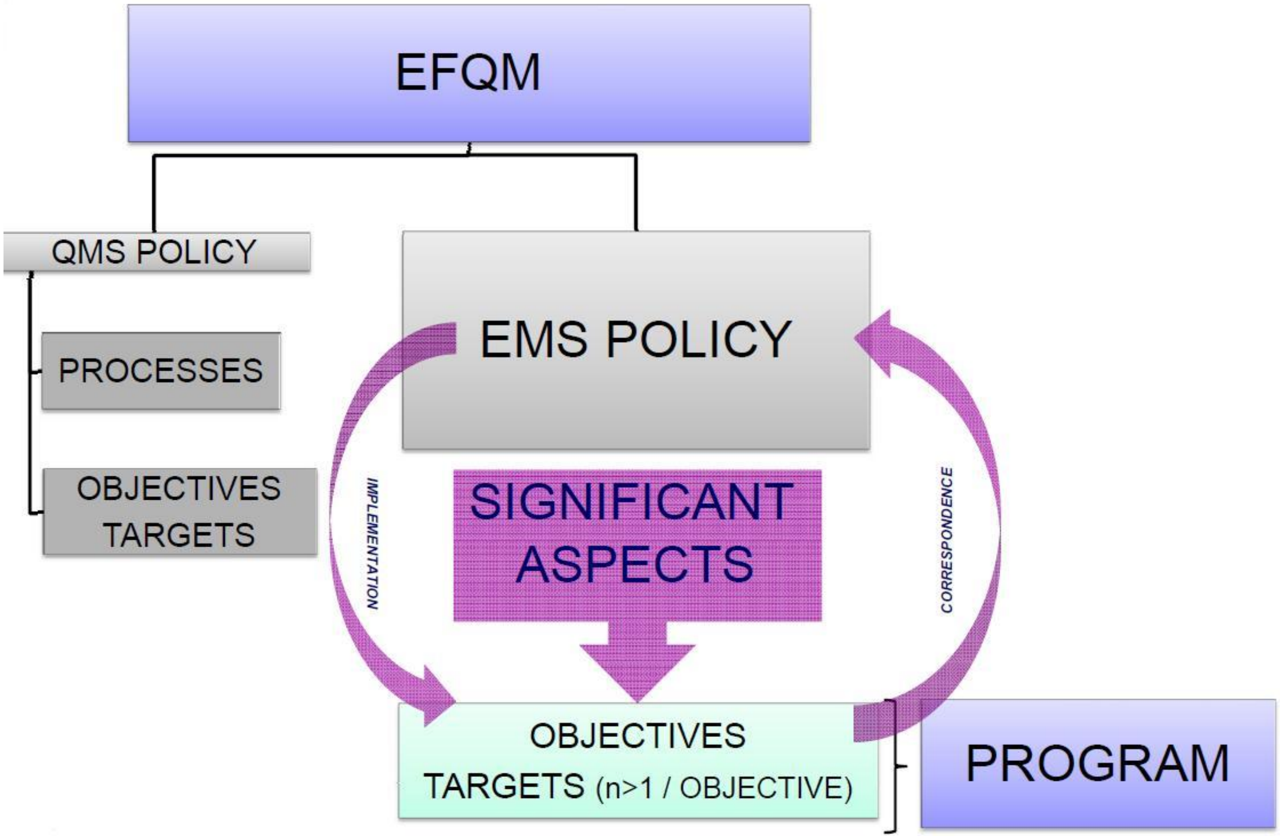

Figure 1. The structure of Mervento's EMS /53/

In this case, three significant aspects, "Use of energy", "Waste" and "Use of raw material" have been considered in the long-term objective "Minimizing the environmental impacts of the Mervento wind turbines during their life cycle". This objective has four targets, of which the last one, “Investigation on the energy payback for the Mervento 3.6-118” is the basis of my thesis. /53/

1.2 Task

The given task was to collect information about the over-all energy consumption from a wind turbine of the model Mervento 3.6-118. This information would then be used together with the theoretical energy production from the wind turbine, to calculate the energy payback, i.e. how long it takes until the energy spent in the manufacture of the components had paid back.

The task also included setting of logical system boundaries, meaning what components and processes should be included in the calculation, and how extensive the analysis should be. The results of the data collection and calculations would then be presented, analyzed, and possibly used to further improve the environmental performance of the wind turbine.

1.3 Purpose

Besides being an actual part of the EMS, the purpose of the energy payback is to visualize what parts or processes from the life cycle of the wind turbine consume the most energy. In the huge process that the manufacturing of a wind turbine is, it can be very difficult to get an accurate overview of how the energy consumption is divided.

The energy payback can further be used in product development, to point out which processes, materials or other aspects that could possibly be changed to improve the energy balance and overall environmental performance of the wind turbine. It can also be used within public relations and sales arguments, since showing an interest in one’s environmental performance gives a nice image.

However, one must not make public comparisons to other companies’ wind turbines using the results from these calculations. This is mainly because it is close to impossible to prove that the same methods and system boundaries have been used and taken into account. It is, however, quite all right to use the results to market the wind turbine itself, without comparisons.

1.4 Mervento

Mervento is a Finnish company in the wind power business that develops and provides onshore, nearshore and offshore wind turbine power plant solutions. At the moment, the company is mainly aiming to reach customers in Finland, Sweden, Norway, the UK, Ireland, France and China. Mervento strives to be the leading provider of multi-megawatt wind turbine power plant solutions globally. /7/

The core business areas of Mervento are product development, sales and marketing, project engineering, nacelle assembly, as well as service and commissioning. The company does not manufacture wind turbines itself, but co-operates with strategic partners that deliver high-technology components and systems, and with contractors who are in charge of transportation, site works and erection. /21/

The original founders of Mervento are Martti Ala-Vainio and Patrik Holm, together with the investors Power Fund II and Soldino Oy. The company started with the name Enmac Wind Oy in 2008 and got the name Mervento in 2009. It is registered and located in Vaasa and employs approximately 60 employees. /7/

2 Theoretical Background

This chapter will provide some quick explanations of the theory behind the energy balance, and some of the methods concerning it. It will supply information on what an EMS is, and how it is being implemented at Mervento, it will explain why the Life Cycle Assessment (LCA) methodology is relevant in this thesis, and why ISO 14000 (ISO = International Standardisation Organization) is a main part of the system. It will also include a quick glance at the history of wind power, a technical explanation of wind power, and some specifications regarding the turbine in question, as well as some collected data about previous energy paybacks in the Nordic countries.

2.1 ISO 14000 – Environmental Management

When companies were starting to manage environmental issues back in the days, the work was often done without structure or guidelines. As the need for a systematic standard regarding environmental management grew, it was decided within ISO to develop such a standard. A similar standard concerning quality assurance had already been launched with great success, and a similar model was therefore used. /41/, /31/

The first environmental standard was developed in England in 1992, called BS7750 (BS = British Standard). This was a national standard, and the present day international standards ISO 14000 and EMAS (Eco Management and Audit Scheme) are largely based on this first, national standard. /43/

An environmental standard could be described as a "how-to"-guide, a means of assuring that the same courses of actions are being taken by all the companies that choose to systematically develop their environmental performance. It was decided early on that following the standard should be voluntary, so that those who chose to, would be given an advantage before those who did not. /31/

ISO 14000 is the so-called family or series of environmental standards, and the standards are usually divided into two groups: the organization-oriented standards and the product-oriented standards. They have been developed to be used in collaboration with one another but can also be handled separately and have the following contents:

Organization-oriented

- Environmental Management (14001 and 14004)
- Environmental Reviews (14010 – 14012)
- Environmental Performance (14031).

Product-oriented

- Environmental Labeling (14020 and 14025)
- Life Cycle Assessment (14040-14025).

There is also a European standard, EMAS (Eco Management and Audit Scheme) that is commonly used. EMAS and ISO 14000 have very similar content, the greatest difference is that EMAS has more specific demands, among others the demand for a public revision and statement every three years. However, they have the same aim – to provide a tool for continuous improvement of a company's environmental performance. /42/

The advantages of following an ISO standard is that you get a certain credibility, a proof that your environmental work is being done in a systematic and orderly way. In a time where environmental performance is getting more and more important to customers and partners alike, showing that you follow a standard can give you commercial benefits. Following a standard might also very likely prove to facilitate your work, and in the end it may gain the company directly through e.g. better communication between departments, diminished waste emergence, or a cleaner work environment.

In this case, the standard in question is ISO 14001, concerning environmental management systems. On some matters the 14040-series also has significance because the energy balance can be seen as a type of life cycle assessment. However, since the plan was never to seek external certification for the energy balance (as opposed to for the environmental management system), the LCA-standard has lesser importance.

ISO 14001 was launched in 1996 and reviewed in 2004 and according to the abstract, it

> *”...specifies requirements for an environmental management system to enable an organization to develop and implement a policy and objectives which take into account legal requirements and other requirements to which the organization subscribes, and information about significant environmental aspects. It applies to those environmental aspects that the organization identifies as those which it can control and those which it can influence. ” /12/*

Following the standard does not necessarily require a company or an organization to seek certification. However, if the work is done according to standard, the possible process of certifying your EMS at a later point is considerably facilitated. A more thorough portrayal of how an EMS works is found in chapter 2.2.

2.2 EMS – Environmental Management System

EMS stands for Environmental Management System, and it is the most central tool in the ISO 14000 series. Its purpose is to organize the environmental work at a company and provide a basis for developing an environmental program, so that the responsibility, environmental awareness and competence are shared. /32/ /4/

2.2.1 Basic Facts on EMS

As mentioned in the previous chapter, one can choose to follow one of the following standards when developing an EMS: 14001 or EMAS. In essence they have the same content, which can be summed up as finding out how the company is affecting the environment and then working towards minimizing this impact by applying a systematic way of working. A constantly reoccurring theme, and something that must not be left out, is the striving towards continuous improvement within the system. /4/

Adopting an EMS will affect the entire company, from the individual employee to the management and possibly also the subcontractors and the company's partners. In this way, the total responsibility is not placed on “somebody in charge of the company's environmental affairs”, but everybody is involved, and everybody has to take responsibility for their share. Also, developing an EMS is not an easy way into “greenwashing” your company. If it turns out that the environmental impact is less than preferable, then following the standards will force you to deal with your problems.

In addition to improving the environmental efficiency of the company, and thereby having a direct improving impact on the nature we live in, there are other benefits from adopting an

EMS. One example is the development of the employees: The personnel often appreciates the involvement, and being able to see the results from the work that they are involved in. /33/

Also, decreasing e.g. the amount of waste that emerges from a process can have economic benefits as well as environmental. This is because avoiding the emergence of waste is much more cost-effective than taking care of the waste when it has already emerged. Also, changing a process to make it less harmful for the environment can result in a diminished use of chemicals or a smaller waste disposal fee, which are also economically beneficial. /30/

2.2.2 The Five Steps of an EMS

An EMS (and ISO 14001) contains five major steps. These are the following:

- Policy
- Planning
- Implementation
- Checking and Correcting
- Management Review.

Figure 2 shows how the steps are meant to be circulatory, and gone through over again, every time improvements are made.

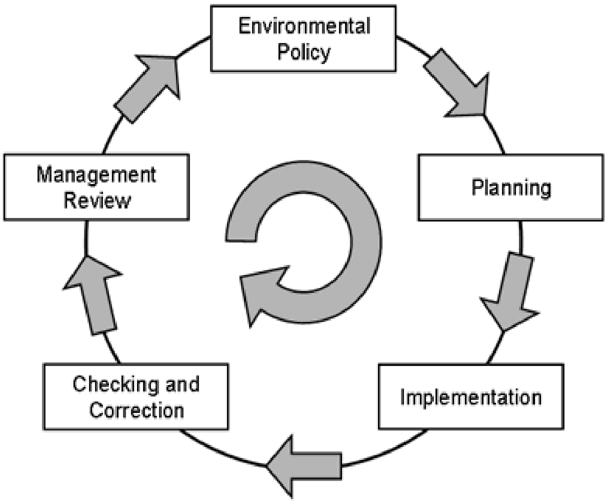

Figure 2. The five steps. /24/

Prior to adopting an EMS, one usually also conducts an environmental investigation. This investigation has no standards, and its purpose is simply to map the environmental aspects of the company and evaluate how well the company fulfills the legal requirements. The environmental investigation can be said to describe the present situation of a company's impact on the environment, and it gives you some starters on what kind of work lies ahead.
/4/ /44/

Policy

In this step, an environmental policy is formed in accordance with the company's activities, products and/or services. The environmental policy is the only part of the EMS that is public, and it usually holds some kind of statement regarding continuous improvement. Other than that, it is down to the management to decide how the policy is formed, but it should be specifically designed for the company in question.

Planning

The planning step is usually divided into substeps, where the environmental aspects of the company are identified, evaluated and prioritized. These steps are further explained in subchapter 2.2.2, since they have greater significance for this thesis than other parts of the EMS. The only thing the standards say about the planning step is that current laws must be followed.

Implementation

This is where the planned work in the planning step becomes reality. This can e.g. be dividing the responsibility, putting down routines and guidelines, educating the employees, improving instructions or updating ways of communication. It all depends on what kind of environmental improvements have been decided on in the planning step.

Checking and Correcting

This stage is mostly about following up the progress and the work that should be done in the implementation step. If something is not being done, or the routines are not being followed as they should, this is the stage where it should be noticed, and tended to.

Management Review

This is the stage where the management reviews the system and the progress, and judges whether the EMS is providing the results that are expected, and what possible changes that ought to be made. In this stage, continuous improvement is very much present. /5/

2.2.3 Plan-Do-Check-Act

An EMS can also be said to follow a cycle called the PDCA cycle (see figure 3). This stands for Plan-Do-Check-Act, and can be compared to the planning, implementation and checking steps in the five-step system. In this cycle, the steps that have significance for the thesis are “plan” and “do”, of which “plan” was mostly carried out by the environmental engineer Camilla at Mervento, while “do” is the work that I have put into the thesis. /34/

Figure 3. The PDCA cycle /9/

As mentioned in chapter 1.1, the first step in planning are identifying the environmental aspects of the company. An environmental aspect has been defined as “the aspect of an organization's activities, product or service that can have an impact on the environment” (ISO 14001, author’s translation). These aspects are usually numerous, ranging from the use of office supplies and the sorting of waste at the office, to the transport of products. Listing all environmental aspects of a company or an organization is not possible, but the list should be updated as new aspects are recognized. /35/

From the extensive list of environmental aspects, one then recognizes the significant ones. Which ones that are significant can be hard to determine, but the important part is that the choices are well argued and documented – only the company itself can choose what aspects they choose to improve. In this case, the identified aspects were the following:

- Maintenance and erection of the wind turbines
- Production of chosen material for the wind turbine
- Disposal of the wind turbine.

The next part in the plan-phase is to research the legal requirements and the current environmental laws that have to be fulfilled and complied with. Then, environmental objectives are formed on the basis of the applicable legal requirements and the identified significant environmental aspects. These objectives shall also correspond to the environmental policy. As Figure 1 on page 2 shows, the objective in this case is “Minimizing the environmental impacts of the turbines during their life-cycle”, and this is a long-term objective. /53/

In the next step, targets are developed to make sure that the objectives are fulfilled. In the case of Mervento's EMS, there were a number of targets, of which number 4, “Investigation of the energy payback for the Mervento 3.6-118”, was the base of this thesis. In the last part of the plan phase, responsibility for the targets is documented, the need for resources are declared, and deadlines are made both for short-term and long-term objectives and their targets. /53/

Two things that are also included in ISO 14001 and EMS but that are not relevant in this thesis are the document management and the procedure for emergency preparedness and response. These mainly describe the routines of documenting your work and the procedures that come into play in case of an emergency.

2.3 LCA – Life Cycle Assessment

A Life Cycle Assessment, or an LCA, is a tool for assessing the environmental impact of a product or a service over its life cycle. The usual aims of an LCA are improvements on the products or processes, a comparison between products for internal communication, or simply to obtain a proof of the product's environmental performance. There are many different types of LCA:s, from comparative to learning-based, from “cradle to grave” (which includes everything from raw materials to the final waste management) to “gate to gate” (which only include the processes and materials used in the factory). /39/

2.3.1 Basic Facts on LCA

Before the term LCA existed, the concept was known e.g. as ecobalance, resource and environment profile analysis, integral environment analysis, environmental profile etc. At a conference in 1991 the term life cycle analysis was coined, and in 1997 the International Organization for Standardization issued the first standard for LCA methodology. The early LCAs were all studies on packaging and waste management, and many connect the first LCAs with the 1970s because of the oil crisis and the energy debate going on at that time. However, what is generally considered to be the first LCA is a study for Coca-Cola conducted in 1969 by the Midwest Research Institute in the US. /1/

The ISO standards concerning LCAs are part of the 14040 series, 14040 covering the principles and framework, and 14044 treating requirements and guidelines. Even though there are different standards for the different phases, one should regard them as a series, since they are based on each other. /13/

There are also a number of practical guidelines on how to conduct an LCA that vary between countries, such as Nord 1995 for the Nordic countries, EDIP (Environmental Design for Industrial Products) for Denmark and US-EPA (Environmental Protection Agency) for the US. However, these were written before the ISO standard was issued, and those who have been updated presently contain about the same requirements as the ISO standard. /2/

The data collection and handling in an LCA are made smooth with the help of an LCA software, of which there are many different kinds available. The software includes one or several databases with huge amounts of data regarding materials, transports, waste management, processes and so on, and therefore one does not have to do extensive background research on one’s own, but can concentrate on the product or service at hand. The program also gathers and presents the data that is added and arranged by the user, so that he or she does not have to do any complex calculations. In the final stage of working with an LCA software, one chooses an assessment method that suits one’s purposes, and the results are presented, accompanied with charts and graphs of one’s own choice.

2.3.1 The Four Stages of an LCA

An LCA study includes the following four stages:

- Definition of Goal and Scope (where the system boundaries are set)
- Inventory analysis (in which background data and foreground data are collected)

- Impact assessment (where a method of assessment is carefully chosen)
- Interpretation (where the results of the LCA are presented and interpreted)

Definition of Goal and Scope; In this stage, the purpose of the study is presented, and the product that is being studied is more specifically defined. The standard demands that the goal and scope must be clearly defined, e.g. stating the reason for carrying out the study and the intended recipient of the results. This is also where the functional unit is chosen. The functional unit according to Baumann & Tillman "corresponds to a reference flow to which all other modeled flows of the system are related". Or in other words, it is the chosen unit that all the calculations that you will be doing are based on. This is best explained with examples, and one such can be found in chapter 4.1. Another aspect that is part of this stage is defining the system boundaries and, for this analysis, this is done in chapter 4.2. /3/

Inventory Analysis; Doing an inventory analysis basically means doing an incomplete flowchart or model of the mass and energy balance for the product or service that is being studied. Simply put, it is a way of mapping what kind of info you will need to go through with the LCA, and then collecting it. It consists of constructing the model according to the system boundaries that have been set up, collecting data for all the activities, and calculating the amount of resource use according to the functional unit. /3

Impact Assessment; The purpose of the impact assessment is to turn the results from the inventory analysis (which mostly contains data on emissions and resource use) into relevant information on what impact they have on the environment. This includes classification (sorting the parameters according to what kind of impact they contribute to), characterization (calculating the relative contribution to each type of environmental impact such as greenhouse effect or acidification), and voluntarily also grouping and weighting the data. These last steps are not included in the standard, and are sometimes frowned upon, since they can lead to misinterpretation of the results. /37/, /3/

Interpretation; In this last phase, the results from the impact assessment and the inventory analysis are evaluated, with the defined goal kept in mind. The essential environmental impacts are identified, the results' exactness and coverage are judged, and a summation of conclusions and recommendations is done. The results shall then be presented in an accurate, transparent and simple way, and if the study is going to be certified by a third party, the certification is the last part of the interpretation phase. /36/

2.4 Wind Power

Electricity generated from wind energy has one of the smallest carbon footprints, meaning that its impact on the environment is small in comparison to other forms of electricity generation. This chapter will give a short review of the history and development of wind power, the different kinds of turbines in existence, and describe the most essential components in a modern wind turbine. /29/

2.4.1 The History of Wind Power

The use of wind as an energy resource has a long history, dating back as far as before Christian times. Windmills for grinding grain were used in Persia and China a millennium ago, and water mills for pumping water was a common sight in Europe. The old Romans, Greeks and Vikings utilized the wind when they sailed across the seas, and the first known historical reference to a windmill is from Hero of Alexandria, who is believed to have lived in the 1st century B.C.E. /19/, /48/

Our type of traditional windmill made its first appearance in Europe in the 11th century, and soon became one of the most important sources of energy, until the invention of the steam engine. These early windmills usually had a horizontal axis and four blades and were used for all kinds of mechanical tasks, such as pumping water, grinding grain and powering tools. The reasons wind power was replaced with e.g. steam power and coal, are mainly attributable to the fact that it is impossible to transport, and that it was only accessible when the wind was blowing. /18/, /50/, /25/

The greatest difference between the old windmills and the wind turbines of today is that a windmill is a machine which converts the wind's power into mechanical power whereas a wind turbine turns the power in the wind into electricity. A wind turbine also includes some kind of battery charger, utility grids and a connection to an electrical network. /17/

There was 147 MW installed wind turbines in Finland at the end of 2010, and there is totally 8000 – 10 000 MW in plans for the coming 10 years. The official target by the Finnish government is to have 2500 MW installed by the end of 2020, so as to reach the so called 20-20-20 goal set by the European Commission. /7/

2.4.2 Power in the Wind

As mentioned in the previous chapter, the energy of the wind is turned into a resource that we can harvest either as mechanical power or as electricity. The moving molecules in the air have kinetic power, so the amount of air molecules that move across a certain area during a certain time determines the power outcome. The efficiency of wind can be determined with the following formula:

$$P_{kin} = ½mv^2/t$$

Here the mass of the wind is determined by the density of the air, which varies depending on the altitude and the temperature. The swept area that the molecules pass is the area covered by the blades of the wind turbine. One soon realized that if the wind speed is doubled, the power is increased 8 times; I. e. the power at 25 m/s is 125 times the power at 5 m/s. This is the reason why a lot of measurements are done when determining the location of a wind turbine, so that the best possible wind conditions are present. /49/

The final efficiency of the wind requires a lot of different calculations, where among other things the wind shear, the wind direction, turbulence and wind variations are taken into account. /26/

2.4.3 The Essential Components

Through history, there have been many different types and models of wind turbines, from the traditional Dutch windmill that is a typical trademark of the Netherlands, to the farm windmills and wind chargers that we usually connect with the great plains of the United States. /18/

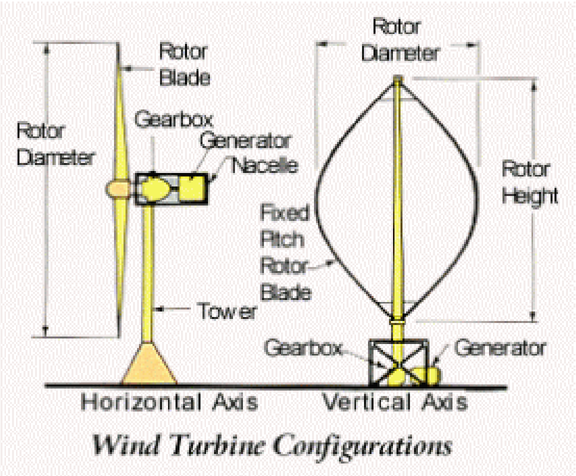

Figure 4. HAWT and VAWT. /47/

One basic division of the different types is that of the vertical-axis turbine (VAWT) and the horizontal-axis turbine (HAWT). The HAWT type usually has three blades, but there are also one-, two- and multiple-bladed versions available. As seen in figure 4, in the horizontal axis wind turbine, the axis of rotation is parallel to the horizon. While the HAWT is more common and generally seen as more efficient and easier to maintain, there are also certain types of VAWT models that are commercially manufactured, such as the Savonius rotor, developed by the Finnish engineer Georg Savonius. /49/

In a typical HAWT, the principal components are these: /17/

- **The rotor**, consisting of one or several (usually three) blades and the rotor hub. These are often considered to be the most important components from a performance view.
- **The drive train**, i.e. the rotating parts inside the nacelle. This usually includes a shaft, a gearbox, a generator, a mechanical brake, bearings etc.
- **The nacelle and the main frame**, including a yaw system. The nacelle covers protect the content from weather, while the yaw system is required to keep the shaft aligned with the wind.
- **The tower and the foundation**, varying a lot depending on the height and the location of the turbine. For example, off-shore turbines require larger foundations.
- **The electrical system**, such as cabling, switchgear, transformers and power converters.

Noticeable concerns about the Mervento 3.6-118 components are that the wind turbine has no gearbox since it is a direct-drive turbine, and that the electrical system is located almost completely in a separate building.

2.4.4 Previous Reports

Even though the results from LCAs and energy paybacks should not be used as public comparisons, some research concerning other companies' results was still done. This was done first and foremost to get a better picture of where the major part of the work should be, and to get some hints on what assumptions are usually made. The research was mainly done on three reports from other wind power companies, all concerning different turbines with different power output in different countries.

From these reports, one can conclude that most life cycle assessments on wind turbines include the following steps:

- Extraction and manufacture of raw materials for the components
- Transportation
- Erection and installation
- Maintenance
- Use
- Dismantling and disposal.

The details of course vary, especially concerning what components are included, but this is quite logical since there are many types of wind turbines with varying technology. For example, a turbine without a gearbox will include other components that are not present in a geared turbine. Some aspects are usually left outside the system boundaries, such as the grid connection. Another example found is the exclusion of possible spare parts.

Since it is unrealistic to include 100 % of the materials in a wind turbine, different projects have different cut-off criteria. The cut-off is usually expressed in percent and is based on the weight of the turbine, or the weight of the separate components. This percentage varies largely from 80 % to 99 % between projects, and also between different components in the same wind turbine. The nacelle usually has an overall lower cut-off because of the intricate electrical components it encompasses, while the percentage for the tower is generally quite high.

The choice of functional unit (see chapter 4.1) varies between projects, and depends mostly on what the results will be used for. Usually, the unit is 1 kWh of produced electricity, to make the results comparable with other means of producing electricity. Different software programs that are common while working with an LCA or energy payback are the EDIP (Environmental Design of Industrial Products) and the Dutch SimaPro.

The results from the energy payback calculations also vary a lot, with estimated payback times of between 6.6 months and 9 months. One thing that should be pointed out is that the estimated lifetime of a turbine has a very large role in the calculation. In this way, the results can be made to look more favorable simply by prolonging the turbine's estimated lifetime.
/11/, /20/, /45/, /8/

2.4.5 The Mervento 3.6-118 Wind Turbine

The wind turbine that has been analyzed in this energy payback is the prototype of Mervento's first model, the Mervento 3.6-118. The numbers in the name points to the fact that the rated power will be 3,6 MW, and the diameter of the area that is swept by the blades is 118 meters. The turbine is type certified and belongs to wind class IIA (meaning that it is a nearshore turbine).

The Mervento 3.6-118 is a horizontal-axis, three-bladed turbine and has direct drive, i.e. it has no gearbox. Instead, it is equipped with permanent magnets in the generator. This technology is still not very common among traditional wind turbines but has a lot of advantages concerning e.g. noise reduction, mass and maintenance. The design includes a lot of other innovations, but because of technical secrecy, they will not be presented further. Aspects that can be mentioned, however, are the very high tower, the electrical system placed in a separate construction on the ground, and the large rotor diameter.

The foundation is in this case molded on site, but this will depend a lot on the ground conditions on the chosen site. Anchor modules will be assembled at the site, and attached to the tower via stay cables for support. The tower consists of five segments, of which the uppermost one has a somewhat conical shape. The nacelle weighs approximately 250 tons and will be assembled before transport to the site and lifted with the help of several cranes. The blades have a length of 57 meters and will be attached one by one after the nacelle has taken its place on top of the tower. The turbine station contains the transformers, switch gear and frequency converter among other things and will be assembled before transport to the site. /52/ /22/

In Januari 2012 the tower was erected with the help of cranes and, in the beginning of February, the nacelle was lifted into place. The wind turbine started producing electricity in March 2012. /46/

3 Methods and Approaches

This thesis is not a full Life Cycle Assessment (LCA) study, even though the same methodology and software are being used. This chapter will briefly explain the LCA methodology, present the program I have used and the database it includes, as well as explain how the collection of foreground and background data was done.

3.1 The LCA Methodology

In a regular LCA, one is usually interested in the broad spectrum of the results available, since the software can calculate everything from square kilometers of land use to the total amount of carbon oxide released, or the depletion of fossil fuels or minerals. In the case of an energy payback though, we are only interested in the energy consumption. The question might therefore arise, whether it is logical to apply an LCA methodology. However, it quite quickly becomes clear that there is no more efficient way of handling the data collection and calculations that are required than with the help of an LCA program. And after having made that decision, the use of the entire methodology is rather self-evident.

For reasons mentioned above, this energy payback is mostly done with the LCA methodology in mind. However, some minor parts of the methodology differ from the regular use, first and foremost the fact that the waste management is not part of the analysis. For more information about how an LCA is conducted, see chapter 2.3.

3.2 Software

This chapter will present the software that was chosen for the energy payback and the impact assessment method included in the software. The choice of software and method is also explained shortly.

3.2.1 SimaPro

The software that has been used while doing this energy payback is SimaPro 7, designed by PRé Consultants. It is the world’s most widely used LCA software, and it is used in more than 80 countries worldwide. It includes databases with a broad international scope, and as many as 17 different impact assessment methods. /24/

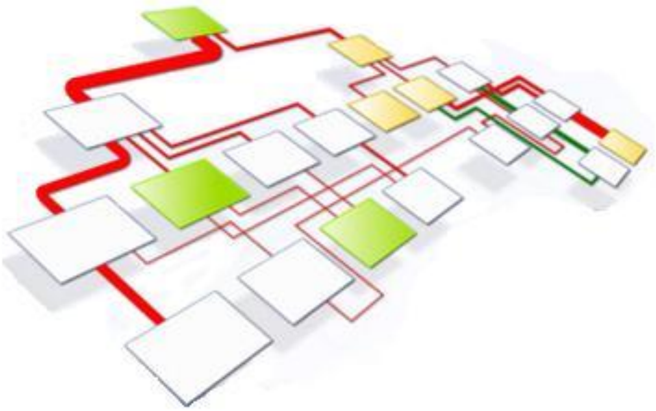

Figure 5: A process-tree in SimaPro /38/

The database in SimaPro is called Ecoinvent and covers approximately 2500 processes, from the production of wooden pellets to the burning of PVC plastic, or the heating of a normal oven. For a simple picture of a process tree, see figure 5. The database was first released in 2003 and is the result of several Swiss organizations that joined together. It covers a very broad range of data and is updated regularly by the ecoinvent center.

It became clear at an early stage that the use of an LCA software was needed, and then SimaPro was the obvious choice. This is mainly because it is a program with which I am already familiar, and also because it was already registered, installed and available at my university. While working with SimaPro, advice was received online from the Swedish consultants at Miljögiraff, the company that supplies SimaPro in the Nordic countries. /23/

3.2.2 Cumulative Energy Demand 1.07

An important step in an LCA is the selection of the appropriate impact assessment method, according to what results you want to achieve in the end, which can be everything from impacts on human health to climate change. In this case, the logical choice was the method called "Cumulative Energy Demand (CED) 1.07". In this method, the total energy use of all processes are added and expressed in Mega Joule equivalents. There are five so called impact assessment categories:

- Non renewable, fossil
- Non renewable, nuclear
- Renewable, biomass
- Renewable, wind, solar, geothermal
- Renewable, water.

With the help of these categories one can see from what kind of sources the energy comes, e.g. the energy consumption for transportation of a component by truck would appear under "non renewable, fossil", since gas is used in the truck. Even if these categories are of less importance in this payback calculation, where only the total energy consumption is interesting, the results are still available. /40/

3.3 Data Collection

The task that usually requires the most time and effort in an LCA is the data collection. One usually distinguishes two types of data: Foreground data and background data. Foreground data is typically very specific to the product or service and might describe a particular product system or a special process. Background data is more generic, concerning materials, energy, transport and waste management systems. The data found in the Ecoinvent database can be seen as background data, while the division of a component into subcomponents might be regarded as foreground data. /39/

In this energy payback, information about the wind turbine's structural composition and the different materials in the components and subcomponents has been collected as foreground data. This has been done through literary studies of Mervento’s design documents, and through contact and discussions with design managers and supply management. Some data has also been received through contact with suppliers. All data on processes and materials have been taken from the Ecoinvent database.

3.4 Energy Balance

The energy payback time, or the energy balance, is the length of time that a device will take to produce the same amount of energy that was needed to make it. In our case, this means how long it takes until the Mervento 3.6-118 turbine has paid back for the energy required in the manufacturing, transportation and erection.

Total energy consumption/ Theoretical annual energy production = Energy Payback

The payback time can be expressed in days, months and/or years, but also in the percentual time relative to the expected lifetime of the device. Another alternative is how many times the device pays itself back during its lifetime. The most common way to present an energy payback when it comes to wind turbines is in months, and usually the result lies between 6 and 12 months, depending on the size and location of the wind turbine.

4 Goal and Scope

This chapter will explain what the goal and scope of the energy payback is, and what is meant by a functional unit. It will also define the system boundaries of the data inventory and explain the limitations present, and the assumptions that have been made. More specific details about the data inventory are presented in chapter 5.

4.1 Functional Unit

Defining the functional unit of an LCA is vital, particularly when dealing with product comparisons. The functional unit is the unit that all the collected data is referring to, and it shall be chosen by the user of the software after careful consideration. For example, when doing a comparative LCA concerning a coffee machine, the functional unit might be “one machine that produces coffee” or “one cup of produced coffee”. One cannot compare one with the other.

In our case, the functional unit is one turbine prototype of the model Mervento 118-3.6, with an estimated lifetime of 20 years.

4.2 System Boundaries

In short, one might say that the scope, or the system boundaries of the energy payback, is the same as the turn-key scope of the turbine, i.e. the different components and phases of the turbine included are:

- Foundation
- Tower
- Nacelle
- Blades
- Turbine station

- Transport
- Erection.

The different components were chosen and handled based on the logical division of the turbine in the technical presentation. The selection of which subcomponents to be included was largely based on the weight of the components, with the goal of including appr. 90 % of the total weight of every component. The cut-off criteria (i.e. the percentage) varied slightly between the components though, since e.g. the nacelle includes a lot more subcomponents than the foundation. On the whole, the choice of inclusion was pretty much based on logic and available data.

The transport phase includes both the transport of the subcomponents to the assembly factory and to the machining workshops, as well as the transport of the assembled components to the site. Transport of raw materials is in most cases included when choosing materials in Simapro. For every subcomponent one or several processes of shaping the material/s has been chosen from Simapro. When the exact materials or processes have not been found or specifically mentioned, assumptions have been made with great consideration.

The erection of the turbine has been handled very simply, since available data was hard to access, and the probability that the erection process undergoes changes was seen as rather high. Also, the energy consumption from the erection might differ greatly depending on where the future assembly factory is located and where the site is. Leaving the erection outside of the system boundaries was however, not preferable, and so the existing assumptions are acceptable. The erection includes the fuel consumption of the cranes used, and the different special components and equipment needed for the erection of the huge parts of the wind turbine.

The decommissioning of the turbine and the waste management and recycling of its materials are not included. This is because the analysis would become too comprehensive and the workload would require more time, but also because the recycling of the turbine is another part of the EMS. Neither service nor operation of the turbine is included (such as the manufacture of spare parts), but the system boundaries start from the extraction of raw materials for the turbine and end when the turbine is erected.

Apart from the components that are part of the actual turbine, a few other components have been included in the inventory. These are devices that are needed for the manufacturing, transportation and erection of the turbine and that will be used not only for this turbine but also for the ones that will be produced in the future. These are the transport supports for the tower sections, the mold for the blades, the transport supports for the blades, the transport frame for the nacelle and the lifting beam that is used in the erection of the nacelle. A few other parts were considered but were regarded as too insignificant, as the contribution from these components has been allocated. This means that the energy consumption has been divided with the number of times the components will be used, so that the correct contribution to this one wind turbine is obtained.

4.3 Assumptions and Limitations

An important point to make is that no LCA is ever complete and exact, but instead it should be considered an advanced model and estimation. Assumptions have to be made and should not be seen as something altogether negative, but rather as a good approximation of the truth. The important thing is to point out the assumptions that are made, and what they are based on.

The limitations set on this project is mainly time limits, and it is the reason why only original materials and production processes from SimaPro have been used (i.e., background data). There is the possibility of researching the exact processes that are used in the manufacture of a product, or finding out the exact origins and processes used for extracting a material that is not available in Simapro, but as this is very time-demanding, in this case assumptions and simplifications have been made. In most cases, this is only for the good of the analysis, and might even improve the results, since the data in the Ecoinvent database is on many levels much more intricate and researched than any data that one would find under the set time limit of a project. Where such assumptions have been made here, it is pointed out under the inventory analysis for the different components in chapter 5.

Site work is not included in the payback, neither is grid connection. This is because they were considered to be factors that change so substantially between locations that any results received would not be reliable. This is also the reason why the transportation of the erection cranes was not included in the system boundaries, as was originally planned. The transportation of the cranes requires a substantial amount of energy, but since no one can predict where the cranes are located before they are shipped to the site, their transportation was omitted.

Originally, the plan was to use exact fuel consumption data from the transport companies and the company involved in erecting the turbine. However, due to lack of time and communication, other options were found using information from Simapro and from the information sheets provided on the website of the company handling the erection. And as mentioned above, this might very well prove to be a more positive thing for the accuracy of the results.

One important choice is whether to include the production and disposal of capital goods (trucks, injection molding machines etc). In this analysis, the data taken from the Ecoinvent database automatically includes capital goods, such as the manufacturing of trucks for the transportation. This data is then of course allocated over the total amount of uses, or transported kilometers, that can be expected from a truck. In the same manner, the special devices or parts that have been manufactured for the prototype, such as the blade mold for the blades, are allocated over the expected times it will be used. In this way, the total energy consumption from the manufacture of the mold is not put on the prototype alone.

5 Inventory

It should be mentioned that the inventory analysis was partly carried out while the turbine design was not completely finished, and so, possible last minute changes in design will not be reflected in the results. Also, the transport and the erection of the prototype might differ slightly depending on the geographical situation of the future sites.

5.1 Subcomponents

This subchapter will give more details about the processes included and choices made for the different components in the turbine. The estimated number of items in the turbine is 2300 (in May 2011) of which approximately the 45 heaviest have been researched and included (some of which occur more than once, such as blade and brake caliper) in this analysis. The information about the materials and processes described below is taken from the Ecoinvent database in SimaPro. A complete process tree of the included components and subcomponents is found in Appendix A. /14/

5.1.1 Foundation

Since the foundation is cast on site, no transports have been added for the foundation. The materials used for the foundation are concrete and reinforcing steel. The data on the concrete is average data from an LCA for the production of prefab concrete in the Netherlands, while the data on the reinforcing steel represent an average of world and European production mix, and is assumed to correspond to the consumption mix in Europe.

5.1.2 Tower

The tower has been handled in five segments, since they are produced and transported separately. The steel in the tower is a normalized rolled weldable fine grain structural steel. There are a lot of different steels of different grades available in Simapro. However, this exact steel type was not found. Instead, the steel used in Simapro is a high strain steel with world average data. In all cases where steel is used in the turbine, this is the steel type that has been chosen as an approximation.

For every material used in the turbine, one or more processes are added for the shaping or handling of the material. In the case of steel, the process chosen is “Sheet rolling of steel” (also called cold rolling). This dataset encompasses the energy consumption for the surface treatment before cold impact extrusion, and the technique used is the average technique for EU, for un- and low-alloyed steel.

For the cast anchors, the material chosen from the Ecoinvent database is an average cast iron that includes an LCA according to world average production. This LCA includes the casting of the iron. For all subcomponents that consist of cast iron, this is the material chosen. The process chosen for the machining of the cast parts is called “milling, cast iron, large parts”, and encompasses the direct energy consumption of the machine as well as compressed air and lubricant oil. The amount of machining is based on how much metal is removed, and the data is based on average technology. There is a considerable amount of different machining processes available in the database, but for simplicity’s sake, and because the time was limited, this is the assumed machining process for the machined cast parts of the turbine. For the cast steel in the stay cable cast parts, a material was chosen as an option for the closest approximation to the inventoried material. This is expressed to be a cast steel with a high carbon content, of world average. The casting of the steel is included in the choice of the material, and the machining is added as another process.

The material chosen for the tower transports, and for all the other components that are considered “extra components” (the lifting beam for the nacelle, the transport frame for the nacelle and the transport supports for the blades) is the same as the one used in the towers. This is, once again, an assumption, and one that has been considered to be of lesser importance, since the so called extra components will be used for many turbines, and their contribution to the total energy consumption of one turbine is insubstantial. The allocation factor of the extra components is 300, i.e. the blade mold is expected to be used approximately 300 times before disposal (according to discussion with project manager).

The recycling of the metal in the tower, or any other components, has not been included in the energy payback, since the waste management phase of the turbine is left outside the system boundaries.

5.1.3 Nacelle

The nacelle is a very complex component and has as such been handled in subcomponents, with the subcomponents having subcomponents of their own. This is better visible in the process tree in Appendix A. The materials and processes for the steel and cast irons in the components in the main frame and shaft system are the same as the ones described in chapter 5.1.2 for the subcomponents in the tower. The same goes for the other metal parts in the nacelle, unless mentioned otherwise below.

For the steel structure of the nacelle, the same steel is used as mentioned above, but an additional process is added for the zinc coating. This includes the process steps degreasing, pickling, fluxing, galvanizing (melt zinc coating) and finishing and is based on the average technique for Europe.

The material used for the cover of the nacelle is a glass fiber reinforced plastic. Finding a suitable material for this in SimaPro proved to be something of a challenge, but finally the option chosen was a gate to gate inventory for “the injection molding of glass fiber with polyamide resin”, including material inputs, process and infrastructure. This is based on an assumption for material uses, and the data for processing are “assumed with generic inventory”. For the rotor and stator segments and the cooling units in the generator, the average steel and cast irons as mentioned previously have been used. The copper chosen for the windings in the stator is based on average data on mining and production, and the processes of sheet rolling and wire drawing were added for the copper.

The strong permanent magnets in the rotor consist of neodymium-iron-boron, of which neodymium is a so-called rare earth metal. Here the chemical formula of the magnets has been used to calculate the proportions of the different elements of the magnets. For neodymium, which is being mined almost exclusively in China, a process on mining data from China on rare earth metals has been used, and since the boron concentration is less than 1 %, it has been omitted. /28/

The amount of cabling in the turbine has been included in the nacelle assembly and for practical reasons, instead of researching the different materials and processes needed for producing the cabling, data for cabling was taken from Simapro's database. This data includes copper, brass and plastic and describes the production of a typical ribbon cable produced by international manufacturers and available all over the world. The processes included are plastic extrusion, tincoating, contouring of the brass and wire drawing of copper. However, to ensure that the correct proportions were chosen, the total amount of copper was added as a specific material first, and the remaining amount of cabling (i.e. plastic etc) was covered by the Simapro process.

5.1.4 Blades

The blade assembly includes the blades, the blade bearings, the blade mould and the transport supports for the blades. The wind turbine has three blades, and even though one extra blade is produced for the prototype (for testing purposes), this extra blade has not been included in the energy payback. This is because no other possible test parts have been included for other components. The energy consumption from the transport supports and the blade mould have been allocated and calculated, so that the contribution to this single turbine is correct. Originally, the blade plug, i.e. "the mould for the mould", was supposed to be included in the payback, but this was later changed, mostly because the information on the plug was hard to access, and also because the allocation factor would reduce the energy contribution to a minimum, and it did not seem to be worth the effort of the research.

The material of the blades is quite complex, consisting of both glass fiber, different kinds of plastics, wood and metal. The glass fiber chosen is a gate to gate inventory for the production of glass fiber from the database, based on a "*state of the art report for the European glass manufacturing industry*" (material description from SimaPro). Another process for the main part of the plastics was added from the database, and the process chosen was injection molding. The data on materials and processes were taken from different European converting companies.

Data for the material and energy requirements for the other plastics were collected from the database, with average data from the USA, since no European data was available, and an additional process was added for the foaming of the plastic. For the use of wood, an LCA on the production and delivery of said wood to Europe was used. Lastly, the material for the nuts and bolts was a material based on world average data, a "*martensitic stainless steel used for bolts, nuts and screws"* (material description from SimaPro) , since the exact metal used in the wind turbine was not found.

5.1.5 Turbine Station

The Turbine Station consists of a lot of electronic equipment and originally, the plan was to collect data on the subcomponents from the suppliers. This was later considered unnecessary, since SimaPro includes a lot of data on electronic devices in its database, including such data on transformers and resistor cabinets. Even if these may not represent exactly the equipment used in the Turbine Station, they were still regarded as the best options available, since they include all the necessary processes that would probably not be included if the components were researched from scratch. The uncertainty of these results has still be noted and considered.

For the frequency converter, the switchgear, the heat exchanger and the UPS (power supply), the process chosen is called "Electronics for control units", and it includes "the composition of a typical control unit for devices in the industry" (material description from SimaPro). The data has no specific geographical origin, and the technology is an estimation based on literature. The LV cabinet has been handled using the process "electronic component, unspecified", covering material input and respective production efforts for electronic components and representing a global valuable average.

For the transformers, a data set covering raw material input and production efforts for the production of high voltage type transformers was chosen. Material data are taken from literature, and production efforts are approximated by using material-specific treatment processes. Finally, the resistor cabinet was handled with a similar process covering raw material input and production efforts for the production of current resistors. The steel frame of the turbine station was handled as other steel parts already mentioned, with the same choice of materials and shaping processes.

5.2 Transports

The transportation of the components and their subcomponents has been divided into five subgroups, referring to the division of the turbine:

- Blade transports
- Turbine station transports
- Erection transports
- Foundation transports
- Tower transports.

Here the only thing covered in “Erection transports” is the lifting beam for the nacelle, while the other extra components are covered in the same group as their assigned component. Every group includes both the transportation of the subcomponents to and from the assembly factory, to and from possible machining of cast parts, and the assembled main components to the site. The blade transports also include the transportation of the blade mould to the manufacturer of the blades.

In SimaPro, one has a lot of choices between different kinds of transportation, by road, railway, water and air. At the beginning of the work with the payback, the intention was to choose the best alternative in accordance with information given from the transportation companies that delivered the components. As no such information was ever received, the best option available was to choose an acceptable average from the Ecoinvent database.

In SimaPro, the unit used for transporting objects is “ton kilometers” (tkm). This refers to 1 ton being transported 1 km with the chosen vehicle. One simply multiplies the distance with the mass of the transported object (not including the mass of the vehicle, since this is already included). The vehicle that was chosen to represent the transportation by road was an average transport by lorry, a process that includes operation of vehicle, production, maintenance and disposal of vehicles, and construction and maintenance of roads. As written in the database; *"For the attribution of vehicle share to the transport performance a vehicle life time performance of 540000 tkm/vehicle has been assumed"*. The data represents Swiss conditions. More information about the single components' transported distances is found in Appendix C. The transports also include some transportation by sea, since a few components are shipped from Europe, and in these cases the transport process "Bulk carrier 1" was used. This is, according to the database, a typical example of a general cargo ship, with no harbor operations included.

The distances between locations by road have been estimated and calculated by the use of google maps. This is, according to other reports done on LCAs, a very common method of measuring distances. As Google maps does not allow the measuring of distances by sea, the transports that were done by sea were measured via the measurement service provided by the World Shipping Register. /10/, /51/

As many of the components are of considerable volume, the use of escort cars (to warn other vehicles of an approaching, large vehicle) is sometimes needed during road transport. These escort cars are also included in the transports, and the process chosen to represent them is called "Passenger car B250". Here the unit is kilometers, and no mass is included, only the production of fuels for the distance. The database also mentions that this process is "used for service and control".

5.3 Erection and Assembly

As mentioned in chapter 4.2, the erection is handled very simply. When contacting the supplier of the erection process proved challenging, data on the energy output from the cranes were collected from the supplier's website. Knowing the capacity of the cranes that would be used for the erection, assumptions were made on specific cranes and their respective engine energy output. Then, using estimates about the time frame provided from the documents and discussions with Mervento’s management, the calculations were carried out. See Appendix B for details. /15/

One crane is used for the erection of the other cranes, whereas two cranes are needed for the tower and nacelle, and one for the blades. No energy output was found for the crane used for the blades, so it was assumed that it was similar to that of the crane used for erecting the crane. This was also a value that lies between the energy output of the smaller crane and that of the larger crane used for the tower and nacelle, and so this seemed like an acceptable assumption.

The transportation of the cranes requires a substantial amount of energy, but since no one can predict where the cranes are located before they are shipped to the site, their transportation was omitted. Originally, the erection phase was named “Erection and assembly”, but since no data was collected on the assembly of e.g. the nacelle, the assembly phase was also omitted. The transportation to and from the assembly factory is, however, included under “Transports”.

6 Energy Payback Calculation and Results

The following is the results of the gathering of data and the final calculations using the data from SimaPro. The unit used in SimaPro is “Mega joule equivalents”, which refers to the fact that all the processes, the extraction of materials and consumption of fuels etc have been transformed into a unit that is equal to one mega joule of energy. In order to be able to compare the number with the theoretical value for the annual energy production received from the management, a conversion into Megawatt hours was made. The exact value of the energy consumption of the main components and processes can be viewed in Appendix D. /6/

Since there are two alternative tower heights, the payback calculations from both options are presented below. However, the more detailed analysis of the contribution of the energy use is presented only for the option with the taller tower (125 meters), since this is the alternative that was chosen for the prototype. The calculation on the shorter (90 meters) tower is included first and foremost as a means of comparison.

6.1 Payback Calculation

As can be seen in Table 1 below, the total energy consumption from the production, transportation and erection of the turbine is 36111745 Megajoule equivalents.

Table 1. The energy balance (125 meter tower)

Total energy consumption:	MJ eq	36111745
	MWh	10031
Annual energy production (at annual average wind speed 8.5 m/s)	MWh	11187
Expected lifetime of turbine	Years	20
Energy Balance:	**Years**	**0.90**
	Months	**10.76**
	Days	**322.80**
Percentual time of turbine's lifespan	**%**	**4.42**

Knowing that 1 MJ ≈ 0.0002777778 MWh, the value was converted into a unit that was comparable with the value given for the annual theoretical energy production, 11187 MWh. In both cases the theoretical value for the energy production has been calculated with a probability of 90 % and an uncertainty of 10 %.

By finally dividing the total energy consumption with the annual energy production, the energy payback is calculated to be approximately 323 days, or 10.76 months. If you divide this with the expected lifetime of the wind turbine, the relative time which it takes to gain back the energy used for the production of the wind turbine is right below 4.42 %. In other words, the turbine will during its lifetime produce almost 23 times more energy than it consumes.

Table 2. The energy balance (90 meter tower)

Total energy consumption:	MJ eq	32511287
	MWh	9031
Annual energy production (at annual average wind speed 8.5 m/s)	MWh	11187
Expected lifetime of turbine	Years	20
Energy Balance:	**Years**	**0.81**
	Months	**9.69**
	Days	**290.62**
Percentual time of turbine's lifespan	**%**	**3.98**

If one does the same calculations with the shorter tower, Table 2 shows that the energy payback will be achieved in approximately 291 days, or 9.7 months. This translates as right under 4 % of the turbine's lifespan, or that the turbine will produce more than 25 times the energy it produces during its lifetime.

6.2 Energy Consumption Sources

When one knows the total energy consumption of the turbine, the next interesting thing is finding out what phases or processes are the main sources of the consumption. This is shown in figures 5-12 below. The light blue boxes are components that have all been added manually (i.e. based on foreground data), while the grey ones are either materials or processes used in/for the components and are as such parts of the database (background data). The process tree in Simapro consists mostly of these socalled grey boxes, but as their single results can be quite unsubstantial (and often also uninteresting), focus has been put on the major processes, i.e. the blue ones.

Note that in Simapro, the main components have been named “assemblies”, e.g. “Nacelle assembly”. This is simply because the term assembly in Simapro means that the component in question consists of subcomponents. It has nothing to do with the actual, physical assembly of the nacelle. First the charts concerning the entire turbine are presented, both the taller and the shorter tower. Then the contribution from the different components of the taller tower are presented one by one. The shorter tower has not been analyzed further, since this report was to be done on the prototype turbine.

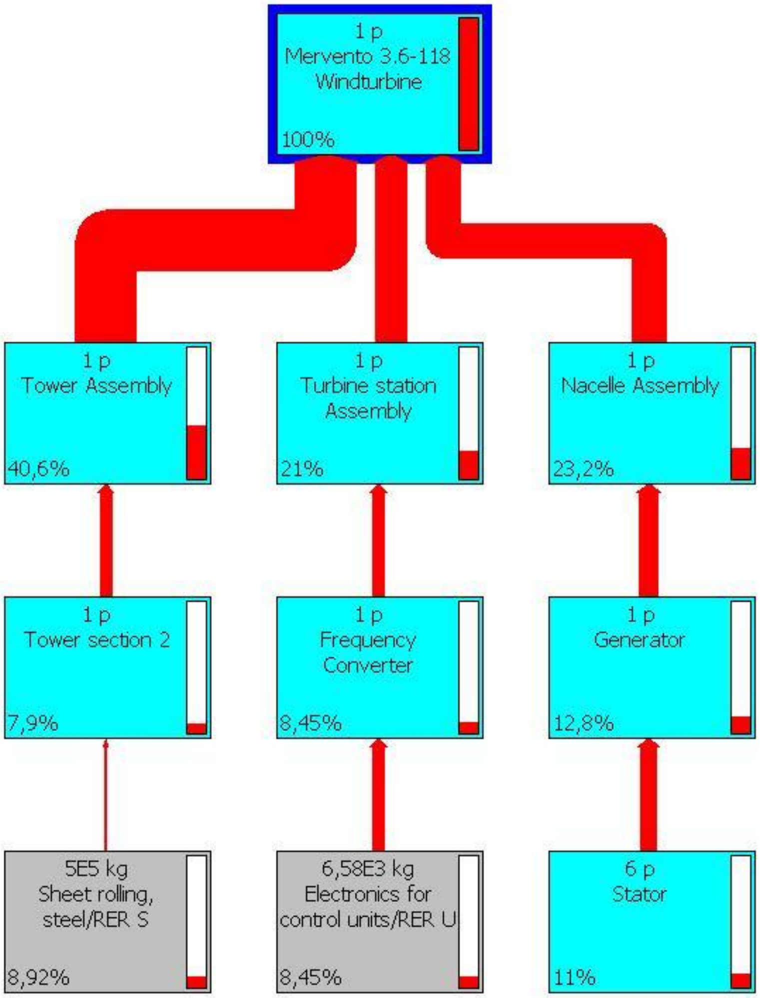

Figure 6. The main sources of the energy consumption (taller tower option).

In figure 6 above, a cut-off percentage of 7.9 is used, meaning that only processes and components that contribute with more than 7.9 % of the total energy consumption are shown. In SimaPro, it is possible to set the cut-off percentage to suit one's purposes, anywhere between 0 and 100 %. Since the entire turbine project consists of more than 2000 processes though, it is not favorable to show too many of them at the same time, since the picture becomes increasingly hard to understand. In this case, the cut-off is on purpose set quite high, so that it will be possible to make out the text in the different process squares. Another figure with the cut-off percentage of 4.7, and thus including more components and processes, can be found in Appendix E. Throughout this report, the cut-off has been set to first and foremost suit the document format. Also, in a few cases the cut-off has intentionally been altered to uphold the secrecy standards concerning material use.

The thickness of the red arrows indicates the relative amount of energy consumption that the process (and its subprocesses) contributes to the total consumption. This is also indicated by the bar at the right side of the boxes, and the numbers in the lower left-hand corner of each box. Thus, the manufacture of the tower sections has the greatest impact, with 40.6 % of the energy consumption. In figure 6 only tower section 2 is visible, even though the others are of course included in the actual calculation. Their single contribution is, however, below the cut-off line. The reason why the steel manufacture has a greater contribution (32.6 %) than one segment on its own (7.9 %), is that the steel manufacture-box is covering the total amount of steel in the entire turbine. This might be a bit confusing, but it is better laid out in the figure in Appendix E.

The second and third biggest contributors of the energy consumptions are the Turbine Station assembly with a percentage of 21 and the nacelle assembly with 23.2. The main components and their contributions are further explained in the next chapters. As can be seen in figure 7 below, the tower logically contributes less to the overall consumption in the shorter tower (by 34 %), and so the other components are given greater significance.

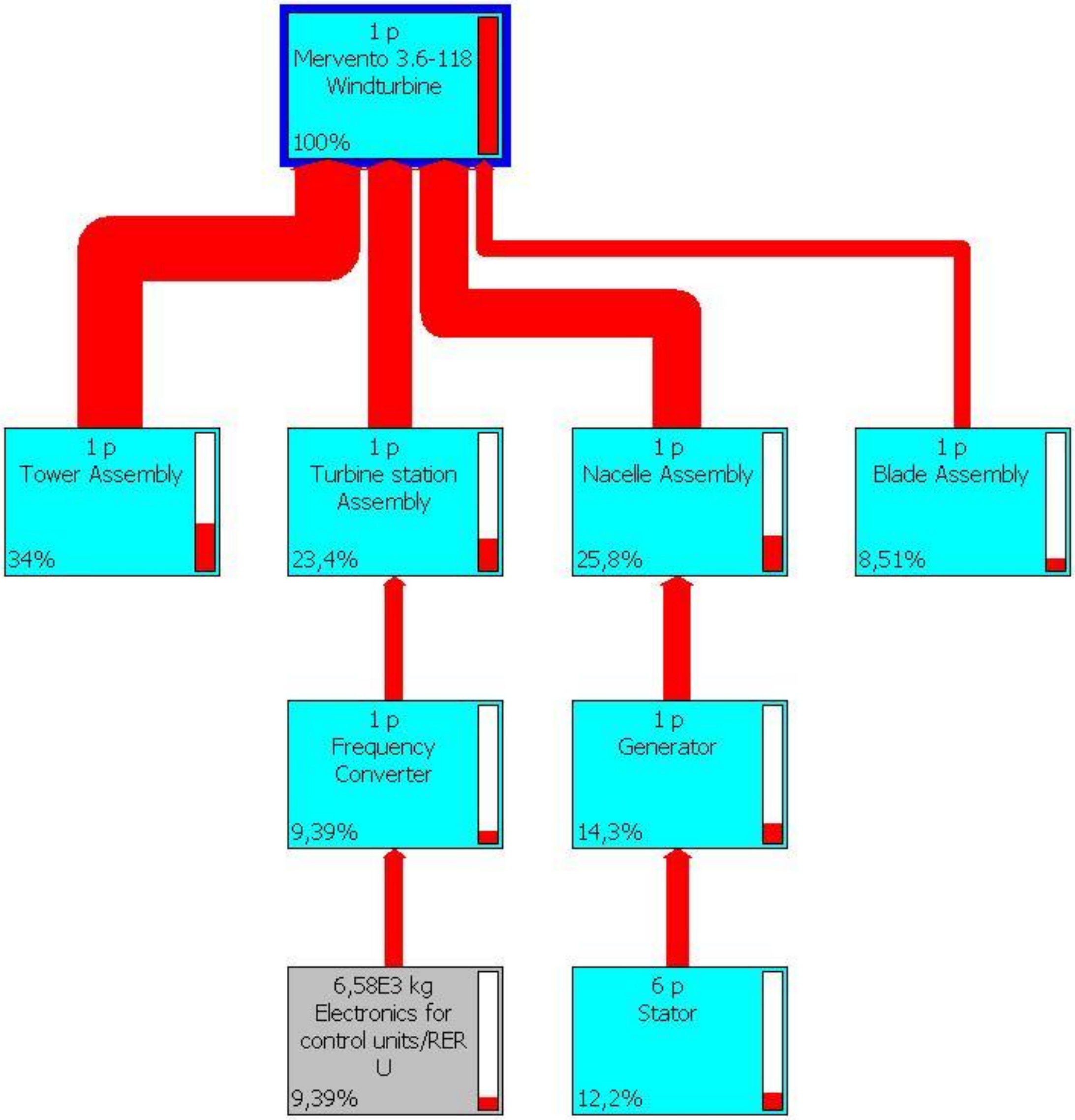

Figure 7. The main sources of the energy consumption (shorter tower option).

6.3 The Division of the Contribution

The contribution to the energy consumption from each of the main subcomponents, the erection and the transports will be presented shortly below. To make the division a little bit easier (and hopefully clearer), the different components and processes are presented one by one. Therefore, the main component/process is here in each case regarded as the object of interest, and regarded as “100 %” (i.e. the percentage of its subcomponents is that of the component in question, not of the whole wind turbine). The order in which they are presented has nothing to do with the contribution in itself, but they are presented in the same order as they were in the system boundaries in chapter 4.2.

6.3.1 Foundation Contribution

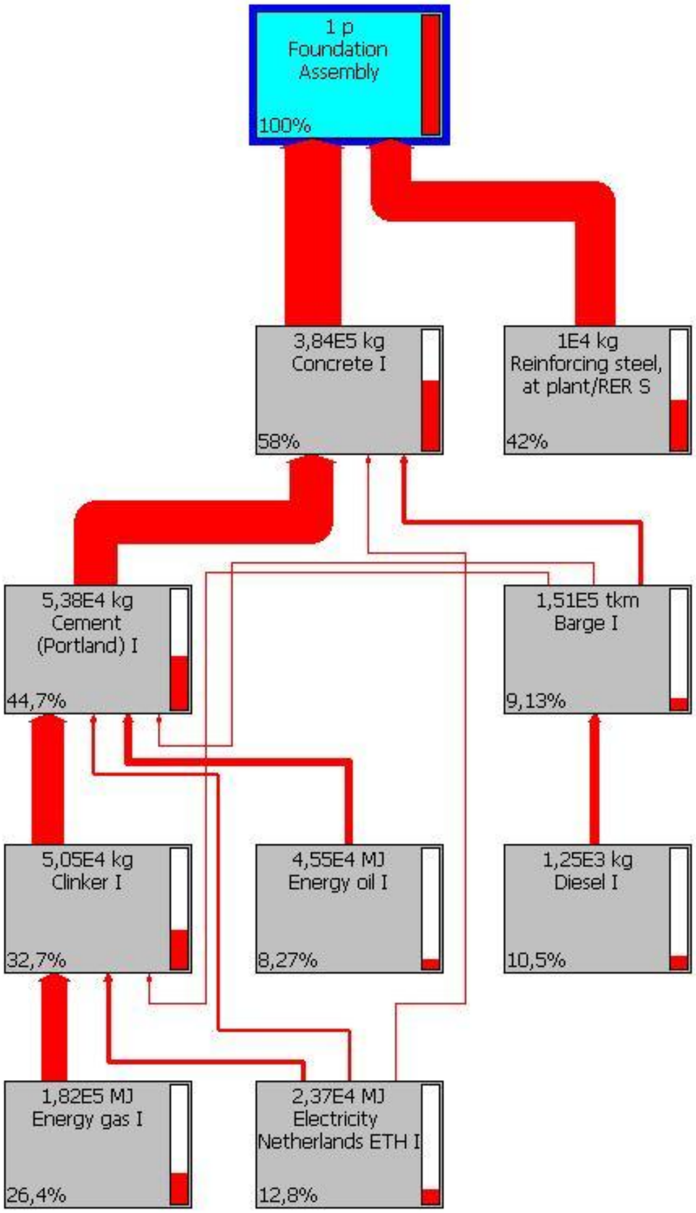

Figure 8: The contribution of the foundation, with a cut-off at 6.9 %.

The contribution from the foundation is 1.52 %, and thus too small to be visible in figure 6 on page 37, but it is rather evenly divided between the concrete and the reinforcing steel that is used, as shown in figure 8 above. However, one might note that the amount of concrete in the foundation is almost 40 times the amount of steel, so the production of steel has a much larger contribution than that of concrete.

6.3.2 Tower Contribution

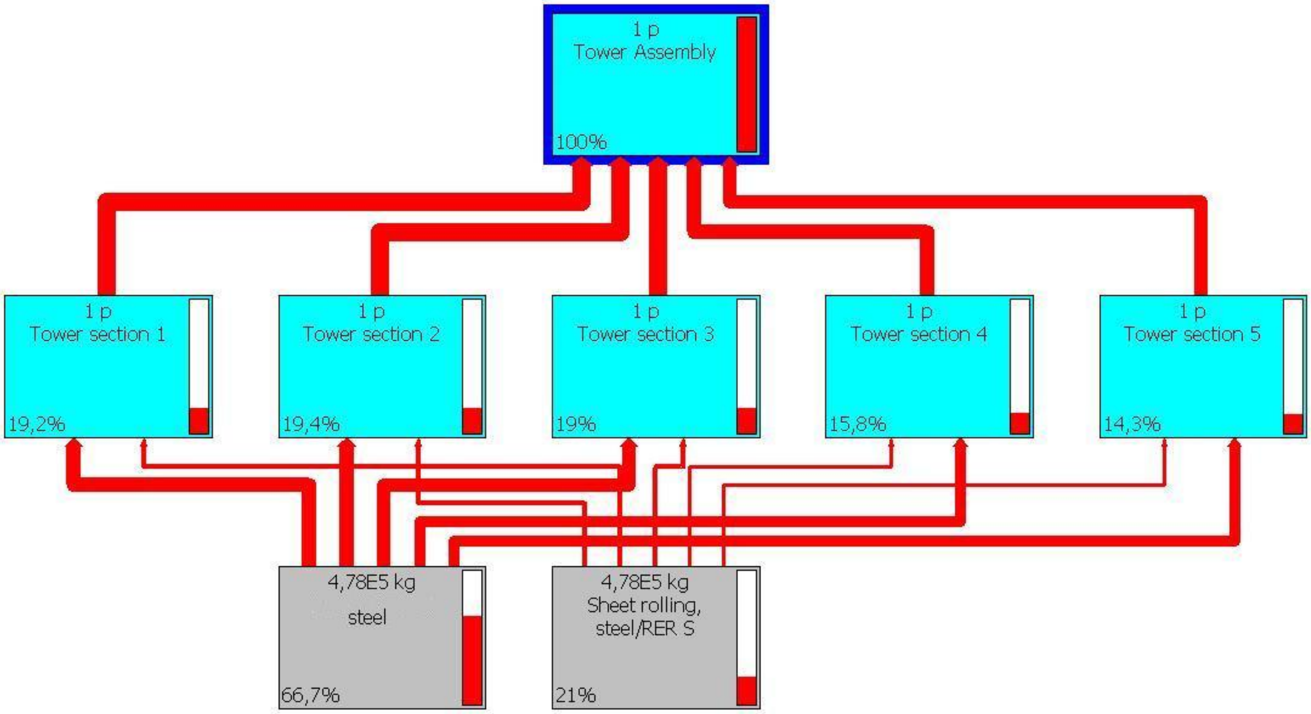

Figure 9. The contribution of the tower, with a cut-off at 13 %.

As mentioned earlier, the contribution of the tower segments altogether has the greatest impact on the turbine's energy consumption, with a total percentage of 40.6 %. The different segments have single percentages varying between approximately 6 % and 8 %. In the tower assembly are also included the anchors, transport supports, the stay cables and the cast parts for the stay cables but, in comparison to the masses of the tower segments, these are minor. As seen in figure 9 above, it is mainly the extraction of steel that requires energy.

The use of steel for the massive tower may be a big part of the turbine's total energy consumption, but one shall keep in mind that metal is very easily recycled. If the recycling of the wind turbine was part of the calculation and the energy payback, the total contribution of the tower would with great certainty be a lot smaller.

6.3.3 Nacelle Contribution

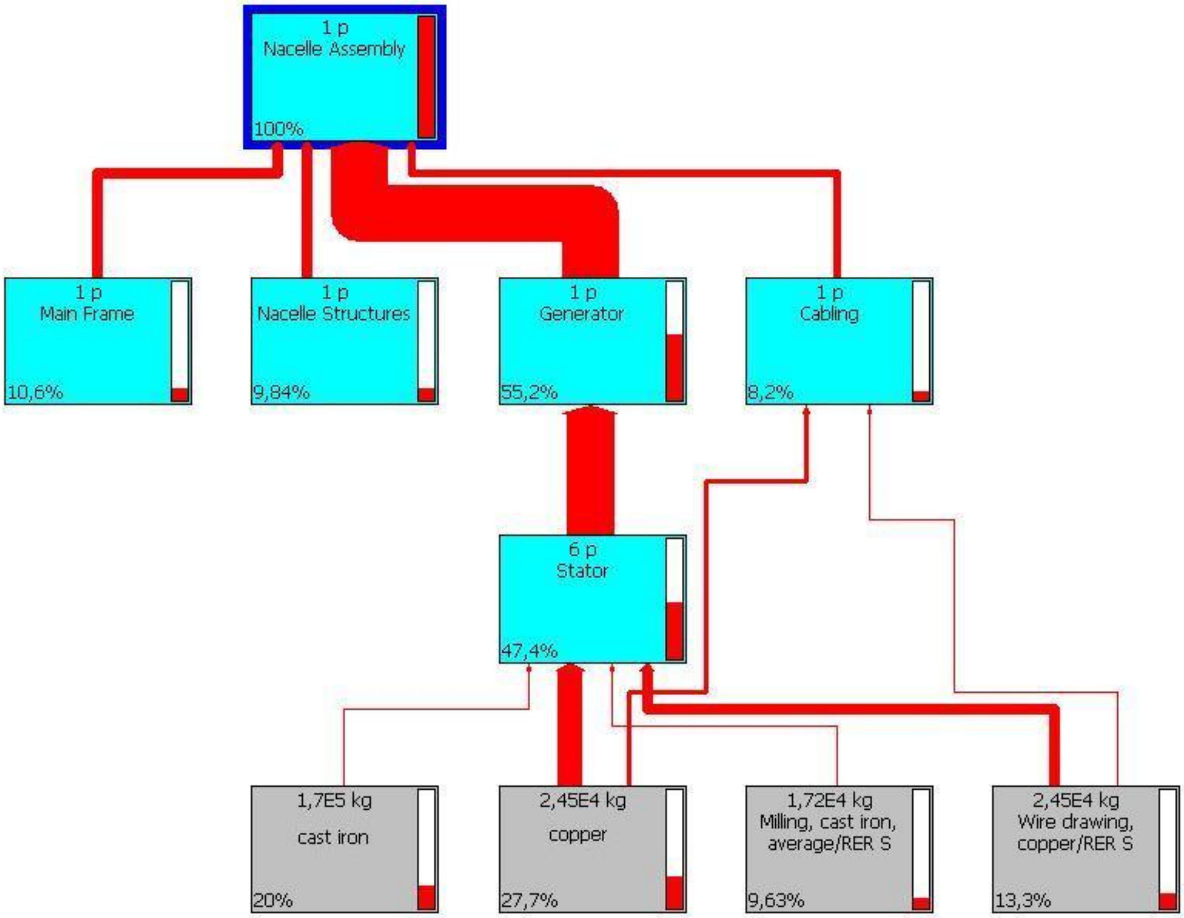

Figure 10: The contribution of the nacelle, with a cut-off at 8.2 %.

The total contribution of the nacelle ends up at 23.2 % with the main focus on the generator, as shown in figure 10. This is not very surprising, since the generator is a very heavy piece of machinery, and the extraction and forming of the copper in the stator is very energy consuming.

6.3.3 Blade Contribution

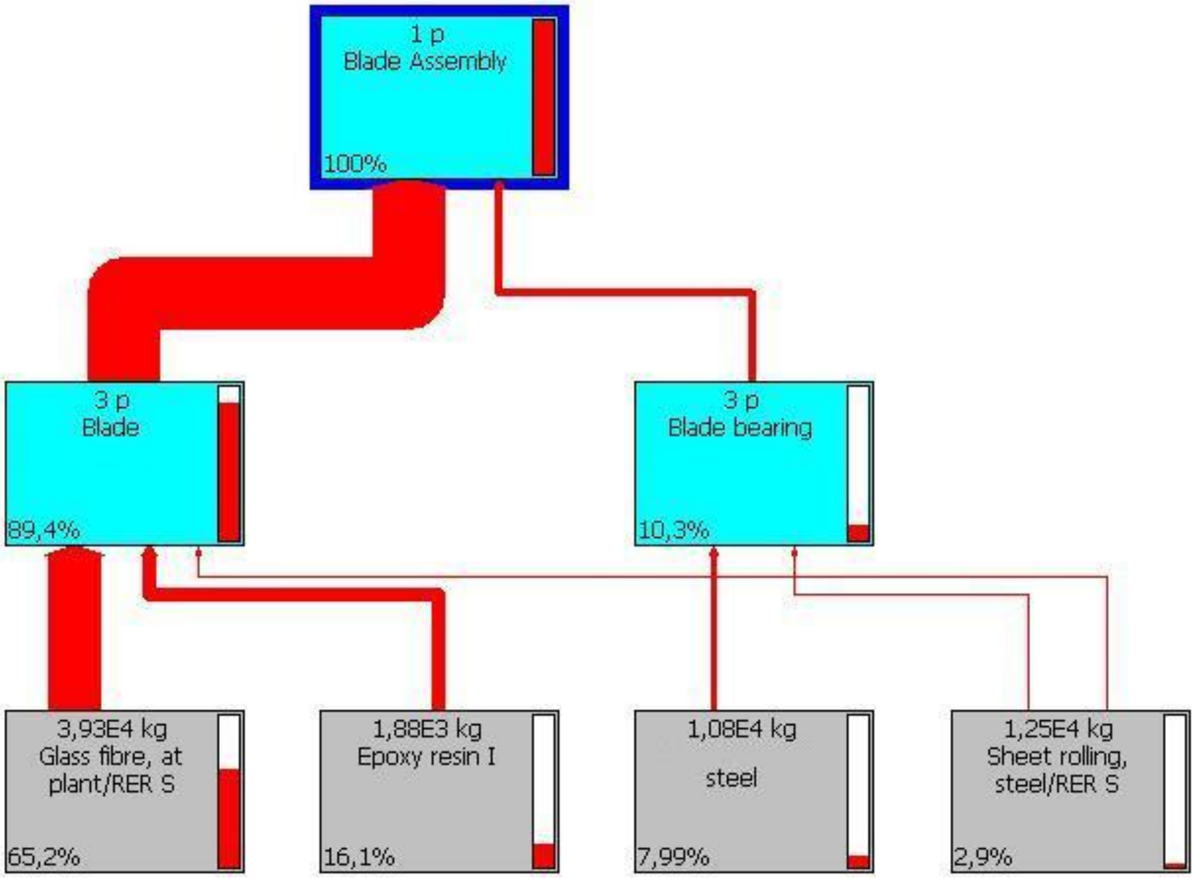

Figure 11: The contribution of the blades, with a cut-off at 2.1 %.

The blade assembly contributes with 7.66 % of the total energy consumption, and in figure 11 above one can clearly see that the main part of the energy use comes from the glass fiber. This is in part because the blades are very large and require huge amounts of both glass fiber and epoxy resin, but also because the process of molding the blades requires a lot of heat, and thereby, a lot of energy. Please note that the blades are not visible in figure 6 only because the cut-off was set at higher than 7.66 % in that figure.

6.3.4 Turbine Station Contribution

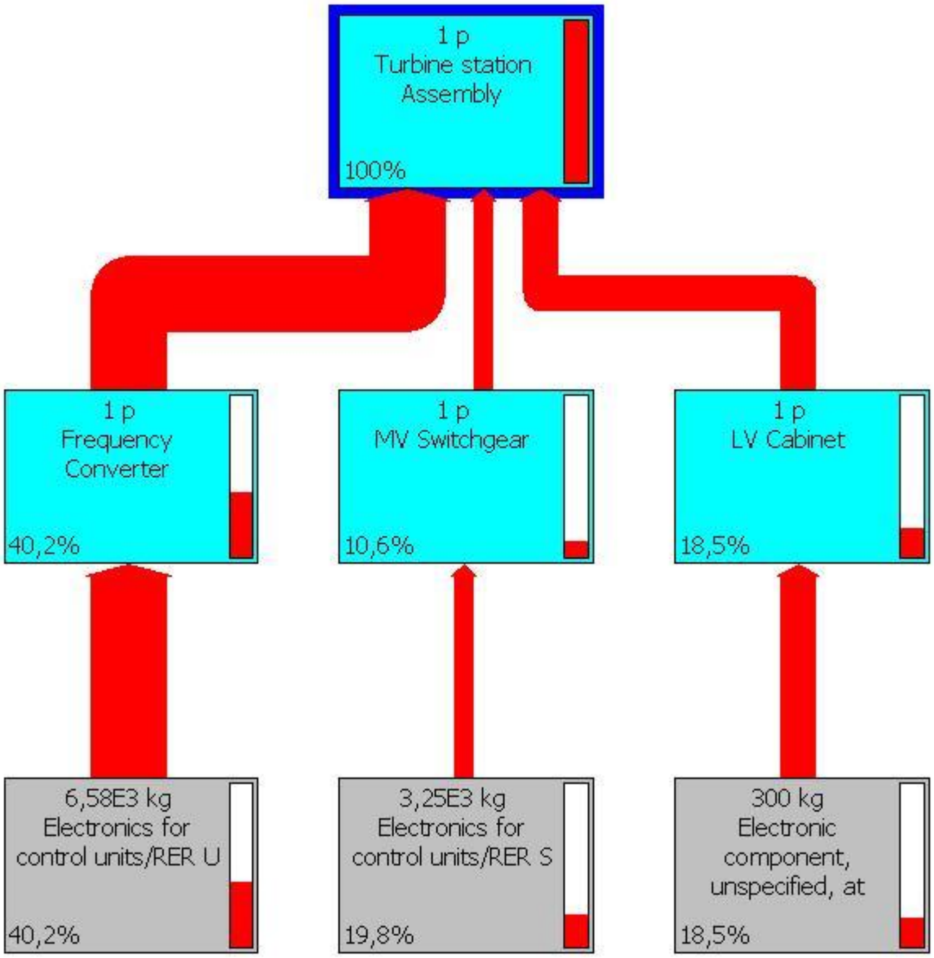

Figure 12. The contribution of the Turbine Station, with a cut-off at 18 %.

The Turbine Station contributes with 21 % of the total energy, and most of it is used in the production of the frequency converter, and the electronics therein. This entire component is handled very simply, with only background data on the materials and processes, and it should be pointed out once more that the results are an advanced estimate. If further work is to be done on a future energy payback, it would be recommended to research this component in particular. It was, however, decided that this is the most approximate data that could be found considering the time limits.

Also, in figure 12, only the socalled top processes are shown. This is because the turbine station assembly consists of 1977 different processes and even with a high cut-off, the figure becomes hard to understand with all the insubstantial boxes present.

6.3.5 Transport Contribution

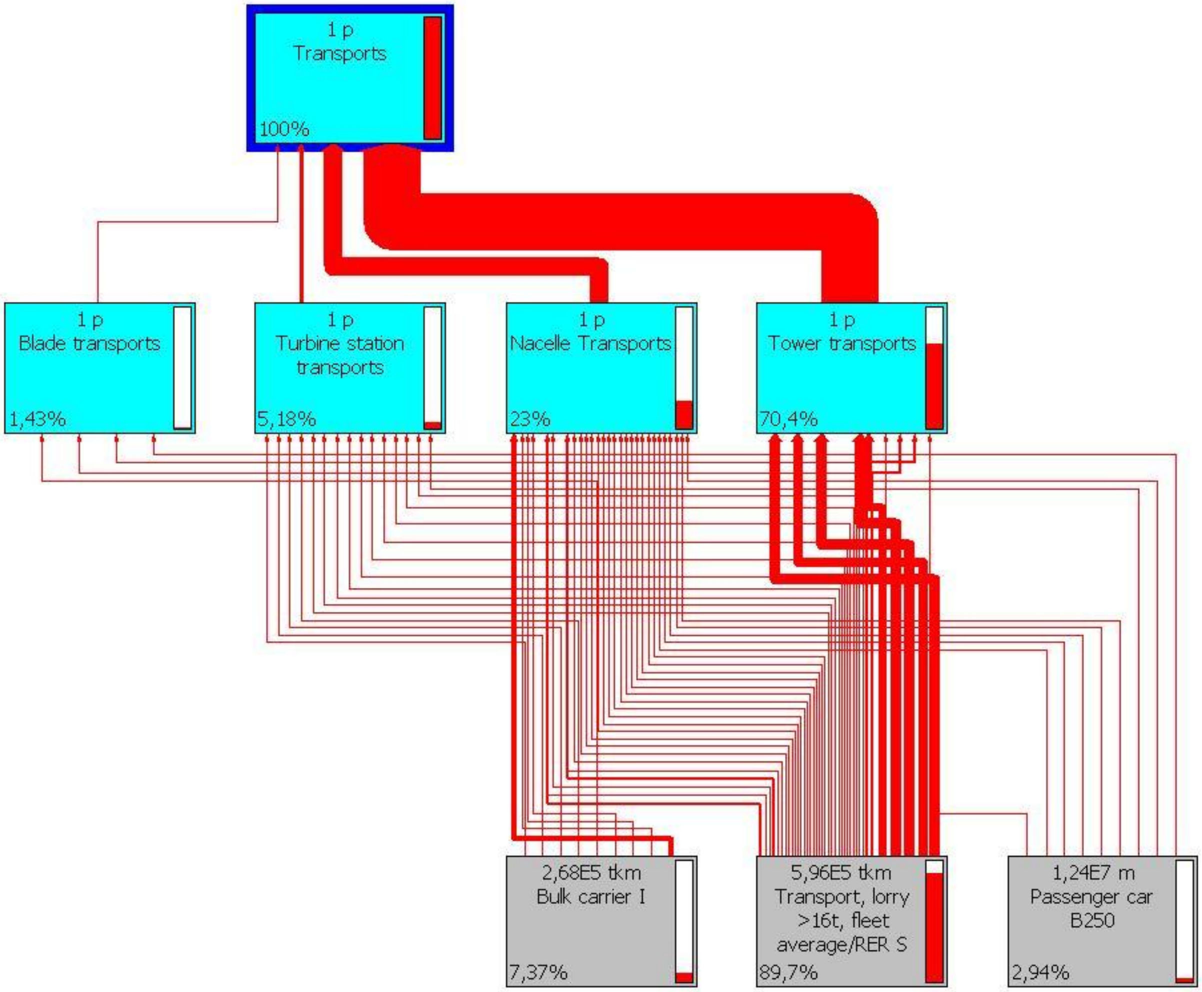

Figure 13. The contribution of the transports, with a cut-off at 0.54 %.

Logically, the contribution from the transports is directly connected with the mass of the transported objects and components. Therefore, the transportation of the tower segments is what makes up most of figure 13. In total, the transports contribute to the total energy consumption with 3.96 % of the turbine's total. More details are available in Appendix C.

6.3.6 Erection Contribution

No process figure was done for the erection, since it consists only of energy output from the cranes, and the processes all look the same. The entire contribution of the cranes was approximately 1.98 % of the turbine's energy consumption. The separate contribution of each crane is available in Appendix B.

7 Critical Review and Discussion

According to all the collected data, the final result of the energy payback calculation is that the prototype of Mervento 118-3.6 has a payback time of 323 days or 10.8 months. This is somewhat higher than the average payback for a wind turbine. There may be several reasons for this; one is mentioned in chapter 5.1.2 concerning the steel tower; the main contribution to the energy consumption comes from the massive amounts of steel in the tower segments. Steel is very easily recycled as a material, and if this was somehow accounted for in the calculations, the result would be that the payback time would be shortened considerably. In a full LCA, the recycling of materials is usually included, but since the recycling of the turbine was another part of the EMS, this was not done here. However, if one looks at the results from the shorter tower options, one realizes that with a more conventional hub height, a more conventional result is achieved.

Another possibility is the fact that Mervento is using designs and ideas that are quite new and still relatively unique, such as direct drive (and again, a tall tower). These features, with heavier components, result in a higher total energy consumption for the single turbine, but may in the long run also result in a greater annual energy production, or a longer lifetime of the turbine. In any case, the results are not supposed to be used for external comparison.

The possible sources of errors are pretty much related to the assumptions that have had to be made because of the time limits. The contribution from the electronics in the turbine station may, if researched further, prove to be over-estimated, as may the energy use of the cranes used in the erection of the turbine. The erection is also the phase that has had the least attention in the data collection, and this might prove to be a source of error, if ever further research is done.

The intention was that suggestions would also be given regarding what changes could be made to decrease the energy consumption of the turbine, based on the results. However, I do not consider myself sufficiently knowledgeable of the different materials and processes that are used to give any specific suggestions. More general comments that can be made are first and foremost regarding the transports; If possible, one should always aim to keep the transport distances as short as possible, i.e. favor suppliers that are located close to the assembly factory. Also, if logistically possible, one might consider co-transportation of components, if they are transported from locations close to each other. Another efficient way of shortening the payback time is of course to find ways of increasing the annual energy production.

Although assumptions have been made, and changes in the system boundaries and original plans were made, they have all been in favor of a more reliable and exact result. If further work is to be done on the energy payback calculation in the future, this report has provided a good basis and has pointed out the weaknesses that will benefit the most from any possible further research and updates.

For my part this has been a really interesting project, and I am very grateful that I was given the opportunity to work with something that I was genuinely interested in. I have gained a greater insight into the practical work of LCA and experienced how things are handled in a modern company within the wind power business. I would also like to claim that I have learned a great deal about myself in the process; what things I do well and what things I have to work more on, e.g. keeping deadlines that I have set myself. In retrospect there are a lot of issues I would have liked to have handled differently or at least more smoothly, but that is easily said when one has the final results. In the end I am happy with the results we got from the thesis; Both the payback calculation and the enlightenment that the learning process provided.

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Appendix A: Component Tree

Turbine Station
Frequency Converter
Main Transformer
Aux Transformer
MV Switchgear
LV Cabinet
Heat Exchanger
Frame + other steelparts
UPS
Resistor Cabinet

Tower
Steel Segment 1
Steel Segment 2
Steel Segment 3
Steel Segment 4
Steel Segment 5
Stay Cable cast parts
Tower transportsupports
Anchors
Stay Cables

Foundation
Foundation

Blades
Blades
Blade mould
Blade transportsupports
Blade bearings

Nacelle

Main frame
Tower extension
Lower tower exension
Main house

Shaft system
Main shaft
Main bearing

Nacelle structures
Cover
Steel structures

Generator
Rotor
Stator
Cooling unit

Other
Hub
Cabling
Rotor disc
Rotor brake disc
Swash plate
Outer ring
Feathering bracket
Brake callipers
Feathering levers
Transport frame
Lifting beam for nacelle

Appendix B: Erection Sheet
Page 1/2

Erection of the Turbine

Rough calculations based on estimates and data on Havator's crane park.
The numbers are deliberately exaggerated, since the overall impact is small.

Erection of the cranes

Crane used:	Liebherr 1050-3.1	
Crane engine output:	270	kW
Mobilization takes approximately	1	week

1 week of work = 7 days * 8 hours = 56 h work
of which 50 % of the time at full efficiency and 50 % at half efficiency

Erection of tower and nacelle

Cranes used:	Liebherr LTM 11200b & Liebherr LG 1750	
Crane engine output:	240	kW
	400	kW
Mobilization takes approximately	1	week

1 week of work = 7 days * 8 hours = 56 h work
of which 50 % of the time at full efficiencyand 50 % at half efficiency
using both cranes simultaniously

Erection of the blades

Crane used:	Liebherr Demag CC280	
Crane engine output:	270	kW
Mobilization takes approximately	3	full days

The blade erection is expected to take 2 - 3 days.
To be sure, 3 full days work have been used in the calculations.

Calculations

Erection of cranes:	270 kW x 28 h + 135 kW x 28 h	=	11,34 MWh
Erection of tower and nacelle:	240 kW x 28 h + 120 kW x 28 h	=	10,08 MWh
	400 kW x 28 h + 200 kW x 28 h	=	16,80 MWh
Erection of blades:	270 kW x 72 h	=	19,44 MWh
Total energy consumtion from erection			57,66 MWh

Appendix C: Transport Sheet

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Appendix D: Payback Calculation
Page 1/2

125 meter tower

Title:	Analyzing 1 p 'Mervento 3.6-118 Windturbine'
Method:	Cumulative Energy Demand V1.07 / Cumulative energy demand

Impact category	Unit	Total	Tower	Foundation	Turbine station	Nacelle	Blade	Transports	Erection
Non renewable, fossil	MJ eq	31497188	13948295	515529	5423907	7218413	2343985	1339530	707531
Non-renewable, nuclear	MJ eq	3651544	577495	28158	1731845	882021	354256	72100	5669
Non-renewable, biomass	MJ eq	147	2	0	13	128	1	4	0
Renewable, biomass	MJ eq	236062	31574	1571	129686	55621	15219	2391	0
Renewable, wind, solar, geothe	MJ eq	61340	9895	429	29366	14697	6328	625	0
Renewable, water	MJ eq	665464	95645	4027	284558	219650	46534	14237	813
Total	MJ eq	36111745	14662905	549713	7599375	8390529	2766323	1428886	714013

<u>Total energy consumtion:</u>	MJ eq	36111745
	MWh	10031
Annual energy production	MWh	11187
Expected lifetime of turbine	Years	20
<u>Energy Balance:</u>	**Years**	**0,90**
	Months	**10,76**
	Days	**322,80**
Percentual time of turbine's lifespan	**%**	**4,42**

90 meter tower

Title:	Analyzing 1 p 'Mervento 3.6-118 Windturbine'
Method:	Cumulative Energy Demand V1.07 / Cumulative energy demand

Impact category	Unit	Total	Tower	Foundation	Turbine station	Nacelle	Blade	Transports	Erection
Non renewable, fossil	MJ eq	28089303	10540410	515529	5423907	7218413	2343985	1339530	707531
Non-renewable, nuclear	MJ eq	3494363	420314	28158	1731845	882021	354256	72100	5669
Non-renewable, biomass	MJ eq	147	1	0	13	128	1	4	0
Renewable, biomass	MJ eq	227439	22952	1571	129686	55621	15219	2391	0
Renewable, wind, solar, geothe	MJ eq	58605	7160	429	29366	14697	6328	625	0
Renewable, water	MJ eq	641430	71611	4027	284558	219650	46534	14237	813
Total	MJ eq	32511287	11062448	549713	7599375	8390529	2766323	1428886	714013

<u>Total energy consumtion:</u>	MJ eq	32511287
	MWh	9031
Annual energy production	MWh	11187
Expected lifetime of turbine	Years	20
<u>Energy Balance:</u>	**Years**	**0,81**
	Months	**9,69**
	Days	**290,62**
Percentual time of turbine's lifespan	**%**	**3,98**

Appendix E: Expanded Process Tree