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Analysis of the environmental impact on remanufacturing wind turbines

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Analysis of the Environmental Impact on Remanufacturing Wind Turbines

Master's Degree Thesis

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Abstract

To deliver clean energy the use of wind turbines is essential. In June 2011 there was an installed wind capacity equivalent to 211,000MW world-wide (WWEA, 2011). By the end of the year 2009 the U.S. had 35,100MW of wind energy installed capacity to generate electricity (AWEA, 2010). This industry has grown in recent years and is expected to grow even more in the future.

The environmental impacts that will arise from the increased number of wind turbines and their end-of-life should be addressed, as large amounts of resources will be required to satisfy the current and future market demands for wind turbines. Since future 10MW wind turbines are expected to be as heavy as 1000 tons each, the study of the environmental response of profitable retirement strategies, such as remanufacturing for these machines, must be considered.

Because of the increased number of wind turbines and the materials used, this study provides a comparison between the environmental impacts from remanufacturing the components installed inside the nacelle of multi-megawatt wind turbines and wind turbines manufactured using new components. The study methodology is the following:

- Describe the life-cycle and the materials and processes employed for the manufacture and remanufacturing for components inside the nacelle.
- Identify remanufacturing alternatives for the components inside the nacelle at the end of the expected life-time service of wind turbines.
- Evaluate the environmental impacts from the remanufactured components and compare the results with the impacts of the manufacturing of new components using SimaPro.
- Conduct sensitivity analysis over the critical parameters of the life cycle assessment
- Propose the most environmentally friendly options for the retirement of each major component of wind turbines.

After an analysis of the scenarios the goal of the study is to evaluate remanufacturing as an end-of-life option from an environmental perspective for commercial multi-megawatt wind turbines targeted for secondary wind turbine markets.

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Let the positive good vibes be with you all.

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Acronyms

ASEA	General Swedish Electric Company
AWEA	American Wind Energy Association
CO_2	Carbon Dioxide
CNC	Computer Numeric Control
Cr	Chromium
DFE	Design for the Environment
E	Egalitarian Version
EMS	Energy Maintenance Service
FRP	Fiber Reinforced Plastic
GHG	Green House Gases
GPH	Gallons Per Hour
GRP	Glass Reinforced Plastic
H	Hierarchist Version
HV	High Voltage
IEEE	Institute of Electrical and Electronic Engineers
I	Individualist Version
IARC	International Association for Research on Cancer
ISO	International Organization for Standarization
kPt.	Kilo Ecopoints
kW	Kilo Watt
kWh	Kilo Watt-hour
LCA	Life Cycle Assessment
LPG	Liquefeid Petroleum Gas
Lt	Litter
LV	Low Voltage
MJ	Mega Joule
MJeq	Mega Joules Equivalents
MRP	Material Recovery Products
MRR	Material Recovery Products
MW	Mega Watt
MWh	Mega Watt-hour
Ni	Nickel
OE	Original Equipment
OEM	Original Equipment Manufacturers
OHT	Oven Heat Treating
PHT	Preliminary Heat Treatment
Pt.	Ecopoints
PVC	Polyvinyl Chloride material
PWHT	Post-Weld Heat Treating
Reman	Remanufacturing
VAWT	Vertical-Axis Wind Turbines
VOC	Volatile Organic Compounds
VPI	Vacuum-Pressure Impregnation
HAWT	Horizontal-Axis Wind Turbines
WEEE	Waste Electrical and Electronic Equipment

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WWEA World Wind Energy Association

Introduction

There are many benefits in using wind energy. Wind turbines are machines that produce electric energy by clean means. They benefit the economy. The American Wind Energy Association (AWEA) states that at the end of the year 2008, approximately 30,000 wind turbines were operative, and just for that year the wind power generation capacity increased by 50%, injecting about $17 billion into the economy. Another benefit is that the life span of wind turbines goes between 20 and 25 years, in which time they can generate as much as 40 times the energy needed to manufacture them. Despite the advantages of using this technology, concerns arise from the large amount of materials consumed in this industry.

Vast amount of materials are consumed in wind turbine manufacture due to the size and number of the machines produced. In the year 2008, the installation of 5,000 new wind turbines in the U.S. represented at least 1 million tons of steel material used for their manufacture (AWEA, 2009). Other materials such as copper, cement, reinforced fibers are also employed, and represent additional stresses on the availability of virgin material. Furthermore, in terms of life-cycle the disposal phase of a wind turbine has not been fully analyzed (Dannemand Andersen, 2008).

In spite of the fact there have been increases in the use of materials, we have not reached the time where disposal of wind turbines is a major issue. However, manufacturing trends show that we are getting close to that time where it will be an issue (Larsen, 2009).

In order to look at future concerns, life-cycle assessment (LCA) is employed as a tool of analysis of environmental impacts. LCA will allow a comparison of different remanufacturing scenarios for wind turbines and their environmental benefits. For example, the remanufacturing alternative has been proven effective in other industries such as the automotive industry where it is as an economical and environmentally friendly option. Therefore, using LCA to study the remanufacturing option for wind turbines could demonstrate additional environmental benefits in the current growing wind energy industry.

Chapter I - Background

1.1 Product Retirement

Design is the most effective manner to influence the environmental impacts of a product (Graedel and Allenby, 1995). Therefore, if governments encourage a take-back program for wind turbine manufacturers, as it is done currently in Europe with electronics through the Waste Electrical and Electronic Equipment Directive (WEEE Directive), design engineers would be encouraged to come up with proper methods of product retirement. This is where the importance of Design for the Environment (DFE) comes into play. Ashby (2009) identifies the following approaches for product retirement:

- Reuse: A product is reused when a product has not completed its life-cycle and the user decides to stop its use, and a consumer sector is willing to accept it in its current use state, perhaps to its original purpose. The reasons to reuse a product can change from case to case. A user might substitute it for the same product of improved technology, the user could decide that the product does not serve his or her needs and see financial incentive in re-selling it, or the product does not meet the user's quality criteria and there is a consumer that would prefer to acquire the lower quality reused product.
- Remanufacture: is defined as the refurbishment or upgrading of the product or of recoverable components. Certain products have large parts with high material content which can be taken to the original standards by undergoing machining processes, and also have high-degradation sub-components which can be substituted for new ones. The product generally matches its intended service for several years or decades.
- Recycling: is a method to reprocess recovered materials at the end of the product life, returning them into the use stream. Those components that cannot be reused or remanufactured can be transformed into raw materials for a new product. The reprocessing tends to be an energy intensive process, so is economically feasible when large quantities of material are recovered.
- Combustion: is a way to capture the energy contained in materials to reuse it by controlled combustion. Materials with high energy content in places where energy or heat is expensive, tends to be used as fuel for electricity or heat generation. Combustion can be used when shortage of landfill space or the disposal of the materials by common methods can be harmful for the local environment, so by combustion the toxic components burned in a safe and controlled atmosphere.

- Landfill: is the placement of discarded products into designated spaces. Sometimes there is little value in recovering the materials, or it has not been put in place a proper supply chain program to recover those materials for other purposes. Space and materials limitation are good reasons to avoid landfilling.

The preferable product retirement option for a component depends on different factors. The recycling option can take materials back into the supply chain and can also be done at a similar rate in which the waste is generated. It generally uses less energy than obtaining the virgin raw material, but is not always cost-effective since it depends on how dispersed the materials are in the product and the quantities contained in them. For example, continuous-fiber composites is not economical and generally do not present a quality material for recycling. In general, these composites may only be employed as fillers or may only be added to certain amount of virgin material to be used for its original intent (Ashby, 2009). On the other hand, metals that are separated during recycling using magnetic and electric properties mostly have a high economic yield.

Wind turbines can be categorized as an industrial good and LCAs for wind turbines show that about 80% of the wind turbines may be recycled (Vestas, 2010). In terms of DFE, it means that at least this recyclability alternative can be employed.

Since the service provided by wind turbines is compromised if they are reused without complying with quality standards, wind turbines must be disposed using an economical and environmentally sound alternative. Recycling might not be the best alternative. Therefore, studying the remanufacturing for wind turbines could make this a possible alternative to dealing with wind turbine retirement.

1.2 Remanufacturing

Lund in 1996, described the size and scope of the remanufacturing industry. His study was motivated by the lack of information from this sector of the economy. A database was created that included 9903 American remanufacturers. The database provided a work platform to estimate economic data about the industry size. Lund’s results showed $53 Billion in annual sales and 730,000 direct jobs in the remanufacturing sector.

As a consequence of that study the Remanufacturing Industries Council was created, in order to give the necessary support to members of the sector. In addition, Lund’s study recommended an analysis

of the environmental benefits from this industry. In figure 1 is shows the number of jobs related and the economic value of the remanufacturing industry for several US industries.

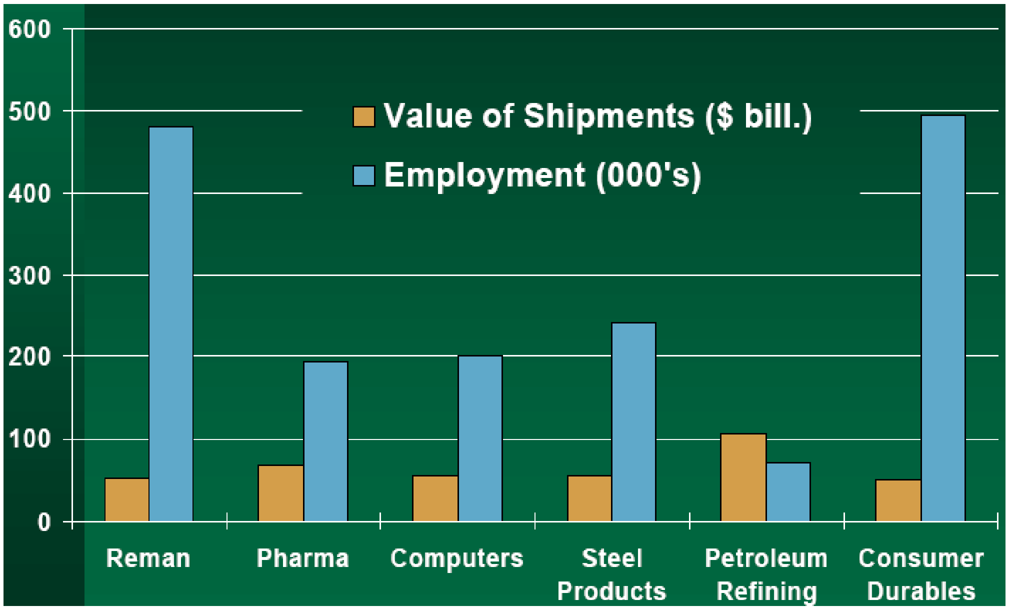


Figure 1. Comparison of remanufacturing industry with other major American industries. Lund, 1996.

Lund claimed that one of the benefits from remanufacturing was the preservation of a great percentage of the original product's value, while making possible a second life for the product. On the other hand, recycling only recovered the value of the material as other values were lost in the process. The monetary value of remanufactured products ranged from 45% to 65% compared to the original-new products. Remanufacturing also permitted segregation of hazardous products in order for them to be properly disposed of.

Lund's work made possible the identification of criteria for remanufacturing; those factors that influence remanufacturability are:

- Whether the technology to give a second life to the product exists.
- Whether or not the product fails functionality.
- The interchangeability of the product's parts.
- The cost of core being relatively low compared to reuse alternatives.
- The technology being stable for additional product life cycles.
- A sufficient market for the remanufactured products.

Description of the remanufacturing process follows.

1.2.1 Remanufacturing process

A product begins a remanufacturing process when a company claims the core, which is the part that offers the structure where most of the individual parts are attached in a product. Parts disassembled from the core are cleaned, inspected, and tested to explore a reuse scenario for them. Some parts are disposed of while others may be repaired. At the end, a remanufactured product must meet quality standards similar to the original product.

To perform the disassembly task, power tools or mechanical devices are employed since there is not an easy way to reverse operations like gluing, riveting, pressing and welding. Two additional steps include identifying parts and disposing of those not reconditionable or reusable. The disassembly process is more difficult than assembly since rust, oil and dust can increase disassembly time. Using robotics can be an option, if the batch sizes are enough to justify the economic investment, and the product contains a lot of screws. But damaged or non-original screws may slow down the process (Steinhilper, 1998).

Cleaning reconditionable or reusable parts is the next step. Many methods are employed such as using chemical products, water jet, water-soluble detergents, hot water and brushing. The state of the component is measured against defined criteria during inspection and sorting. During this process the component is subjected to equipment for measuring and detecting defects to test the part's condition under the given criteria.

Reconditioning implies restoring the material's proprieties and components to the original standard. As mostly metal removal processes after disassembly are used, geometrical dimensions can change. Therefore, it is necessary to use slightly larger replacement components to maintain the original tolerances. Surface treatments are a suitable option to make the product look like new. Then the product is reassembled with the original equipment that was employed to assemble the product the first time.

The factors that favor remanufacturing and the processes involved are well known and in use, but inhibiting conditions affect the application of remanufacturing in the mainstream of a product value chain.

1.2.1.1 Factors affecting remanufacturing industry

Factors that have to be addressed by the remanufacturing industry were summarized and detailed by Guide (2000).

- Uncertainty in the timing and the quantity of returns: factors like the life-cycle stage of a product and rate of technological change influence the planning for remanufacturing operations. Firms that use some core deposit system, leasing procedures and return policies have some control over availability of cores.
- Balancing returns with demands: this is crucial for a firm in order to maximize profits. So that there is no need to keep a cores inventory, or fall into lower levels of consumer service due to lack of available products, coordination among the functional areas is needed to properly balance cores and purchase of replacement parts. If this balance is done properly, staffing and scheduling improve.
- Disassembly: coordination with reassembly operations must be fully coordinated. The design for assembly is not necessarily a good design for disassembly. Lack of coordination may produce less predictable material recovery rates, higher disassembly times, and may generate more waste.
- Uncertainties in material recovery: high use of material recovery products (MRP) for remanufacturing systems and material recovery rate (MRR) data is part of MRP systems. It is often used to determine the size of the purchase lot and the remanufacturing lot sizes.
- Reverse logistics: product acquisition activities such as the selection of number and locations of take-back centers, incentives for product returns, transportation methods, and third-party providers are important to perform this process successfully.

In addition, Hammond, Amezquita, Bras (1998) mentions several issues concerning the remanufacturing industry:

- The misalignment between Original Equipment (OE) divisions on product design needs for remanufacturing, which results in ineffective efforts during remanufacturing and may produce failed business opportunities.

- The existing of lack of technical, environmental, and quality data within OE divisions fails to convince new customers to use remanufactured products.
- OE divisions tend to have a “mass production” mentality that does not fit well with the low volume remanufacturing requirements for replacement parts.
- Program managers frequently make belated decisions based on remanufacturing volume, due to the lack of well-defined remanufacturing business case analysis models.
- The lack of metrics to measure the impact of missed remanufacturing business opportunities.

Östlin et al. (2009) states:

“One competitive means for remanufacturing companies in this phase (introduction of a product) is to quickly develop and present remanufactured products to the market once a new type of product has been introduced”.

Östlin’s comment suggests that a remanufacturing strategy could increase availability of repair components for operating wind turbines, which could reduce the lead time after requesting a wind turbine or a part. In addition, to the economic and environmental benefits presented by remanufacturing. Therefore, the use of wind turbine remanufacturing or components might be beneficial for the industry and its clients.

1.3 Wind turbines

A machine that converts energy from the wind into kinetic energy is called a windmill. The first known horizontal axis windmills were installed in the Persian region 1,300 AD. They were in enclosed walls so that just one side would be in contact with the wind to drive it like a turbine. The original uses of these windmills were to grind corn, pump water and crush sugar cane (Hassan and Hill, 1986). Windmills were employed to drain the Rhine River delta in the Netherlands during the 14th century. Later in 1887 James Blyth built the first windmill for electric generation in Scotland (Oxford DNB, 2010).

When wind is converted into electricity the device is called a wind turbine. Two categories of wind turbine designs are vertical-axis wind turbines (VAWT) and horizontal-axis wind turbines (HAWT). The latter one is the common design for a utility scale (AWEA, 2010) and is the one studied in this thesis.

A HAWT is a machine composed of a rotor with wing shaped blades, united to a hub. The nacelle is a housing which contains the drive train of the wind turbine; the drive train consists of a gearbox,

shafts, bearings, and generator. These parts are supported by the tower and base or foundation. In general, the components of a wind turbine can be found as is shown in Figure 2.

Figure 2. Parts of a wind turbine. Windmillsusa.com

Ancona and McVeigh (1999) described the materials generally employed in wind turbines. The materials for these machines were diverse, and Ancona and McVeigh expected new materials technologies and manufacturing methods to be introduced. Materials estimated to be used in small and large turbines are shown in Table 1. The total shown by Ancona and McVeigh was obtained by weighing the estimated market share of various manufacturers and machine types.

Large Turbines and *(Small Turbines*[1])

Component/ Material (% by weight)	Permanent Magnetic Materials	Pre-stressed Concrete	Steel	Aluminum	Copper	Glass Reinforced Plastic [4]	Wood Epoxy [4]	Carbon Filament Reinforced Plastic [4]
Rotor								
Hub			*(95)* - 100	*(5)*				
Blades			5			95	*(95)*	*(95)*
Nacelle [2]	*(17)*		*(65)* - 80	3 - 4	14	1 - *(2)*		
Gearbox [3]			98 -*(100)*	*(0)* - 2	*(<1)* - 2			
Generator	*(50)*		*(20)* - 65		*(30)* - 35			
Frame, Machinery & Shell			85 - *(74)*	9 - *(50)*	4 - *(12)*	3 - *(5)*		
Tower		2	98	*(2)*				

Notes:
1. Small turbines with rated power less than 100 kW- (listed in italics where different)
2. Assumes nacelle is 1/3 gearbox, 1/3 generator and 1/3 frame & machinery
3. Approximately half of the small turbine market (measured in MW) is direct drive with no gearbox
4. Rotor blades are either glass reinforced plastic, wood-epoxy or injection molded plastic with carbon fibers

Table 1. Wind Turbine - Materials and Manufacturing Fact Sheet. Ancona and McVeigh,1999.

As it can be seen in Figure 3, Ancona and McVeigh also projected the overall annual materials quantity usage trend over two periods, 2001-2005 and 2006 – 2010. This projection shows that the use of steel, copper, glass reinforced plastic (GRP), permanent magnet materials, and concrete will increase in the future.

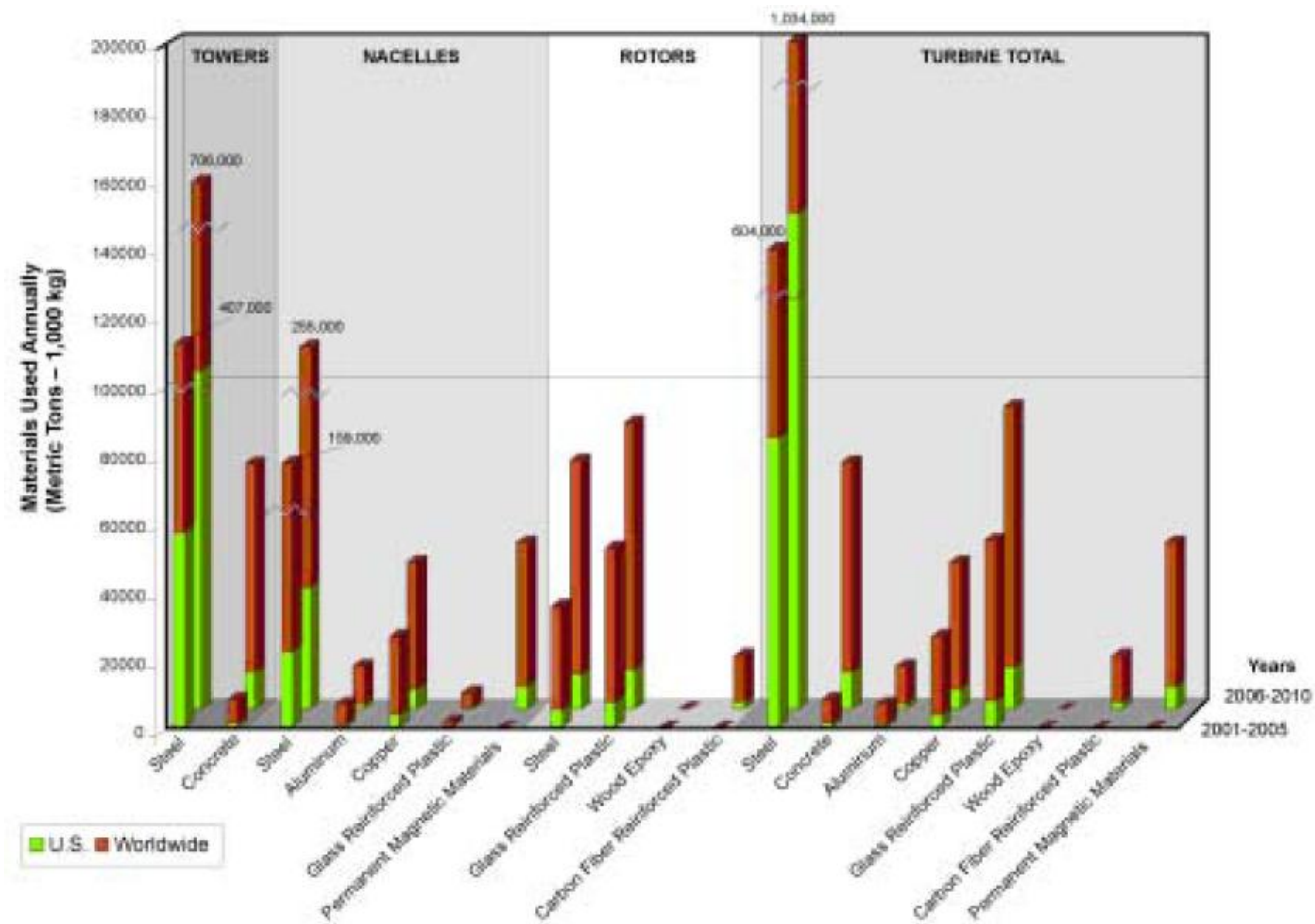


Figure 3. Projected materials quantity use trend for each wind turbine section. Ancona D, McVeigh J, 2000.

The annual projected use of materials for the manufacturing of wind turbines shows large quantities of resources employed. It is important to understand the overall environmental benefits of this technology, not only from the positive impact in the reduction of Green House Gases (GHG) but over the demand for virgin materials, even though wind turbines provide a clean energy service. System components and their current retirement strategy are described in the following section.

1.3.1 Blades

Blades consist of reinforced fibers, the most common of which is glass fiber. Carbon fiber is also an option for designers looking for reinforced fibers, but as this is a more expensive option, it is less likely to be used. Plastic polymers such as polyester are also employed, as are other materials such as

PVC, PET and balsa wood. Holmes, Brøndsted and Sørensen in 2009 studied the possibility of using Bamboo as a rotor blade material (RISØ DTK, 2010).

Between 1990 and 1995, several German authors studied recyclability for blades (Lenzen, Munksgaard, 2002), finding there were technical problems on the separation of fiber glass, epoxy resin and PVC contained in rotor blades. The resulting low quality recycled plastic was only useful as filler material. Today the problem remains.

Larsen (2009) identifies landfilling, incineration, recycling and less commonly, reuse, as methods used to dispose of wind turbine blades. He argues that land filling is not an option in the future as countries pass legislation to decrease the amount of space available for it. For example in 2005, Germany prohibited GRP in landfill due to its high organic content (Canadian Plastic Industry Association).

Incineration using combined heat and power plants (CHP) that convert the material into electricity would leave 60% of the scrap as ashes (Larsen, 2009). Ashes, however, could be a source of contamination due to the presence of inorganic compounds; in addition there is the danger of emission of hazardous gases. Finally, in order to be incinerated, there is the additional process to convert the blades into small pieces by shredding before incineration.

The recycling option is a less likely end-of-life option as just 30% of fiber reinforced plastic (FRP) can be used again as a new blade composite. In most cases, the FRP ends up as filler material. REACT project (2003) addressed the mechanical recycling of FRP by shredding blades while monitoring the Volatile Organic Compounds (VOC). Then the fiber was upgraded using chemical bonding. A positive claim from this project was the possible applications of recycled FRP. But two disadvantages were the energy used for shredding the material compared to the low cost of FRP and the final quality of the recycled blade.

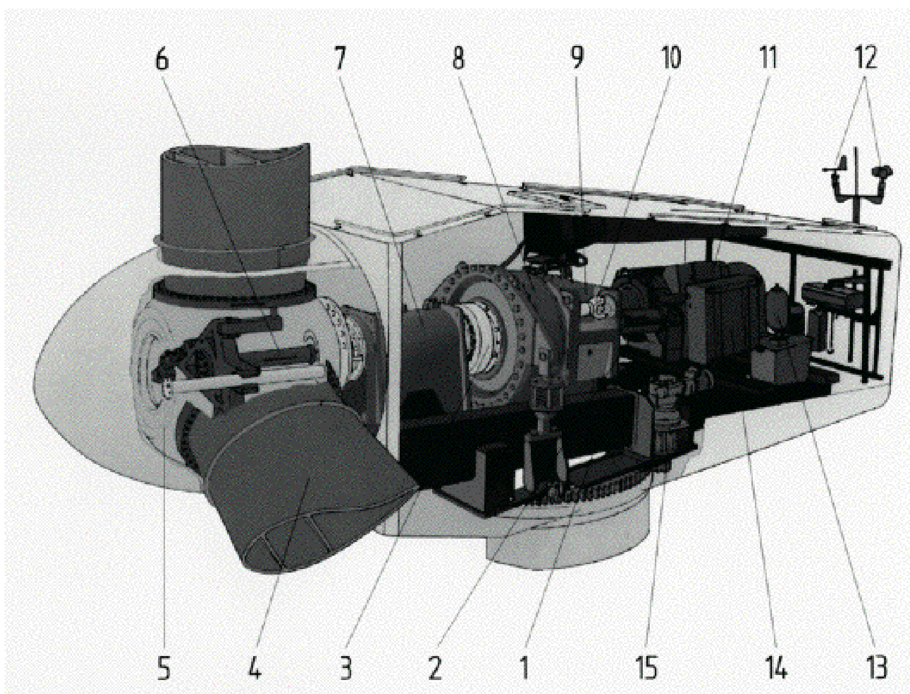
A Danish company ReFiber ApS (2007) is also involved in the study of possibilities in reclaiming the material from blades, but in the form of a chemical process called Solvolysis. This process keeps the tensile strength of the composite without requiring vast amounts of energy. The down side of Solvolysis is that hazardous chemicals are used which make the process expensive.

According to ReFiber ApS the best option to deal with the material at the end-of-life of the blade is pyrolysis and gasification. In this process, heat is recovered for electricity generation and the final product is a thermo-resistant material used for different purposes.

According to the wind turbine service company Energy Maintenance Service (EMS) the blades remanufacturing process consists of the following: the rotor blades integrity is checked by performing a deflection test. The roots (where the connection between blades and hub takes place) are closely inspected with particular emphasis on checking for de-lamination of the root bundles. The aerodynamic brake tip mechanisms are inspected and metal parts replaced if wear is present. All surface cracks and blemishes are repaired. Finally, the blades are then weighed and fully balanced prior to installation.

1.3.2 Nacelle

The Nacelle is a structure in which the powertrain system is mounted. A cast nacelle bedplate with a non-load bearing fairing is found in modern wind turbine nacelles. The non-load bearing fairing structure can be made of aluminum or steel sheet. Laminated glass-fiber reinforced composite is also employed. The components placed inside the nacelle can be seen on figure 4.



1. Nacelle bedplate	6. Blade pitch mechanism	11. Generator
2. Blade pitch actuator	7. Rotor main bearings	12. Wind measuring system
3. Rotor shaft	8. Gearbox	13. Hydraulic supply system
4. Rotor blades	9. Rotor brake	14. Electrical control system
5. Rotor hub	10. Generator drive shaft	15. Yaw drive

Figure 4. Powertrain system of a Vestas V-39. Erdmann, N.: Offshore-Windenergieanlage Multibrid M500, Erneuerbare Energien, 10/2004

To define where to assemble and how to transport the nacelle, the size of the rotor blades and the weight of the nacelle are considered. Nacelles for wind turbines with a rotor diameter up to 80m can still be assembled in the factory and transported to the place of operation. Prospective designs heavier than 300 tons for 5MW wind turbines would need to be assembled on site.

1.3.3 Hub

The hub is the spherical structure where the rotor blades are mounted. Hubs are mainly made from cast steel. Welded sheet steel and forged steel were used in the past. Welded sheet steel was not a good solution because of low resistance to metal fatigue. Forged steel was not economically viable due to high cost. Therefore, through the development of better materials it was found that under the dynamic conditions that wind turbines are exposed to, and to lower the cost, cast steel was the right material for this component (Hau, 2006).

The cast steel in a hub used as a structural component, and under certain inspection criteria, can be reused or remanufactured. If the inspected cast steel hub has considerable damage and does not comply with quality standards only then must it be recycled or disposed of.

1.3.4 Blade pitch mechanism

The blade pitch mechanism has two functions which are to control the power and speed of the rotor by adjusting the blade pitch angle, and to aerodynamically brake the rotor. The components of this mechanism are:

- The rotor blade bearings make it possible for blades to turn around their longitudinal axis. These bearings are exposed to high static loads. Despite the fact that these rotor blade bearings are designed to last 20 years, experience has shown that sometimes there are premature failures. As a result, conventional frictional bearings have recently been replaced with plastic-coated friction surface bearings. These bearings made of Teflon, synthetic-resin adhesive, and reinforcing fibers are said to be maintenance free.

- Blade pitching drives substituting for hydraulic pitching systems with an electric system controlled by a compact drive are the current preferred option for manufacturers. Batteries offer the power supply for this system.
- Emergency brake pitching systems: This system is composed of vibration sensors and centrifugal switches.

An exhaustive inspection is done to the mechanism to explore end-of-life scenarios. Depending on the result of the inspection the blade pitch mechanism may be reusable. If the wind turbine is suitable for remanufacturing, replacement of rotor blade bearings is recommended, and the blade pitching drive and emergency brake system with newer technology (Eliason, 2010). Wind turbines that use a fixed-pitch mechanism are updated with microprocessor-based controllers for modernized operation (Halus Energy System, 2010). Any defective components may be recycled when parts do not comply with remanufacturing quality standards.

1.3.5 Rotor shaft system

The rotor shaft is a forged heavy component that transmits mechanical rotation from the rotor blades to the gearbox. Roller bearings maintain the rotor shaft in static position while only allowing its rotation. The rotor shaft system permits the gearbox to absorb only torque loads. Trade-offs in rotor shaft and bearing configurations depend on how compact the designers want the system to be. The goal is to transmit loads by the shortest path to the tower while making the system easy to repair and maintain.

The traditional solution is configured as a floating shaft on a bedplate with two separated bearings; this configuration permits the use of standard gearboxes and bearings. The preferable rotor shaft system for big wind turbines has a three-point suspension of a rotor and gearbox. It is preferable because the distance between the bearings is shorter, and also because the heavy load carrying part of the bedplate is concentrated. Other good configurations integrate the main bearing into the nacelle structure to reduce weight, or to cast the shaft to the tower flange (Hau, 2006).

Rotor shafts may be reusable if certain standards are met. But, the most common practice is to remanufacture them. Recycling is performed only if the component has major damage. The remanufacturing process for bearings begins with cleaning, inspecting and measuring them to determine if

they comply with Original Equipment Manufacturers (OEM) standards in order to be reused. Otherwise, the safest approach for bearings is to replace them (Eliason, 2010).

1.3.6 Bedplate

The bedplate carries the drive train components and should transmit rotor forces to the tower. Bedplates with welded steel frames and longitudinal and cross beams tend to be very heavy given the required stiffness for this component (Hau, 2006).

Being a structural component, it does not wear as much as rotating parts. Hence, the bedplate is very likely to be inspected, repainted and finally reused (Eliason, 2010). Otherwise, the bedplate undergoes mechanical and chemical surface preparation prior to coating application (FESCO Direct, 2010). Nevertheless, the recycling alternative remains since the bedplates are made with a substantial amount of steel which has recycling value.

1.3.7 Rotor brake

The rotor brake is a common disk brake which stops the system to allow servicing a wind turbine or for emergency stops under high wind conditions. It is engineered to handle the large output torque generated by the high ratios found in wind-turbine gearboxes. For large wind turbines the rotor brake works only as a parking brake in the high speed side between the gearbox and generator (Dvorak, 2010).

Because rotor brakes do not get a great amount of use, after inspection it’s possible to reuse or remanufacture them. Rotor brakes can also be recycled since they are made from ductile cast iron, which is also a high demand recyclable material.

1.3.8 Gearbox

A gearbox is a machine mainly made of quality aluminum alloys, cast iron and stainless steel that allows the conversion of a certain number of revolutions per minute delivered by the rotor blades to a higher number, which then will be delivered to the generator.

The search for the best gearbox configuration for a given wind turbine has been a difficult task in the past for engineers due to not being able to establish an accurate load range. Now with the current

experience, designers have achieved the proper dimensions for different wind conditions. For small wind turbines, a two-stage parallel-shaft gearbox is commonly used. But as general rule for the class up to 500kW, the parallel-shaft gear type is preferred for low costs. The megawatt power wind turbine class employs a three-stage planetary design which uses only a fifth of the overall mass of the parallel-shaft; consequently it is less expensive than other gearbox (Hau, 2006).

In some cases a gearbox can be reusable, but that is not a common practice. Therefore, remanufacturing or recycling is the preferable end-of-life outcome for gearboxes. The procedure of gearbox remanufacturing consists of an inspection of all components. Remanufacturers replace high speed and intermediate bearings, inspect teeth, and replace it if deterioration is detected. Tolerances are all checked. Oil filters, seals and oils are replaced (FESCO Direct, 2010). In order to secure long-lasting gearbox teeth, proper lubrication, and stiffness for the gearbox housing is needed.

The next step in gearbox technology is actually not to use a gearbox at all. Companies such as Siemens and GE are testing gearless wind turbines. The way this system works is by having synchronous generators excited by permanent magnets, which directly transform the blades' rotational movement into electricity. Despite the fact that this is a more expensive system, it provides savings in maintenance and service in the long term. Since the gearbox is the most expensive component in the maintenance of a wind turbine, its elimination is considered as an advantage from a cost and environmental perspective.

1.3.9 Electric generator

The electric generator is used to convert the mechanical movement transmitted by the gearbox into electric power. Currently the variable-speed electric generator with frequency converter is the most common configuration used for generators. In order to avoid deformations in the drive train due to transmission vibrations, flexible connection between the gearbox and the electric generator ought to be provided. In addition, some clearance is needed between the back of the gearbox and the front of the generator. A proper water or air cooling system is necessary to protect generators and elastomeric bearings supporting the generator to the nacelle's bedplate. These factors permit better generator performance.

Following the recommended operational conditions by the manufacturers, electrical generators tend to remain in use if they do not suffer important wearing by hot summer winds, causing rapid

deterioration of bearings and insulation. The remanufacturing option for a generator is carried out by rewinding the generator, replacing bearings and thermal protection (FESCO Direct, 2010), balancing dynamically the rotor, sandblasting the stator and end bells, cleaning all parts and applying coating (FESCO Direct, 2010). Since the preferred materials for electric generators are copper for the coil and cast iron for the housing they are considered valuable in case of recycling.

1.3.10 Yaw system

The function of this system is to automatically position the blades into the wind. Some parts of this system are integrated into the nacelle and others to the tower head. The main components for the yaw system are the azimuth bearing or yaw bearing, and the yaw drive. Figure 5 shows the parts of a yaw system.

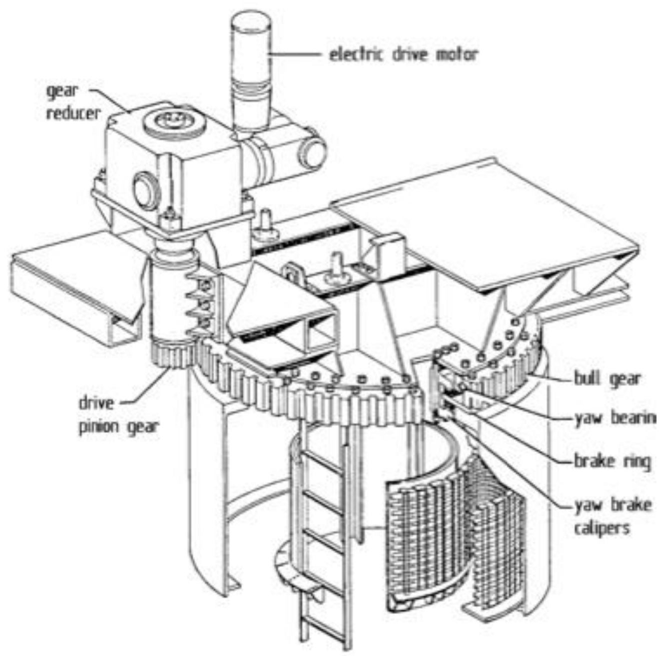


Figure 5. Structure of a Yaw system. Hau, 2006.

The yaw bearing has two functions. First it permits easy running of the system and secondly yaw damping eliminates yawing oscillations. These two functions can be obtained either by a roller bearing (generally a four-point ball bearing), or a frictional bearing which doesn't require a yaw brake or brake rings.

There are two options for the yaw drive: electrical and hydraulic. In current practice the electrical yaw drive has been replacing the hydraulic option in which the yaw brake is integrated. The yaw brake is used to avoid drive motors from absorbing the yawing moment. Two or three electric yaw drives are used for larger wind turbines.

Full inspections in many cases determine if yaw bearings can either be reused or remanufactured (Eliason, 2010). But in general, yaw components can be remanufactured. Recycling is also a valid option due to metallic materials present.

1.3.11 Towers

Towers constitute between 10% and 20% of the cost for wind turbines (Hau, 2006). Materials available for the construction of towers are steel or concrete. Designs range from lattice constructions to guyed or free-standing steel tubular towers up to massive concrete structures. The common way to build towers is to use free-standing tubular towers. There are some reasons for this preference as it takes less time to raise a tubular tower. It is easier to build this kind of tower on-site and another benefit is that the price of steel has been low in recent years.

Towers up to 20m tall are commonly made in one piece by the manufacturer and later bolted to the foundation on site. Towers with heights up to 100m are bolted together in several sections to avoid welding (Hau, 2006).

Towers are made to be conical as this shape decreases the mass for a required stiffness. Towers consist of a number of prefabricated sections with a length of up to about 30 m. The sections are produced from sheets of steel plate with a thickness of 1-5 mm. The sheets, which have a width of about 2 m, are rolled into a circular shape on a rolling stand. From these segments, the tower section is welded together. In most cases, automatic welders are used for this. The welding requires special attention in view of the loading situation of the tower. The quality is checked by means of the usual methods such as ultrasonics, X-rays and examination for surface cracks. The tower sheets consist of commercially available St52 grade structural steel plate, and more rarely, St48. Higher-strength material is used for most of the forged joining flanges and the foundation section (Hau, 2006).

Blasting is employed as a surface treatment for the tower; chiefly zinc coating is thermally applied and then at least three layers of paint are applied. Other components such as cables, control and supervisory systems, and ladders are placed inside the tower's structure. Towers are inspected and painted to the customized color so that they can be reused. Otherwise, depending on the material towers could be landfilled for concrete towers, and recycled for steel towers.

1.3.12 Foundation

Foundations are the concrete structures that support the towers and the wind turbine mechanism. When slab foundations are employed, rather than pile foundations, the steel tubular structure is anchored by a foundation section joined to the steel reinforcement of the concrete (Hau, 2006). After a wind turbine is decommissioned foundations are generally not removed from the site and are covered with sand and grass, since there is no value in recovering the material. Each state has its own regulations in this matter. For instance, New York State requires the removal of the foundation to restore the site to its original state (NYSERDA).

After looking at the parts of wind turbines, and dealing with their end-of-life, it is clear that the remanufacturing option is available for most of wind turbine parts, especially those located inside the nacelle.

1.4 LCA

The EPA defines LCA as a technique to assess the environmental aspects and potential impacts associated with a product, process, or service, by:

- Compiling an inventory of relevant energy and material inputs and environmental releases.
- Evaluating the potential environmental impacts associated with identified inputs and releases.
- Interpreting the results to help make a more informed decision.

LCA is a pollution prevention strategy used to evaluate the potential environmental damages from the inputs and outputs of a product. The evaluation begins with the extraction of the raw materials

employed for the product's manufacture, continues through manufacture, transport and use phases, and ends at the disposal of the product. The inputs and outputs of the LCA are resources like materials, chemicals and energy which are taken from or put back either from the environment or from another industrial process. LCA provides a comprehensive view of the environmental trade-offs in product and process selection.

To carry out an LCA for a product, five stages of a product's life-cycle are analyzed:

- Premanufacturing: performed by suppliers who extract in most cases virgin materials employed for manufacture.
- Manufacturing: processes related to the transformation of the virgin materials into usable products.
- Product delivery: the transport of the product to the customer.
- Use: the intensity and frequency of the use of the product.
- Disposal: a product that is no longer needed could be reused or remanufactured to use it once again, recycled or incinerated if materials permit, or landfilled.

1.4.1 LCA framework

A general agreement on the formal structure of an LCA is given by a goal and scope definition, inventory analysis, impact analysis, and finally the interpretation of results; all described as follows:

- Determining the goal and scope is the most critical step in an LCA. It evaluates what materials and processes are to be considered. The goal and scope identifies characteristics, limitations, and the breadth of the study. Factors to consider are the amount of control the person doing the study will have over the implementation, the resources and information available to perform the study. It is important to know how limited the scope can be that may provide adequate results. The functional unit, which is the quantifiable and comparable measure of a service provided by a product, plays an important role in the definition of the goal and scope.

- Inventory analysis establishes the quantities and types of materials and energy input to an industrial system, and the product output and environmental releases that result. This is done over the entire life-cycle of a product.

- Impact analysis relates the outputs of the system to the impacts on the external world into which those outputs flow.
- Interpretation is used to discuss conclusions and recommendations about how to reduce environmental impacts from the results of the other three stages.

1.4.2 LCA limitations

- The availability of data can make an LCA a time consuming activity, and industries reserve information in order to avoid comparison between their products and competitors
- There is usually not a definitive conclusion if a product is better than others using an LCA, since some products perform better than others in certain aspects of their life-cycle
- How an LCA allocates the positive impacts of recycling has been criticized (Danish Toxicology Center, 2005)
- Uncertainties also exist in the allocation procedure for recycling in ISO 14040 standards regarding degradation of recycled materials

For the time being, LCA is a complex and difficult procedure to substantiate positive recycling impacts, especially regarding reuse and remanufacturing (Koltun, 2010). LCAs are performed using specialized software, such as SimaPro.

1.4.3 SimaPro

SimaPro is a LCA software tool used to analyze the environmental impacts of products following ISO 14040 guidelines. SimaPro allows the quantification of the burden carried at each stage of a product life-cycle. SimaPro is a convenient tool because it makes a complex analysis such as an LCA, into a more straightforward analysis. Results can be displayed on one process tree window tracing back results to their origins.

Chapter II - Literature review

Previous studies in life-cycle analysis, with its associated end-of-life stage for wind turbines and remanufacturing strategies are listed below:

2.1 LCA

Created in the 1970's, LCA has become an environmental performance tool widely employed for product manufacturers. But in the last 15 years the use and importance of LCA has increased for interested parties. In parallel, wind turbine production world-wide has sky rocketed making the use of LCA for a wind turbine a very recent alternative for analysis of environmental impacts.

One of the first life-cycle analyses from an energy point of view on wind turbines was provided by Pernkoft (1991). Pernkoft demonstrated that for a 30 KW wind turbine the exchange of rotor blades, pitch control, hub, bearings, cogs, hydraulics and cables, required only 20% of the total energy requirement of manufacturing a new wind turbine. He was in favor of complete recycling from an energy point of view.

Hassing (2001) provided one of the most important LCA studies on offshore wind turbines, in this case, for several 2MW offshore Vestas wind turbines placed on Horns Rev in the North Sea. The study revealed that the production and disposal phase have the most environmental impact, especially with the use of normal and high-strength steel for the nacelle and foundation as most of the wind turbine weight was concentrated there.

"The disposal scenario is very important for the environmental profile of a wind turbine".

On the same study, Dong Energy Company (2002) remarked on the importance of recycling the materials when scrapping the wind turbine.

One of the sources of criticism on the use of LCA for wind turbines, is the variability of results. Motivated for that reason, Lenzen and Munksgaard (2002) compared 72 different wind turbine life-cycle assessments to identify the source of variation in results. They concluded that despite the fact that wind systems were similar over different models, discrepancies existed in the energy contents of materials and in the methodologies and scope. Other factors for the differences among the LCAs were country of manufacture, turbine end-of-life strategy, tower material employed, and CO2 variations due to fuel mix

by country. This study suggested the solution for a decrease in variations would be a standardized methodology and the use of input-output-based hybrid techniques.

Lenzen and Muskgaard (2002) cited Domrös (1992) about concrete foundations. Domrös claimed that recycling the concrete foundations did not significantly affect the energy balance given that transport and processing were energy-intensive. On the other hand, conventional recycling of copper, steel, and aluminum in metal works represented a considerable energy gain.

Component	Main material	Relative mass (%) μ_t	Energy content (MJ/kg) $\varepsilon_i \pm \Delta\varepsilon_i$	Rel. energy req. (%) $e_i \pm \Delta e_i$
Blades	Glass fibre, epoxy, PVC	2.7	61.8±35.7	8.7±5.5
Hub and mounting	Steel	3.5	36.8±18.5	6.5±3.7
Transmission	Steel	5.2	36.8±18.5	9.7±5.5
Generator	Copper	2.6	86.2±65.5	11.5±9.2
Nacelle cover	Glass fibre	0.3	61.8±35.7	0.9±0.5
Tower	Steel	23.3	36.8±18.5	43.6±24.7
Foundations	Concrete	60.3	3.2±1.9	9.8±6.4
Electrical	Copper	2.1	86.2±65.5	9.4±7.5

Table 2. Summary of results from process analyses of HAWT. Lenzen and Muskgaard (2002).

Some of the results of Lenzen and Muskgaard (2002) are displayed in Table 2. The heaviest components were the foundation and tower accounting for 84% of the total mass. On the other hand, the generator and tower were the most energy intensive parts of the wind turbines analyzed for reprocessing.

The uncertainty about the future removal and recycling processes of wind turbines was first addressed using foresight techniques to develop technologies and life cycle assessment methods applied to offshore wind turbines (Andersen, Borup, and Krogh, 2007). The first part of this work wasn't published as a formal paper until 2007; the removal phase still is a problem no one has fully addressed so far. The group states:

"The removal phase of the life cycle of wind turbines has been identified as a blind spot in the analyses of the environmental impacts of wind-power systems".

Furthermore, there is not enough practical experience in removal and recycling such devices, especially when referring to the recent phenomenon of offshore wind turbines. The case study presented by Andersen P, Borup M, and Krogh exchanged knowledge between the design and removal phase in a Danish context.

Weinzettel, Reenaas, Solli, and Hertwich (2008) compared existing LCA studies of onshore and floating offshore wind power, because offshore wind turbines required more steel and concrete than onshore systems, and it is required the use of rigs, ships and helicopters for installation and maintenance. The team concluded there was a similar impact on power generation from floating offshore systems compared to onshore wind turbines. The production stage had the greatest impact on a wind turbine life cycle. Finally, a recycling strategy at the materials' end-of-life provided significant credits at the disposal phase (Weinzettel, Reenaas, Solli, and Hertwich, 2008).

Using data from Gamesa, Risø National Laboratory and SimaPro database, Martınez et all (2008) analyzed the whole impact of a 2 MW Gamesa onshore wind turbine model GX8 using an LCA. The functional unit 1 kW of electricity produced was selected, using Eco-Indicator 99 as methodology. The researchers did not include the connection components to the grid in the LCA analysis. The components included in the life cycle inventory were base, tower, rotor and nacelle. Figure 6 shows the flow diagram by Martinez et al.

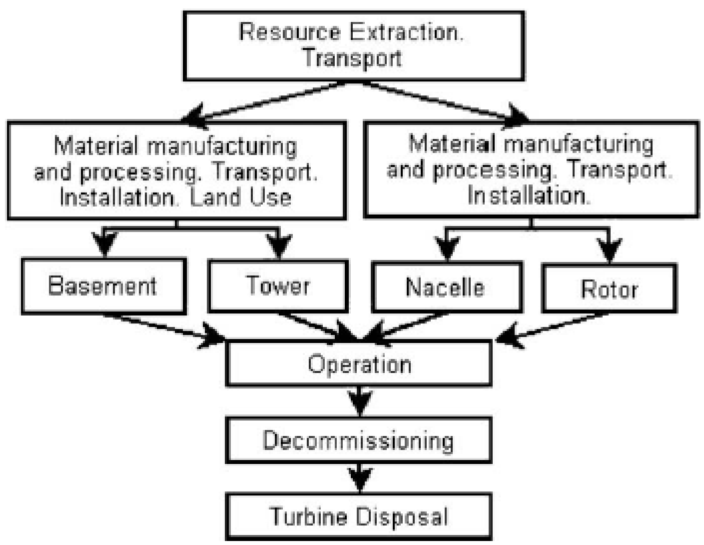


Figure 6. Wind turbine LCA model. E. Martınez, F. Sanz, S. Pellegrini, E. Jimenez, J. Blanco., 2008

Their results showed that the foundation affects the environment the most, and they recommended looking closely at the recycling and reuse alternatives for cement. Because steel is a fully recyclable material, they recommended keeping the use of it for towers. Most of the nacelle's components impact came from the use of copper, so they recommended the reduction of the amount of copper used or a change to other materials with similar characteristics.

2.2 Remanufacturing

In 1998, Guide compiled studies related to remanufacturing in areas such as forecasting, reverse logistics, production planning and control, inventory control and management, and general descriptions of remanufacturing. He concludes that production planning and control activities were complex for the remanufacturing industry given the stochastic behaviour on product return, imbalances in return and demand rates, and the unknown conditions of products returned.

Some academics believed that a closed-loop supply chain would provide a win-win strategy in terms of profits and the environment, Jackson (2004). Others have questioned this perspective, Westkamper, Feldman, Reinhart, Seliger (1997). To obtain a better picture, Seitz (2007) questioned if the usual reasons that motivate product recovery such as economics, ethics, moral responsibility, and environmental legislation could be applied to automotive engines. Based on more than 130 interviews across five case companies the study showed that none of the above seemed to be an important reason for OEMs to establish remanufacturing programs. An availability of spare parts and under-warranty engines, market share, brand protection, and customer orientation turned out to be more significant reasons for the recovery of old engines. The conclusion of this study can be applied to the wind turbine industry because the lead times on waiting for spare parts can be reduced using remanufactured parts.

An example on how remanufacturing efforts can reduce the CO_2 emissions over the several life-cycle of products is shown in the work by Sutherland et al (2008). They compared CO_2 emissions between the manufacture and remanufacture strategy for diesel engines. They provided a model for both strategies on energy requirements per use cycle for a given number of cores and use cycles. Using this model they found that increases in efficiency of core remanufacturability could significantly reduce energy consumption per part over multiple cycles.

Östlin et al. (2009) using product life-cycle theory and relying on empirical data from several case studies, investigated how to achieve the balance of demand for remanufacturing products with the rate of products return. Figure 7 provides the relationship between core quality and money paid according to the product recovery option for a forklift truck case.

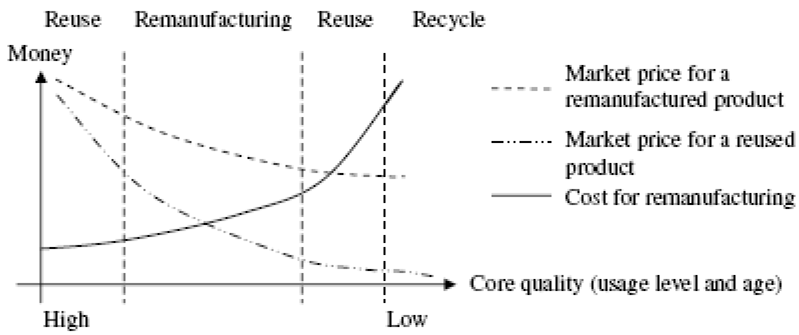


Figure 7. Economical preference of product recovery option as a function of the core quality. 0stlin et all, 2009.

Among the conclusions of this study was the fact that there existed a breakpoint where the supply of cores was greater than the demand for remanufactured products. Another conclusion that could lead to an increase in the potential remanufacturing volume was to upgrade products to the latest trends. The development of methods to predict the returns of cores was also important. Finally the studies showed that leased products gave the security that the product would return at a specific time and price.

The availability of enough wind turbines for remanufacturing has to be considered in order to have an economically stable wind turbine remanufacturing industry. The countries where most of the wind turbines were installed during the 1990s and 2000s are Germany, Spain, Denmark, and the US, meaning that most of those wind turbines have been in operation for 10 years or more and some of them have reached the end of their useful life. The most common type of wind turbines after the 1990s are the small scale-commercial class (CRR, 2008) making this type of wind turbines available today for a remanufacturing process. Another reason for the availability of potential remanufacturable wind turbines is the incentives provided mainly by the German, Danish and Spanish governments to upgrade the existing wind generation to encourage the installation of distributed wind energy for small communities. The best on-shore sites for wind energy were taken by wind turbines installed 20 years ago. As a result, old wind turbines are being decommissioned since those incentives target newer, more efficient machines to be placed on those good wind areas. But the question that remains is: what to do with the old wind turbines? Remanufacturing can provide an answer.

The decommissioned machines have the potential to be remanufactured as new in order to be installed in areas where there is poor access to the electric grid. The fact that the remanufactured

equipment tends to be small sized-commercial wind turbines makes them a perfect fit for small towns (CRR, 2008).

LCA studies have not addressed the remanufacturing alternative for the wind turbine industry, since the predominant end-of-life scenario for wind turbine is recycling. Therefore, the objective of this study is to provide knowledge for the environmental impacts of the remanufacturing end-of-life scenario for wind turbines.

Chapter III - Problem Statement and Research Questions

The end-of-life options for modern wind turbines have not been fully addressed by the manufacturers. The retirement options for wind turbines should be an important part of the design criteria used by engineers, given the size, and amount of material and energy invested in manufacturing these machines. Hence, in order to reduce negative environmental impacts from the disposal of wind turbines while maximizing economic benefits for this industry, criteria to provide multiple life-cycles for wind turbine parts, to reduce material exploitation, to decrease pollution by manufactured by-products and to minimize landfill disposal have to be obtained by means of LCA analysis. The intention of this work is to help inform original equipment manufacturers (OEMs) and the wind remanufacturing industry regarding the suitability of a remanufacturing end-of-life option for wind turbines.

While some authors have analyzed the environmental impact of wind turbines relying on LCAs, none has explored the remanufacturing alternative after the wind turbine has completed its useful life. Furthermore, experts have agreed that there was not enough experience in the recovery of modern wind turbine materials. Additionally, there has not been a study that considered remanufacturing as an important end-of-life alternative for wind turbines.

With the increase in the number and size of these turbines, it is crucial to lessen their environmental impact and to obtain economic benefits from the disposal stage by integrating proper end-of-life strategies into the wind turbine design. The task is to obtain the most environmental and efficient process for the use of the components at the end-of-life of the wind turbine.

Currently, wind turbine designers are focused on delivering bigger, lighter and more durable blades, which can generate more energy, more efficiently. One measure of the energy produced by a wind turbine has been to use the capacity factor, defined as the ratio of output power over a period of time and the peak power during the same period. Nowadays, the achievable capacity factor ranges between 20% and 40%.

Designers are hoping to achieve close to a 59.3% capacity factor by using new materials and processes for the manufacture of wind blades for the 20 years life span of the machines. During the process of achieving greater capacity factors, it is important to avoid environmentally negative impacts. If by reaching capacity objectives, engineers do not take into consideration the end-of-life of those massive

machines, then employing the capacity factor-focused technology would lead to other environmental problems during the disposal phase.

Any future design considering the capacity factor and the end-of-life phase of the wind turbine will lead to trade-offs. However, merely delivering bigger wind turbines adds more stress on the world-wide requirement for virgin materials, energy use and toxic wastes in manufacturing processes, energy consumption and GHG releases in transportation of bigger components, and greater requirements for landfill sites. All these factors reaffirm that reuse, remanufacturing, or recycling must be employed as possible end-of-life scenarios.

The idea of this work is to ensure that the trade-off decisions are made in the right framework so that wind turbine developers analyze the benefits of employing a new wind turbine over a remanufactured model. This study addresses the following questions:

In terms of impact assessment, what would be the best environmental retirement strategy for conventional wind turbine components?

What are the environmental impacts of remanufacturing a wind turbine and transporting it to another Continent compared to the total environmental impacts from manufacturing a new wind turbine?

What are the factors that contribute to a successful remanufacturing process for wind turbines?

Chapter IV - Research methodology

4.1 Overview of the study

This study is based on a comparison/contrast of the life-cycle assessments for a wind turbine using the typical materials for manufacturing, versus a wind turbine undergoing remanufacturing. LCAs permit us to understand the relevant environmental impacts of a particular product through its life-cycle.

The use of SimaPro software is a key element in comparing if a remanufacturing scenario for wind turbines has fewer impacts compared to a manufacturing scenario from an environmental perspective. Therefore, understanding both options from the point of view of materials and processes will make possible the comparison between them. One of the objectives is to characterize the greatest contributing factors from the remanufacturing option.

The analysis begins with choosing the parts to analyze inside the nacelle of a V80 2.0 wind turbine. The manufacturing process of a new wind turbine is explained, describing those elements that can be used to complete a remanufacturing process, the transportation for the assembly plant for both options, and finally the processes and inputs involved in remanufacturing the components inside the nacelle. Afterwards, the LCA is performed for the manufacturing and for the different remanufacturing scenarios. Finally, a sensitivity analysis of the results is performed to understand the impact of variations in the scoring systems.

4.2 Methodology

In order to perform a LCA to compare a manufacturing versus a remanufacturing approach, the following steps are needed:

4.2.1Goal and Scope

The objective of the LCA is to analyze the environmental impacts of wind turbines. A conventional LCA for a wind turbine analyzes one life-cycle period of the components, generally estimated to be twenty years. This LCA analyses the second twenty-years of operation of the wind turbines, since the components of a remanufactured wind turbine will come from a wind turbine that

already covered its first twenty-years of operation, and the LCA for the first twenty-year cycle of operation is common for both, the newly manufactured and the remanufactured wind turbine. Therefore, the functional unit will be the amount of energy that can be provided over the second two twenty-year periods of usage.

It is assumed that the same materials are used to manufacture components when the wind turbine was originally manufactured are used if a new component is included in the remanufacturing scenario. Therefore, new developments in materials or composites will not be considered for the remanufacturing. Data will be gathered as much as possible from technical specifications for wind turbines, and others from available literature. Assumptions made by looking at the state of a wind turbine's components after its usable life, and quality standards of remanufacturing processes will be considered.

One of the assumptions on which this study is based is that the remanufacturing scenarios and the original wind turbine design will deliver the same rated power and have the same dimensions, so each component will have similar component characteristics for a realistic comparison. The LCAs will be focused on the nacelle subcomponents, considering those as the ones that carry most of the wear of the wind turbine. Since the foundation is likely to remain on site without any special treatment it will not be taken as an important piece of the analysis.

4.2.2 Inventory analysis

This will provide data collection regarding material characteristics, related processes and releases along the life cycle stages for both the original wind turbine and the remanufactured wind turbine configurations. The analysis will be focused on the use of steel, copper, fiber glass, aluminum, and iron because those are the most common materials employed for manufacturing and remanufacturing. In addition, the energy, the water, and other basic inputs involved on the material transformation into finished parts are described. The quantities of materials are defined by the wind turbine models chosen for this study, which are for the remanufacturing scenarios a Vestas V80 2.0MW, and a Gamesa G8X 2.0 MW for the manufacturing scenario. Environmental releases regarding materials and processes will be compiled from the Ecoinvent V2 database.

Among the reasons to choose Vestas V80 2.0MW as the wind turbine model based for the remanufacturing analysis are:

- Vestas is one of the most important wind turbine manufacturers

- Vestas has installed worldwide 2,768 wind turbines of the V80 2.0MW model as of June 30th 2010
- Rated power makes this model belong to the multi-megawatt category, mostly installed for to generate electric energy for utilities

Vestas has produced the V80 2.0MW model since 1999 making this model attractive for remanufacturing in the near future. On the other hand, the Gamesa G8X 2.0 MW was chosen because data is available from a LCA performed by Martinez et al (2009).

4.2.2.1 Wind turbine parts included in the LCA

This research is focused on analyzing those remanufacturable components that represent 95% of the weight installed inside the nacelle cover of the wind turbine. The tower, the foundation, and the blades are not considered for the analysis since the tower is generally reused, the foundation is generally not removed from the location in which the wind turbine was originally installed (some states require its removal), and the blades are assumed to be reused. Therefore, this LCA studies the components shown in Table 3. Those parts, including those produced by Vestas and sub-contractors, are the gearbox, the generator, the transformer, the nacelle structure, the main shaft and the bedframe.

Main component	Sub components	Material	Weight [T] (Vestas)
Nacelle	Nacelle	GFRP	4
	Bedframe	EN-GJSF400-18U-LT-D / EN 1560 (ductile iron casting)	9.052
	Generator bedframe	S355J2H EN 10025 (European standard for hot rolled products of structural steel)	2.5
	Rotor shaft	42CrMo4 / V / EN 10083 (hardened & tempered chrome/Moly steel)	6.078
	Gearbox	Stainless steel 98% (carburized steel for gears: The gears are made of high chromium, high molybdenum steels like 4320, 4820, 9310 and 18CrNiMo7-6.), Copper 1%, Aluminum 1%	15.731
	Generator	Copper 35%, Steel 65%	6.13
	Transformer	Silica 0.15T, Copper 1.5T, Steel 3.3T	5.5
		Total Weight	**48.991**

Table 3. Weight and type of material for the major components of the V80 2.0MW nacelle. Technical Specifications/ Main components V80 2.0MW, 2005.

In general, Vestas produces the nacelle structure, the blades, the tower and the control system. But specifically for the parts inside the nacelle, Vestas manufactures the main shaft, the nacelle structure and the generator foundation. Other major components inside the nacelle such as the gearbox, the generator and the transformer are outsourced. When Vestas installs a factory, the outsourced components are provided mostly by local suppliers. But given the importance of the gearbox, the generator and the transformer in the performance of a wind turbine, only specialized suppliers outside the US are considered. A key element for the analysis is the similarity in weight between the wind turbines chosen. The total weight of components analyzed for the remanufacturing scenario for the V80 2.0MW is 48.99 Tons, and for the wind turbine used in the manufacturing reference LCA scenario is 46.1 Tons, making of this a fair comparison between both models.

4.2.2.2 Manufacturing process for each component inside the nacelle

The description of the classic manufacturing of as-new components, whether they are built using virgin or recycled materials, serves as a narrative and comparison for a the LCA described by Martinez et al (2009) versus the remanufactured wind turbines in this work. From this section, only new manufactured gears, bearings, windings of the generator and the transformer, and steel laminations for the generator are considered as part of the remanufacturing process.

4.2.2.2.1 Nacelle cover

The most common procedure to manufacture the nacelle cover has been the open mold process; but nowadays, due to increased quality and better tolerances the close mold process has been gaining popularity (ReinforcedPlastics.com, 2010). The nacelle covers analyzed in this work were manufactured using the open mold process.

Automatic fiberglass cutting machines can be used to cut each layer of fiberglass. A release agent is employed to detach the GFRP section from each mold, and then a gel coat is sprayed over the mold to make the exterior coat. A spray-up process is used to spray fiberglass-chopped roving and resin simultaneously through a chopper gun; a fiberglass mat can be also employed. Once the material has cured, the section is removed from the mold and trimmed. Finally the sections are assembled, painted, and

additional hardware is added (WindTurbines.net, 2011). For this study, it is considered a remanufactured nacelle which is analyzed further in the research.

4.2.2.2.2 Main Shaft

The main shaft is a high quality steel forged part. The chromo/molly steel is melted in an EAF at 1000^{O}C (Bonus Energy A/S, 1999), and then purified in an ASEA (Allmänna Svenska Elektriska Aktiebolaget) ladle. The next step is to bottom-pour the molten steel into a cast iron mold (ingot). This is an expensive process. However, the bottom-pouring process extends mold life and provides a better ingot surface (David J, 1994). Then, the ingot is reheated to a glowing red color in order to perform a forging process, which provides more strength to the grains of the main shaft. To provide the final shape the main shaft is heated at 500 ^{O}C using a Preliminary Heat Treatment (PHT) and then machined (Pilsen Steel, 2011). The reason behind forging the main shaft instead of use casting is to obtain a metallurgical recrystalization; this strengthens the resulting steel part (ATC Group, 2011). The amount of energy used to melt and forge the steel ingot is between 500 and 800 kWh/meter (Industrial Technologies Program, 2005) (Department of Environment UK, 1993). For calculations, the remanufactured main shaft is analyzed in this work. Figure 8 shows a flow diagram of the main shaft manufacturing process.

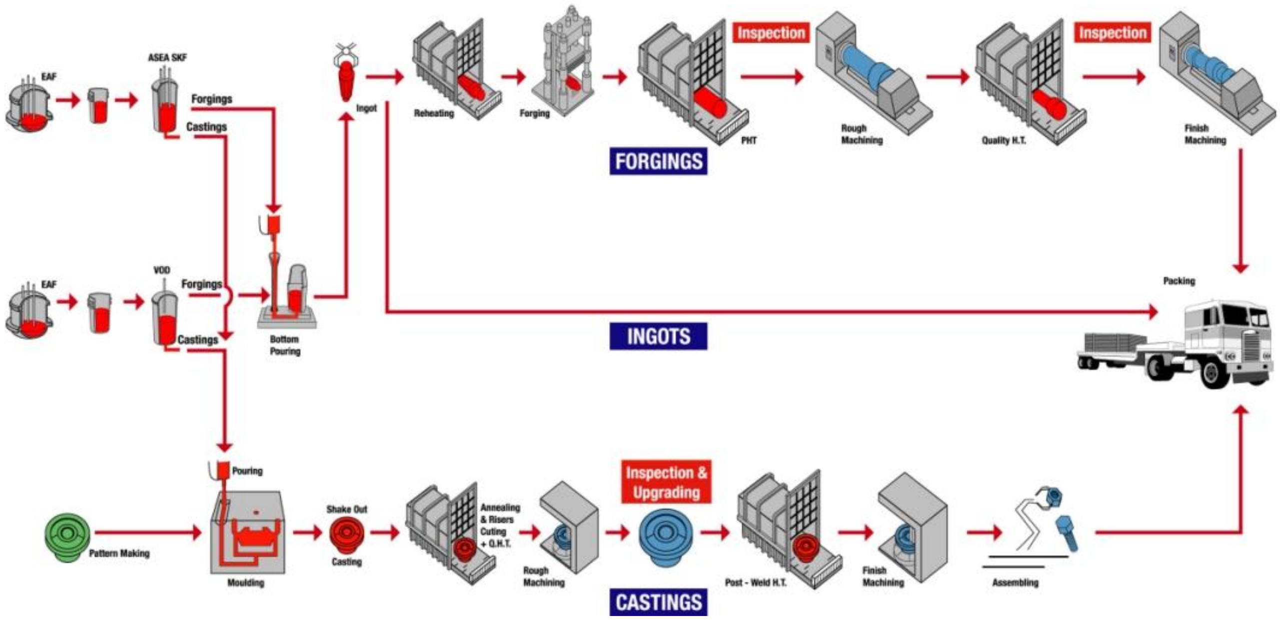


Figure 8. Forged and cast steel production. Pilsen Steel, 2011

4.2.2.2.3 Bedplate

The melting and filtration process is the same as to manufacture the steel for the main shaft; though for the bedplate, a structural steel is used. The melted steel is poured inside a sand mould for casting. When the bedplate has its rough shape and is still hot, it is removed from the sand mold and placed on an Oven Heat Treating (OHT) where the bedplate is annealed and risers are cut for better cold working properties (Pilsen Steel, 2011). After the bedplate has been cooled down then holes are drilled for stability reasons, and to avoid resonance with mechanical components when the wind turbine is in operation; the largest hole allows entrance for maintenance through the bottom of the nacelle.

The machining usually takes place in a horizontal boring mill. The machining of flat surfaces, taps, and holes is executed in this step, which involve different set ups, and in some cases, several machines. In the case of a V80 wind turbine, the bedplate consists of two different pieces that are welded together (Canadian Wind Energy Industry, 2011). In order to relax residual stress from welding, a Post-Weld Heat Treating (PWHT) is used. A common post heating temperature is 400 ^{0}F (250 ^{0}C) maintained

for 1 hour per inch of thickness (Funderbunk S, 1998). Like the main shaft and nacelle, the manufacturing of the bedplate is not considered in the LCA analysis.

4.2.2.2.4 Gearbox

Good quality steel is employed for gear manufacturing, which can come in round bars for pinions or forged round blanks with similar size of large gears. In the case for the Lohnman & Stolterfoht GV 440 and 441 gearbox models (1 planetary stage, 2 helical stages), stainless steel 18CrNiMo 7-6 is the typical material employed for manufacturing (Schultz, D, 2009), which is the one used in the V80 2.0MW. Stainless steel meant for gears is cut in plates using an automated bandsaw to the thickness of the intended design. Then, the gears are placed in a CNC lathe to get similar dimensions to the final gear, and a center hole is bored. Afterwards, a CNC mill is used to drill holes followed by a gear shaper machine used to make the tooth in the center hole of the gears. Once inner teeth have the proper shape, the gears are placed in a CNC hobbing machine to manufacture the outer teeth, taking them to a measure close to the required tolerances for bearing fit. Finally, gears are taken to the gear grinder to be finished. The parts treated by this process are: ring gear, planet gears, sun gear, spur gear, output gear, and bearings. The figures 9 and 10 display the parts in a gearbox for a wind turbine.

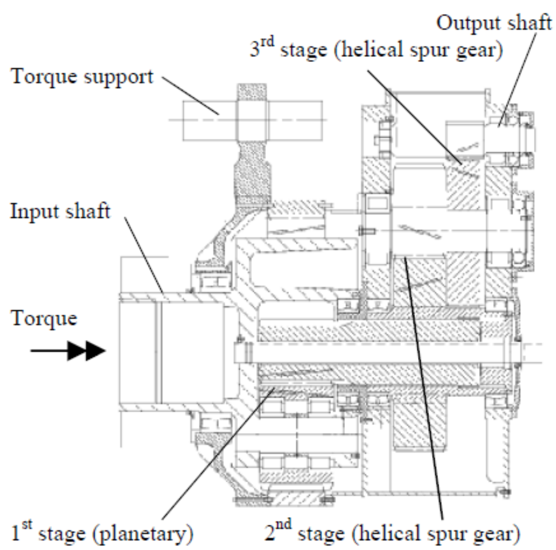


Figure 9. Structure of a typical 1 planetary stage, 2 helical stage wind turbine gearbox. Germanischer Lloyd WindEnergie GmbH

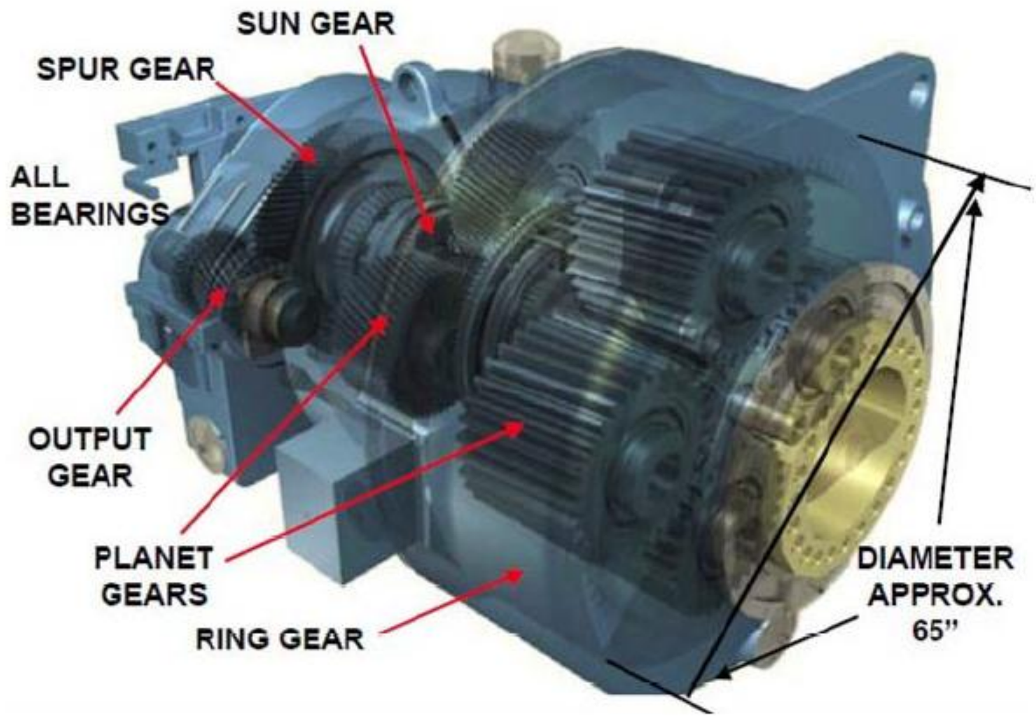


Figure 10. Heat treated parts of a typical wind turbine gearbox. AGMA Technical Paper, 2010

To acquire the desired strength on gears teeth, a carburizing heat treatment is employed; one of the most popular is a pit furnace. Carburizing consists of applying carbon to the surface of the teeth using extreme heat. A typical gear is placed inside the pit furnace heated at temperatures around 926 °C (1700 °F), for times that range between 7 to 35 hours (Titus, 2010). The model followed in this study is to heat to 1700°F (926°C) for 7 hours, then carburize at 1700°F (926°C) for 21 hours in presence of charcoal and elements like nitrogen in the furnace atmosphere (Titus, 2010). After the desired carburizing time is reached the gears are cooled to 1550°F (843°C), then gears are quenched in an oil bath for 3.5 hours. To finalize the carburizing process, the gears are washed at 82°C (180°F) for 1 hour and tempered at 182°C (350°F) in oil for 6.5 hours (Titus, 2011).

The ductile iron casting for the housing is set up, machined, and made ready for the assembly. Most castings come primed to prevent rust. End caps and other parts are also machined and made ready for assembly.

All the parts come together in assembly. Gearboxes are mounted on assembly stands and all components are installed and adjusted. The lubrication system, bearings, gears, temperature sensors, and end caps are all assembled and made ready for final testing.

During testing, the gearboxes are mounted in the test stand and run under load to "wear in" the gear teeth. This requires several hours of testing and monitoring the oil for cleanliness. Once testing is complete, the gearboxes receive a final coat of paint and are made ready for shipping to the customer. Dimensions and weight for the sub-components of a typical 2 MW variable speed gearbox are provided in Table 4.

	Dimensions				
Component	**Long [m]**	**Wide [m]**	**Diameter [m]**	**Volume [m3]**	**V80 2.0MW [Ton]**
Ring gear	-	0.4	1.7	1.185	3.067
Planet wheels [total]	-	0.32	0.5	0.063	1.513
Sun pinion	-	1	0.35	0.096	0.772
1st stage gear	-	0.27	1	0.212	1.702
1st stage pinion	0.75	-	0.3	0.053	0.425
2nd stage gear	-	0.170	0.75	0.075	0.603
2nd stage pinion	1	-	0.175	0.024	0.193
Shink disk	-	-	-	-	1.225
			Total	**1.834**	**9.500**

Table 4. Calculation of weight for parts of a V80 2.0 MW wind turbine gearbox. Canadian Wind Energy Industry, 2011. Seekpart.com, Gear Ring -wind power machinery Ring, 2011.

The estimates in Table 4 for dimensions and weights should not be used for engineering purposes. However, they can provide an estimate of the size of machinery, and materials quantity needed to produce gearboxes and their subcomponents. It should be noted that gearbox manufacture is an extremely specialized procedure. The previous information is used for the analysis of the end-of-life scenarios in which due to the degree of the damage present in the gears, the only option is to replace them for new gears. The description of the manufacturing process for new gears is described in the Tables 5, 7, and 8.

Process	Input	Value	Source/ Comments
Planet gears material	30CrNiMo8 I	1.513Tons	30CrNiMo8 I is the most similar high grade steel to 18 CrNiMo7-6 found in SimaPro
Machining	Deep drawing, steel, 10000 kN press, single stroke operation/RER U	1.513Tons	Total weight of planet gears, table 4
	Turning, chromium steel, conventional, average/RER U	$1.513\ Tons \times 0.23\% = 0.348\ Tons$	Estimation of 23% of material removed based on the value of final weight, according to the description of the SimaPro database for this process
	Drilling, CNC, chromium steel/RER U	$1.513\ Tons \times \frac{15cm}{50cm} = 0.453\ Tons$	Assuming 15cm of center hole diameter
	Milling, chromium steel/RER U	$1.513\ Tons \times 0.23\% = 0.348\ Tons$	Estimation of 23% of material removed based on the value of final weight, according to the description of the SimaPro database for this process
Carburizing		1.513 Tons	Process described in table 5

Table 5. Inputs for manufacturing a planet gears for a V80 2.0MW gearbox.

Process	Input	Value	Source/Comments
Carburizing	Gears	$\frac{15400\ lb}{2.2\frac{lb}{Kg}} = 7{,}000\ Kg$	15,400 lb of gears for carburizing process converted to Kg. Titus (2010)
	Charcoal ETH U	$\frac{30\ lb \times 21\ h}{10\ h \times 2.2\frac{lb}{Kg}} = 28.6\ Kg$	30lbs of charcoal is used every 10hours, for 21 hours and 2.2lb=1kg. French (1920)
	Electricity, natural gas, at power plant/US U	435 kWh	Heating chamber. Titus (2010)
	Nat. gas into elect. boilers	1554 ft^3	Atmospheric additions. Titus (2010)
Quenching	White mineral oil, at plant/RNA	$\frac{2\frac{gal}{day} \times \frac{3.7854\ Lt}{gal} \times 0.869\frac{Kg}{Lt}}{21h} = 7.62\ Kg$	2 gallons per day for 21 hours. 1 gallon=3.7854 Lt. Density of oil 0.869 Kg/Lt. French (1920)
	Electricity, natural gas, at power plant/US U	153 kWh	Titus (2010)
Tempering	White mineral oil, at plant/RNA	$\frac{2\frac{gal}{day} \times \frac{3.785\ Lt}{gal} \times 0.869\frac{Kg}{Lt}}{21h} = 7.62\ Kg$	Assuming 2 gallons per day of operation
	Electricity, natural gas, at power plant/US U	241 kWh	Titus (2010)
Washing	Water demineralized ETH U	$\frac{7000\ Kg \times 16.92\ Lt \times \frac{1\ Kg}{Lt}}{141\ Kg} =$ 840 Kg	141 Kg of gears are washed using 16.92 Lt of water, extrapolating this value to the 7000Kg of gears washed. Titus

			(2010)
	Electricity, natural gas, at power plant/US U	2 kWh	Titus (2010)

Table 6. Inputs for carburizing planet gears for a V80 2.0MW gearbox.

The values in Table 5 can be adjusted for the helical and ring gears from Table 7, and 8.

Process	Input	Value	Source/Comments
Helical gears material	30CrNiMo8 I	2.923 Tons	Represented by in table 4 by: 1st stage gear: 1.702 kg 1st stage pinion: 0.425 kg 2nd stage gear: 0.603 kg 2nd stage pinion: 0.193 kg
Machining	Deep drawing, steel, 10000 kN press, single stroke operation/RER U	2.923 Tons	Final weight of gears resulting from machining
	Turning, chromium steel, conventional, average/RER U	$2.923\ Tons \times 0.23\ \% = 0.672\ Tons$	Estimation of 23% of material removed based on the value of final weight, according to the description of the SimaPro database for this process
	Drilling, CNC, chromium steel/RER U	0.1Tons	Assumed amount of drilled material from center hole

	Milling, chromium steel/RER U	$2.923\ Tons \times 0.23\ \% = 0.672\ Tons$	Hobbing of external and internal tooth, estimation from SimaPro
Carburizing		2.923 Tons	Process described in table 6

Table 7. Inputs for manufacturing helical gears for a V80 2.0MW gearbox.

Process	Input	Value	Source/Comments
Ring gears material	30CrNiMo8 I	3.067 Tons	Refer table 4
Machining	Deep drawing, steel, 10000 kN press, single stroke operation/RER U	3.067 Tons	Final weight of gears resulting from machining
	Turning, chromium steel, conventional, average/RER U	$3.067\ Tons \times 0.23\ \% = 0.705\ Tons$	Estimation of 23% of material removed based on the value of final weight, according to the description of the SimaPro database for this process
	Drilling, CNC, chromium steel/RER U	0.1Tons	Assumed amount of drilled material from center hole
	Milling, chromium steel/RER U	$3.067\ Tons \times 0.23\% = 0.672\ Tons$	Hobbing of external and internal tooth, 23% estimation from SimaPro
Carburizing		3.067 Tons	Process described in table 6

Table 8. Inputs for manufacturing ring gears for a V80 2.0MW gearbox.

4.2.2.2.5 Generator

The generator components are stator, rotor, excitation system, cooling system, insulation system, and bearings; among these parts, the stator and rotor are the most relevant for the analysis and are studied in detail in the LCA as remanufactured components. The following is a description of the stator and rotor.

- Stator: contains a series of coils, the number of which must be divisible by three. It consists of three main components (Industrial Training at BHEL, Rhagunath):
  - Stator frame: Is a welded single piece construction supporting the core and winding; it has axial and radial ribs to reduce vibrations and increase cooling. Guide bars are bolted or welded inside the stator frame.
  - Stator core: Supports the stator coils and carry the electromagnetic flux generated by the rotor coils. Is made of individual segments of thin silicon steel sheets coated with synthetic varnish that are suspended from insulated guide bars; the varnishing process takes place at temperatures between 350 and 250 ^{o}F. Before being placed on the frame each segment is punched and deburred, then hydraulically staggered and heated layer to layer and stacked on the outer circumference using insulated rectangular bars.
  - Stator coils: Consist of individual bars placed on slots of rectangular cross section uniformly distributed on the circumference of the stator core
- Rotor: sits in an axle inside the stator, and is made of three components (Industrial Training at BHEL, Rhagunath):
  - Rotor shaft: is manufactured by forging, and longitudinal slots are milled where field winding is inserted
  - Rotor pole: Punched or fabricated from high-strength steel
  - Rotor winding: consist of several coils, in which two coil groups from one pole. The windings are machine wound on the poles with high temperature insulated copper wires. The complete rotor could be either vacuum-pressure impregnated or wet wound before the shaft is pressed

- Bearings: The generator rotor is supported by two bearings

4.2.2.2.6 Transformer

The transformer may come from different companies, namely Siemens, ABB, SBG, and France Transfo. The type of transformer used for the V80 is a dry-type transformer, since it uses resin as an isolation medium and not liquid mineral oil as the liquid type transformer. The main parts in a transformer are:

- Core: thin sheets of silicon steel of low carbon content are used to manufacture the transformer's core. Silicon is used for manufacturing because it increases the electric specific resistance, but it makes the steel brittle; so the content of silicon is kept lower than 3%. Cold rolling is employed to manufacture the sheets of steel and requires equipment with high surface pressure; this process helps to orient the magnetic domains in the steel sheet. Then finishing treatments such as laser treatment are employed to divide those magnetic domains into smaller sections with lower losses of the magnetic field as result (ABB, 2003)

  The sheets are insulated from each other, in general using an inorganic material. To complete the core several layers of the steel sheet are built up together using a pre-specified geometry. The different strips are loaded onto a turret-type feeding system used to feed the stamping die which will cut each section, typical thickness of the steel sheets is between 0.23 and 0.30mm. Then the sections are transported using a high-speed conveyor system to the stacking station to finally form the appropriate core geometry

- Coil winding: CNC machines adjust the speed and tension for wire and sheet winding process. The conductor materials are either aluminum or copper. The use of copper permits the transformer to be physically smaller. The copper sheets are wound together with a piece of insulated material

- Casting: coil winding is fitted into a mold that is placed inside the casting chamber. Oil diffusion pumps create the necessary vacuum pressure to eliminate trapped gasses as the mold is filled with an epoxy resin mixture

- Assembly: castings are loaded on the core legs and then the enclosure is fabricated using CNC machines through processes like punching, shearing, and forming (JTC, 2009)

4.2.2.3 Transportation of components for new wind turbine assembly

Vestas has a nacelle factory in Brighton, Colorado, where the outsourced components are shipped for assembly. Reasons for choosing this location are:

1- Easy access to rail services and highway infrastructure from the central U.S.A. to the wind power corridor in the Midwest, where most of the wind farms are installed
2- Proximity to Vestas blades plant in Windsor, Colorado. The factory is expected to produce 1,400 nacelles. In addition, Bach Composite Industry located in Fort Lupton, Colorado, is the nacelle's material provider for the Vestas nacelles factory in Colorado.

For the wind turbine model V80 2.0MW two options can be considered for the gearbox, a Bosch Rexroth or a Hansen Transmissions model. For this study, a Bosch Rexroth GPV 441-R3 gearbox is considered. The gearbox is transported via train from one of the two gearbox manufacturing plants located in Germany (Witten or Nuremberg) to either Bremenhaven or the Hamburg port. From there the gearbox will be transported to the port of Louisiana, then railroad transportation to Denver, Colorado. Finally, the gearbox is transported by truck to Brighton, Colorado. Bosch Rexroth also has a gearbox factory in China.

As for the transformer, the Siemens transformer also comes from Germany, but from the city of Kirchheim. The same transportation route as for the gearbox is assumed to deliver the transformer from Germany to Colorado, even though Siemens plans to install a transformer factory in the US Amteck (2012).

The generator is manufactured by ABB and WEIER, the last one acquired by Vestas. ABB has 4 wind turbine generator factories, one of them located in Vadorara, India. The generator is assumed to be transported from India through the Indian sea and the Pacific to the port of Los Angeles. Then, rail transport to Brighton, Colorado is required.

The main shaft and the bedframe are manufactured by Vestas in the factory of Lem, Denmark. Both are transported by truck to the port of Ringkøbing, Denmark. Then they are exported to the US to the port of Louisiana, train transported to Colorado, and finally arrive to Brighton, Colorado by truck. Since the components inside a newly manufactured and a remanufactured nacelle come from different

places in the US and the World, the scenarios are compared to see if it makes a difference in the life-cycle of each alternative.

4.2.2.4 Transport and erection of the nacelle

The remanufactured V80 2.0MW wind turbine is assumed to be installed in Abilene, Texas, where 67 units of V80 1.8MW are currently in operation. The reasons for choosing that location are threefold; potential of generating wind energy in that region, remanufacturing capabilities in Abilene, and easy access to railroads for transportation of the wind turbine subcomponents from the assembly factory in Brighton, Colorado.

To lift a nacelle and for technicians to secure it at the top of the tower a crawler crane is used. A Kobelko CK850-III ---crawler crane has the following fuel consumption:

Approximate fuel consumption
0.342 lb / HP-hr (208 g / kW-hr)
10.53 US gal. / hr at 100 % HP

Table 9. Crawler Crane CK850-III fuel consumption. Bigge, 2011

This operation is not taken into consideration because is a common procedure for a new or a remanufactured wind turbine.

4.2.2.5 Operation and Maintenance

The replacement of any major component during the 20-year servicing of the wind turbine is not needed (ELSAM Engineering, 2004). The following maintenance operations are carried out during the wind turbine operation:

Material	Renewal frequency
Gear oil, type 1	8 years
Gear oil, type 2	8 years
Hydraulic oil	5 years
Lubricating grease, various types	6 months

Table 10. Maintenance frequency for the V80 2.0MW. LCA ELSAM Engineering A/S, 2004

The nacelle cover is considered maintenance free. The dry-type transformer used in the V80 wind turbine requires cleaning once a year, and is safer during operation than liquid types because the air is the insulation medium. This stage is assumed common for the new and the remanufactured equipment.

4.2.2.6 Remanufacturing

The process starts from the disassembly from the tower of each part inside the nacelle, because any unusual situation on the components should be registered and reported for the remanufacturing team: Among the abnormalities that can be found are alignment or vibration issues, oil or any other liquid leaks, obvious maintenance shortcomings, evidence of overload, electrical imbalance, or other damage caused by outside forces such as turbine over-speed (Zipp, 2010). All parts should be included in the shipment to assure the wind turbine is repaired properly. Then the nacelle is removed from the tower. This work assumes that all remanufacturable parts go to the same shop.

4.2.2.6.1 Main shaft

Initially when transported to the remanufacturing facility, the main shaft is cleaned and the bearings are uninstalled from the main shaft. Then the main shaft is placed in a large lathe where it is turned, balanced, and tested. The main shaft is shipped to the location where the remanufactured wind turbine will be installed. Depending on the state of the bearings, they can be either replaced for new ones or remanufactured; in this study both alternatives are considered. The replaced bearings account for a total weight of 945Kg (472.5 Kg. per bearing). Table 11 shows the inputs for remanufacturing the main shaft.

Process	Input	Value	Source/Comments
Bearings	New or remanufactured	945 Kg	Vestas, 2005
Main shaft cleaning	Degreasing, metal part in alkaline bath/RER U	$2 \times \pi \times 0.5\ \text{m} \times 2.69\ \text{m} = 16.9\ \text{m}^2$	1m average diameter of main shaft, length 2.69 m Degreasing area =$2 \times pi \times r \times l$ Vestas, 2005
Main shaft turning	Turning, steel, CNC, average/RER U	10 Kg	Assumed value, material removed due to surface imperfections
Balancing test for main shaft	Electricity, production mix, US/US U	2000 kWh	Assuming test is performed for 1h in a RENK LABECO test system Renk LABECO, 2010

Table 11.Inputs for remanufacturing a main shaft from a V80 2.0MW.

The following section explains bearings manufacturing in detail. Later in the remanufacturing section the remanufacturing process for bearings is described.

4.2.2.6.2 New bearings

In a typical remanufacturing process bearings are replaced for new ones. The remanufacture of bearings is possible, but the best advice is to replace them since they are one of the components that suffer most of the damage during operation. Figure 11 shows a flow diagram for the manufacturing of a 24024 SKF roller bearing. Detailed information about the inputs from those processes were obtained from a LCA performed over that bearing. According to the appendix 2 of the technical description of the Tymien wind farm project in Austria, spherical roller bearings are used to support the main shaft (Austria JI/CDM programme, 2004). Therefore, for this research it is assumed that the results of the LCA for the 24024 SKF roller bearing 5.4Kg bearing can be extrapolated for the two bearings used for the main shaft.

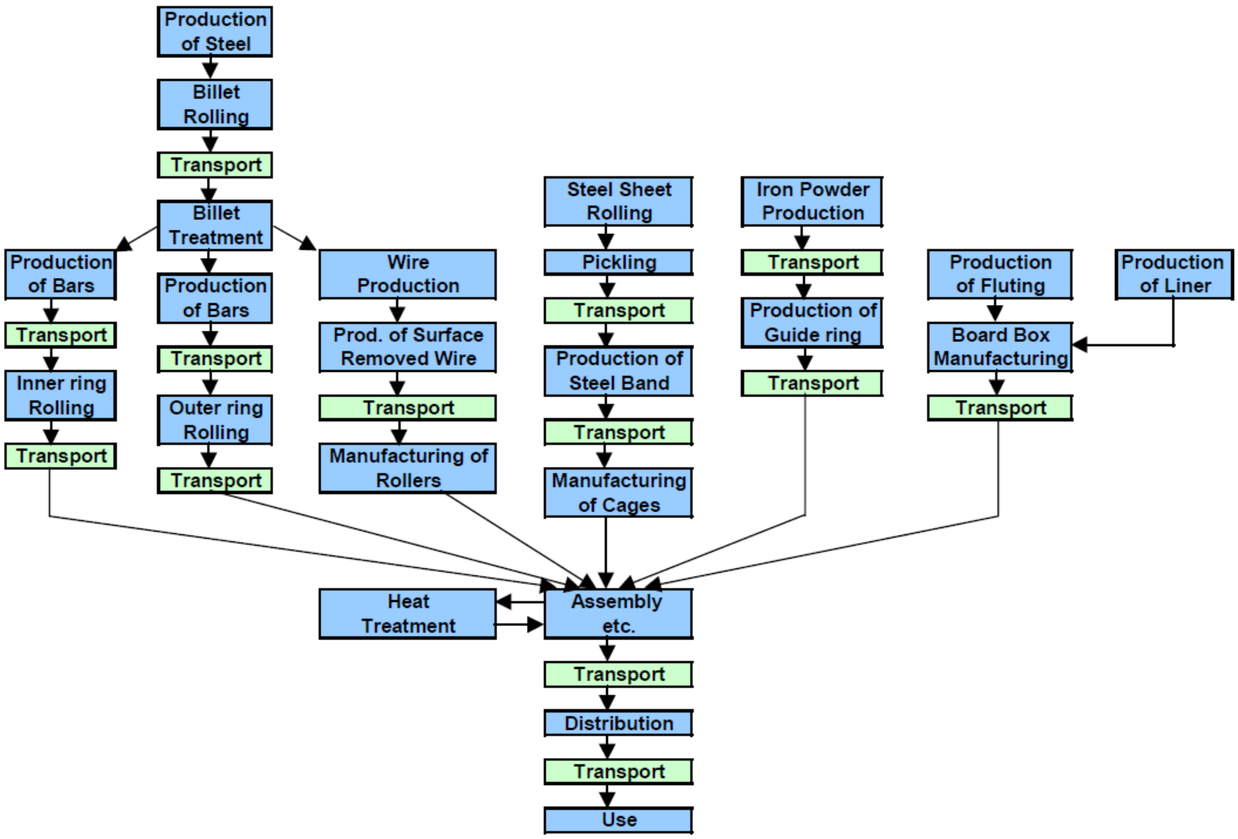


Figure 11. Flowchart for the life cycle of the SKF spherical roller bearing 24024. SKF, 2001

4.2.2.6.3 Bearings remanufacturing

The first step consists of an initial inspection, in which turning torque, free-state clearance, gear size and external features are inspected and documented to apply the proper corrective measures. Then bearings are disassembled from the rotary part for which it was installed and cleaned. After disassembly, non-destructive testing is performed. This consists of visual, magnetic particle inspections, and hardness readings; these tests will help to determine the repairability of each bearing. The machining for bearing remanufacturing consists of precision grinding to achieve the proper geometry, optimizing load, and carrying capability. During the assembly, the old rollers and seals are substituted for new ones. Final inspection is performed before the installation of the bearings back to the main shaft, the gearbox, or the generator (Kaydon, 2011). Figure 12 shows the process of bearing remanufacturing.

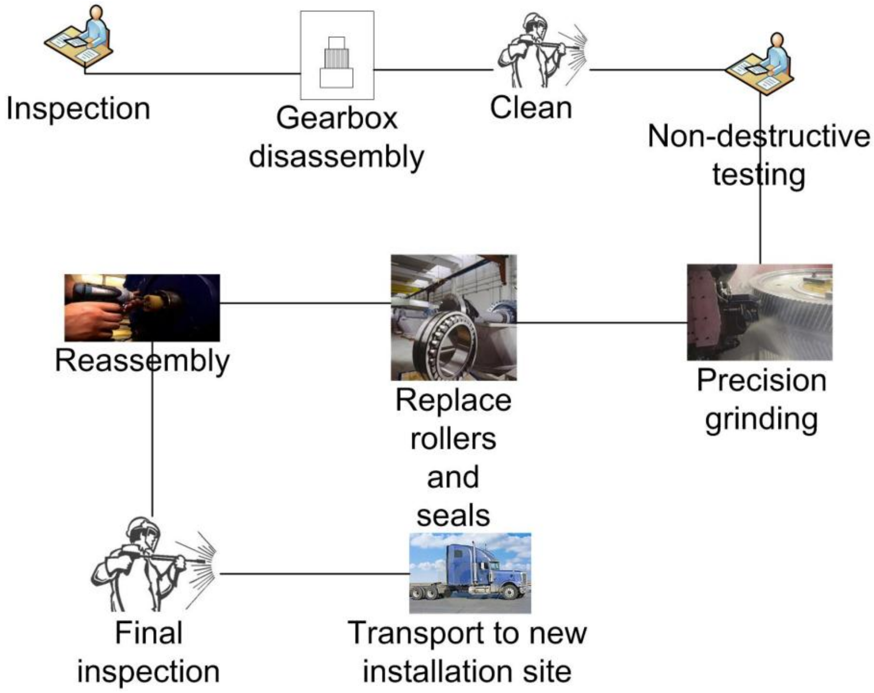


Figure 12. Bearings remanufacturing processes

Values in Table 12 are established for a 5.4Kg roller bearing, but in SimaPro these values are scaled to satisfy the weight of the roller bearings for each part in the wind turbine.

Process	Input	Value	Source/Comments
Initial inspection, bearing remanufacturing	Electricity, production mix US/US I	1 kWh	Inspection is a very low energy intensive process
Disassembly & cleaning, bearing remanufacturing	Degreasing, metal part in alkaline bath/RER U	$2 \times \pi \times (0.18\,m - 0.12\,m) \times 0.06\,m = 0.0226$ m2	Cleaning of bearings based on the area of the SKF 24024 roller-bearing: Dimensions: 18mm external diameter, 12mm inner diameter, 6 width.

			Ekdahl A. (2001)
	Electricity, production mix US/US I	1 kWh	Manually disassembled
Non-destructive testing, bearing remanufacturing	Magnetite, at plant/GLO U	0.5 Kg	Use of magnetic particle inspection, assumed value for 5.4 Kg bearing
Repairability, bearing remanufacturing			Evaluation of data, no inputs or outputs
Precision grinding, bearing remanufacturing	Turning, steel, conventional, primary roughing/RER U	0.087868461 Kg	Refer to table 13
Assembly, bearing remanufacturing	Manufacturing of rollers	1.5288 Kg	Weight of new rollers. Ekdahl A. (2001)
	Lubricating oil, at plant/RER U	0.2 Kg	Assumption for a 24024 SKF roller bearing
	Electricity, production mix, US/US U	1 kWh	Manually assembled

Table 12. Inputs for remanufacturing bearings used in a V80 2.0MW.

Material removed for remanufacturing of a SKF roller bearing 24024

	Inner diameter [m]	**Outer diameter [m]**	**Width [m]**	**Area1 [m2]**	**Area2 [m2]**	**Volume removed1 [**	**Volume removed2 [m3]**
Inner piece	0.12	0.14	0.06	0.424528	0.002512	0.000269575	1.59512E-06
Intermediate piece	0.14	0.16	0.02	0.5652	0.002512	0.000358902	1.59512E-06
Outer piece	0.16	0.18	0.04	0.725968	0.002512	0.00046099	1.59512E-06
Depth of cut [m]	0.000635						
						Total volume removed [m3]	**0.001094252**
						Density steel [ton/m3]	**80.3**
						Total material removed [kg]	**0.087868461**

Table 13. Material removed from bearing according to the depth of cut. Timken

4.2.2.6.4 Bedframe

The bedframes are cleaned with high pressure hot water and a biodegradable solvent. After a thorough cleaning, they are inspected for any cracks or other anomalies. The bedframes are made of welded, galvanized steel. According to Scientia Energy, in over 20 years of operation, they have never observed any stress related cracks or other failures attributable to normal operations (Scientia Energy, 2009). Therefore, it can be assumed for study that no other treatment or process is performed to remanufacture a bedframe. Otherwise, the bedframes undergo mechanical and chemical surface preparation prior to coating application (FESCO Direct, 2010), which is not considered in this study. Table 14 describes the inputs for bedframe remanufacturing.

Process	Input	Value	Source/Comments
Cleaning of bedframe	Tap water, at user/RER U	$5\frac{gal}{min}\times 60\frac{min}{h}\times 2.5h\times\frac{3.785\ lt}{1\ gal} = 2839.05$ Kg	Using 5 GPM of water, assuming 750 Gallons for 2.5h. One gallon= 3.785 lt. Gladen (2011)
	Gasoline, combusted in equipment/US	$1.1\frac{gal}{min}\times 2.5h\times\frac{3.785\ lt}{1\ gal} = 10.4$ L	Assuming fuel consumption of 1.1 GPH for the 18hp engine of the steam machine, for 2.5 hours. Gasoline high pressure washer model QH-250 Zhejiang Kingwash Electromachinery CO., LTD (2011)
	Fatty alcohol, from coconut oil, at plant/RER U	1 Kg	Vollenbregt, L. Terwoert, J. 1996
Painting bedframe	Automotive painting, pretreatment /RNA	10 m^2	Vestas, 2005
	Automotive painting, top coat, per m^2/RNA	10 m^2	Vestas, 2005
Powder	Powder coating, Steel	11 m^2 for bedframe, 4.83 m^2 for	Vestas, 2005

coating	RER/U	generator bedframe	

Table 14. Inputs for remanufacturing a bedframe from a V80 2.0MW.

4.2.2.6.5 Nacelle

The process starts with removing components of the nacelle and removable pieces; around 600 pieces can be attached to a Gamesa wind turbine nacelle cover including heaters, lights, sound absorbers and computer electronics equipment (McClarin Plastics, Inc., 2010). Then, the nacelle structure is pressure washed with warm water and eco-friendly degreaser, followed by a visual inspection to search for any damage. The degree of damage leads to the decision of whether to patch or repair the nacelle, replacing the nacelle is not considered in the analysis. Later the nacelle is shot blasted and repainted; some companies such as Fesco Direct LLC prefer to powder coat the surface of the nacelle, since it offers far superior finish. No scrap is generated on any of these processes, unless a piece of material has to be trimmed to fill a whole (Gladen M, 2011).

The entire process of nacelle cover remanufacturing takes between 30 and 40 man hours of work, including disassembly and assembly of the components. A fair estimate of the water usage is between 600 and 900 gallons of water for the cleaning process. A baking process is carried out to apply the powder coating. Table 15 offers a summary of the input data for SimaPro.

Process	Input	Value	Source/Comments
Removal of components from nacelle	Electricity, production mix, US/US U	1 kWh	Mostly manually disassembly
Cleaning of nacelle cover	Tap water, at user/RER U	$5\frac{gal}{min}\times 60\frac{min}{h}\times 2.5h\times\frac{3.785\,lt}{1\,gal} = 2839.05$ Kg	Using 5 GPM of water, assuming 750 Gallons for 2.5h
	Gasoline, combusted in equipment/ US	$\frac{900\,gal}{2.4\frac{gal}{min}*60\frac{min}{h}}*3.785\frac{lt}{gal}*0.4\frac{lt}{h}=9.46\,lt$	Gasoline high pressure washer model QH-250 Zhejiang Kingwash Electromachinery CO., LTD (2011).

	Fatty alcohol, from coconut oil, at plant RER/U	10 Kg	Vollenbregt, L. Terwoert, J. 1996
Repair of cracks over nacelle cover	Glass fibre I	20 Kg	Assumed value for small repairs
	Epoxy resin, liquid, at plant /RER U	20 Kg	Assumed value for small repairs
Powder coating	Coating powder, at plant RER/U	10 Kg	Assumed value for small repairs
	Electricity, production mix, US/US U	20 kWh	Power gun used for 2h, assuming 0.1Amp 100 ×0.1 ×2 = 20 kWh
Baked dry of nacelle cover	Electricity, production mix, US/US U	120 kWh	Assuming same power rating (30kW) as for baked dry of transformer for 4 hours
	Heat, natural gas, at industrial furnace, low-NOx >100kW/RER U	152 kWh	Assumed 4 hours in oven at 38kW
Reassembly of subcomponents in nacelle cover	Electricity, production mix, US/US U	2 kWh	Mostly manual process

Table 15. Inputs for remanufacturing a nacelle cover from a V80 2.0MW.

4.2.2.6.6 Generator

The first step begins with disassembly of the parts in the generator. Components are cleaned and inspected as required, steam cleaning and baking are common for cleaning purposes before electrical

testing; temperatures not higher than 194 ^{0}F are recommended (BidderMegger.com, 2011). The winding insulation resistance is measured under the IEEE 43 standard test, showing any damage to the windings, then surge testing and high potential testing are also performed to identify any damage. When a winding failure is located a core-loss test (IEEE 112) to the rotor and stator laminations is performed; this test is also applied when there is a mechanical failure on the stator laminations. Loose wedges, blocking materials, average-core losses, and hotspots locations should be noted and recorded. Bar integrity is checked for induction rotors. Every mechanical fit must be measured and compared to original standards.

The stator and rotor are cleaned of insulation and wire. To clean the rotor from the insulation material, a pyrolysis process in which the organic material is burned in an oven at 680 ^{0}F, and 750 ^{0}F for inorganic material, is commonly used (Bonnett and Gibbon, 2011); using these temperatures avoids damage to stator laminations when conductors are carefully removed. Stator laminators should be replaced for new ones in case of damage (TAW Wind Turbine Generator Repair Service, 2011). The winding data is collected, coil construction, materials, layout, and connection details for further assembly.

Core losses are checked again after the stator and rotor are cleaned to assure nothing has changed during the process. After the wire has been removed, rotor and stator are rewound with new insulating coils using the proper isolation design for the application, which generally is different given the mechanical and electrical requirement of each component. Those differences are not analyzed in this work. A winding machine is used to manufacture the new coils for the generator. The coil installation will depend of the size and weight of the generator, for a small generator the coils are manually installed in the generator, and then immersed in a dip/oven bake process; the vacuum-pressure impregnation (VPI) is performed according to the suggested time and temperature by the resin manufacturer design.

For a large generator like the V80 2.0MW analyzed in this research, after the winding process is over, the coils are foiled with insulation tape in an insulation machine; the reason for using this and not the VPI process is that the size of the generators makes it difficult to be placed in an oven. Then coils are placed in a preforming machine, which provides the exact required shape for each coil. The final step for a large generator is to hot press the coils. Rotor leads are replaced and properly supported, when needed. Mating surfaces are cleaned and inspected; threaded holes are cleaned and re-tapped.

Collector rings and grounding rings are replaced or refurbished. The rotor is dynamically balanced with all shaft components mounted, once balanced the generator is reassembled, cleaned, painted and shipped back to the wind site to reinstall the generator (Alewine, K. Zipp, K. 2010). The flow diagram in Figure 13 explains the processes described before.

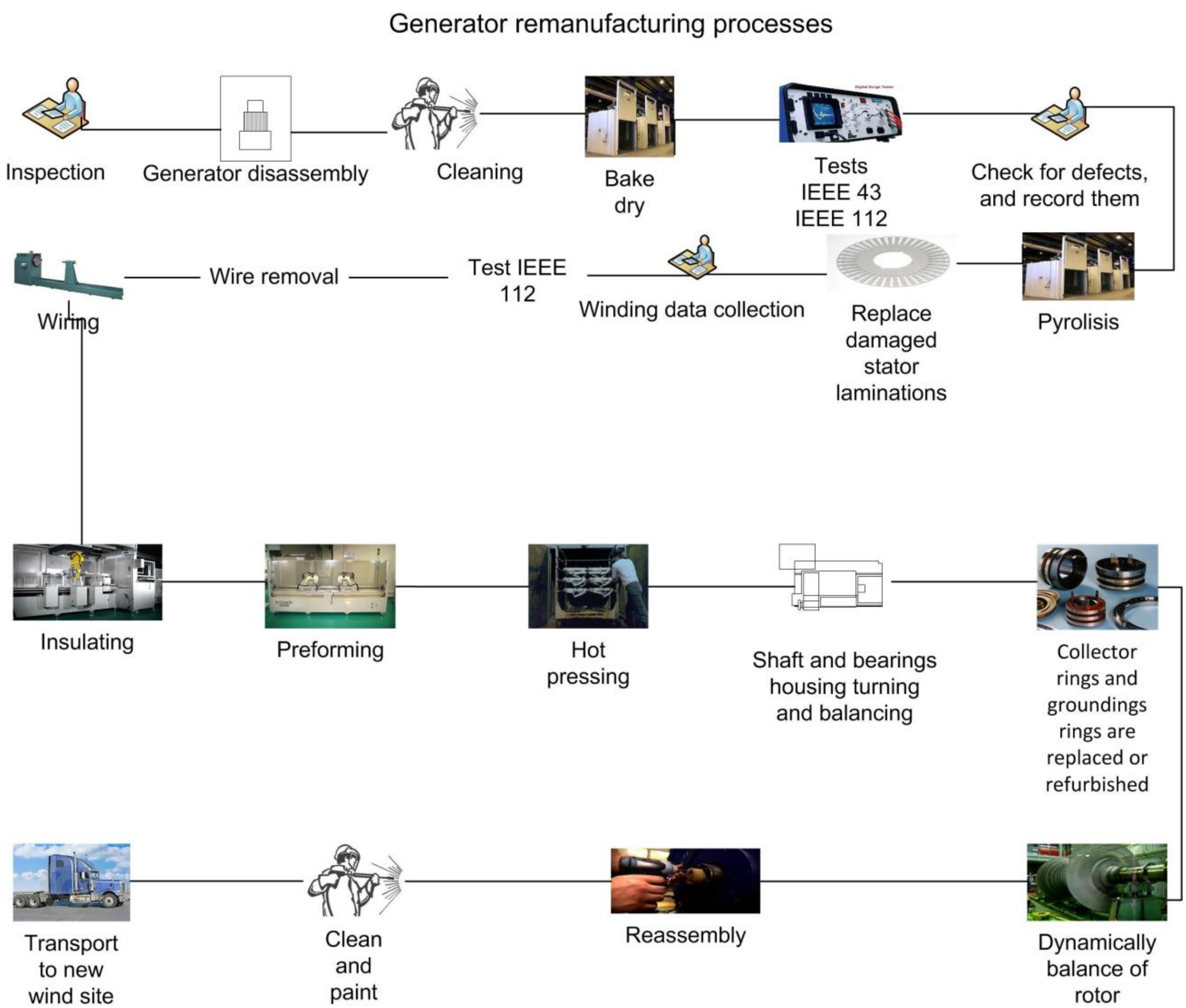


Figure 13. Generator remanufacturing processes

Depending on the degree of damage collector rings and groundings could be either remanufactured or replaced, these smaller components are not taken into account for this study. Table 16 shows inputs for the generator remanufacturing.

Process	Input	Value	Source/Comments
Disassembly of generator	Electricity, production mix, US/US U	1 kWh	Mostly a process that uses low electricity consumption in power tools
Steam cleaning for generator	Gasoline, combusted in equipment/US	$\frac{10\ gal}{11\ h} \times 1h \times \frac{3.785\ lt}{1\ gal} = 3.44\ lt$	Assuming fuel consumption of 10 gallons for 11hours for the 18hp engine of the steam machine. Zhejiang Kingwash Electromachinery CO., LTD (2011).
	Tap water, at user/RER U	$5\frac{gal}{min} \times 60\frac{min}{h} \times \frac{3.785\ lt}{1\ gal} = 1135.5\ lt$	1h cleaning with 5GPM of water usage for steam cleaning. Assumed value.
Dry bake generator after steam cleaning in remanufacturing	Heat, natural gas at industrial furnace low – NOX > 100kW/ RER U	304 kWh	8 hours given the information for baked dry of transformer, 30 kW. Barnett et all. 1991
IEEE 43 test for generator remanufacturing	Electricity, production mix, US/US U	6000 kWh	Typical IEEE 43 test last a day, assuming 3 hours of operation for testing
IEEE 112 test for generator remanufacturing			Test do not imply energy or resources consumption

Pyrolysis in generator remanufacturing	Heat, natural gas at industrial furnace low – NOX > 100kW/ RER U	$\frac{11.62218\ m^3 \times 5\ kW}{0.097845\ m^3} = 593.90\ kWh$	Based on the volume/energy relationship between a microwave pyrolysis oven and a typical pyrolysis oven. Lam et all. 2011
	Tap water, at user, RER U	10 Kg	Assumed value
Replacing stator laminations in generator remanufacturing	Cold rolled sheet, steel, at plant /RNA	20 Kg	Other common materials for stator laminations are Silicon Steel, Nickel Alloys (not good for flux greater than 8 Gauss), and Cobalt alloys (Aerospacial applications)
	Electricity, production mix, US/US U	0.5 kWh	Assumed value from welding
IEEE 112 test for generator remanufacturing			Test do not imply energy or resources consumption
Wire removal from generator	Electricity, production mix, US/US U	0.3 kWh	Strip wire from the generator can be done using a 800 W electric hoist
Rewinding process for generator	Copper wire for coil	2150 Kg	6.13 Tons is the total weight of generator, 35% of it is copper. Vestas, 2005.
	Compressed air, optimized installation, >30Kw, 6 gauge bar, at supply network, RER/U	$0.018\frac{m^3}{sec} \times 60\frac{sec}{min} \times 60\frac{min}{h} \times 3\ h = 194\ m^3$	Coil taping machine for large generator. Ridgway, taping machine specialists
	Electricity, production mix, US/US	$2h \times 5hp \times \frac{0.745\ kWh}{1\ hp} =$	For large Generator preforming coil machine. 2 hours use of a 5HP drive motor and conversion

	U	$7.45\ kWh$	from HP to kWh 0.745. Giam Ming Enterprises Co
	Electricity, production mix, US/US U	$55.95\ kW\ \times 2h = 112\ kWh$	Rewinding machine can handle up to 9T generator. Broomfield USA
Shaft turning and balancing for large generator	Turning, steel, CNC, average CNC/U	2 Kg	Assumed value
	Electricity, production mix, US/US U	100 kWh	Assumed value
Painting stator of large generator	Automotive painting, treatment, RNA / U	7 m^2	Approximate surface area of generator cover. Vestas, 2005.
	Automotive painting, top coat, per m^2/RNA	7 m^2	Approximate surface area of generator cover. Vestas, 2005.
Reassembly of generator	Electricity, production mix, US/US U	1 kWh	Assumed value

Table 16. Inputs for remanufacturing a generator from a V80 2.0MW. Shermco Industries, 2011

4.2.2.6.7 Gearbox

Tests for the gearbox include non-destructive testing, vibration, materials and oil analysis. Most of these tests can be performed in a special designed test stand which could represent a big energy burden for the gearbox remanufacturing, but these test stands are designed to recover most of the energy

employed to run the gearbox (Gearbox express, 2011). Figure 14 represents a diagram of a test stand for a wind turbine gearbox.

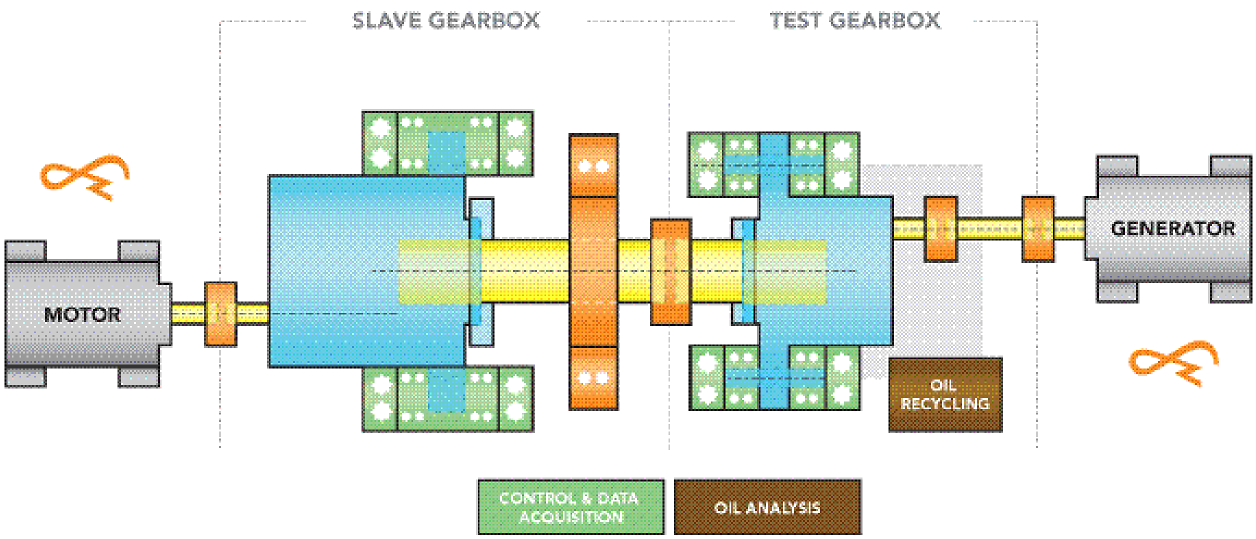


Figure 14. Wind turbine gearbox test stand configuration. Gearboxexpress, 2011.

After the tests, the remanufacturing process starts by disassembling the gearbox, paying attention to any damage presented over each subcomponent. Those defects are recorded during the inspection. The information collected will be used to apply the correct remanufacturing strategy. The remanufacturing strategy will depend on the state of the gears. Machining the gears and shafts is the most common remanufacturing procedure, but in case of greater damage it would be necessary to replace the gears for new ones. The components that suffer most of the wear out – and the reason behind most of the failures in wind turbines are the bearings; therefore, replacement of all the bearings and seals is recommended by remanufacturers. Nevertheless, the bearing remanufacture is still possible (Timken). Before reassembly, oil filters and oil are replaced for new ones. Finally, the remanufactured gearbox is painted and delivered to the new operation area of the wind turbine. Figure 15 shows the gearbox remanufacturing process.

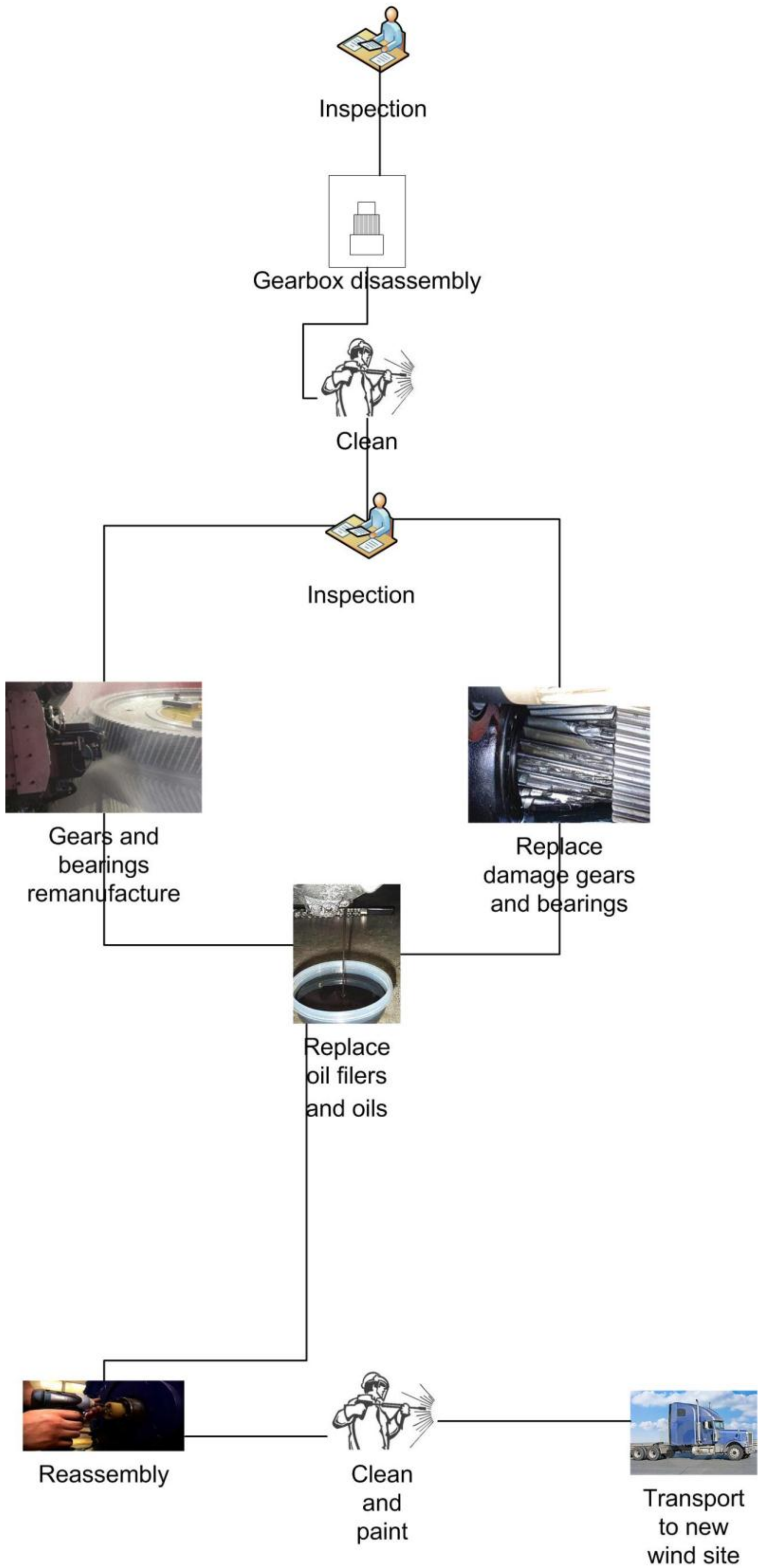


Figure 15. Gearbox remanufacturing processes

Gear	Bearing type	Weight [kg]
Planet carrier	SL 18 18	35.73
	SL18 29	98.3
Planet pinion	SL18 22	43.12
	SL18 30	140
	SL18 22	43.12
	SL18 30	140
	SL18 50	196.5
	LSL19 23	253
Hollow shaft	SL 18 18	35.73
	SL 18 29	98.3
	SL 18 30	140
Intermediate shaft	LSL 19 23	140
	LSL 19 23	196.5
Output shaft	QJ248-N2-MPA	53.1
	QJ248-N2-MPA	53.1

Table 17. Quantity, type and weights estimation of bearings for the gearbox analyzed. Gebauer and Ruhl. 2001

Table 17 displays an estimation of the weight distribution of the bearing used for the gearbox. The following is a description of the remanufacturing procedure for gears and bearings.

4.2.2.6.8 Gears remanufacturing

Gears are cleaned before machining. Table 17 summarizes the energy consumption for different cleaning processes, only one is used:

Cleaning process	**Energy consumption per ton of Steel cleaning [kWh/ton]**	**Gears [9.5tons]**		**Case [4.14tons]**	
		Energy consumption [kWh]	Material use	Energy consumption per ton of Steel cleaning [kWh/ton]	Material use
Ultrasonic	3.8	36.1	Water: approximately two times the volume of the parts: $Vparts = 1.83m^3 \times 2 = 3.66m^3 = 3660L$	15.73	$7.8\ m^3 \times 2 = 15.6\ m^3 = 15600\ L$ of water
CO^2 Blasting	100	950	11117 Lb of dry ice	414	804.7 Lb
Water spray washing	4	38	2006 L of water	9.10	874.19 L
Vapor degreasing	3.2	30.4	888 L of water	13.25	386.98 L

Table 18.Energy consumption for cleaning of steel gears. Govetto, S. 2008

According to the Table 4, the total volume of the steel gears is approximately 1.833 m^3, which represent 9.5 tons of steel, if the amount of steel cleaned per ton using an ultrasonic process is 3.8 kWh (Govetto, S. 2008), then for 9.5 tons, 36.1 kWh would be needed. Conversely, the amount of solution is a function of the total volume of cleaned gears. The amount of solution should be two times the volume of the parts 1.83m^3 (Govetto, S. 2008).

Besides the 100 kWh/ton of cleaned steel gears using the CO_2 blasting process for 9.5 tons of gears, the amount of dry ice consumption is determined. For this calculation the surface area of gears is

needed first. Based on an average rate cleaning area of 750 cm^3/min and the gears dimensions of Table 4, then in Table 19 the calculations for the amount of dry ice obtained are shown.

CO2 blasting cleaning with dry ice							
Part	One circular surface area	Two circular surface areas	Area of tooth	Total area	Cleaning time [min]	Cleaning time [h]	Amount of ice [lb]
Ring gear	90746	181492	360406	541897	722.5305	12	1806
Sun pinion	3846	7693	360406	368098	491	8.2	1227
1st stage gear	31400	62800	360406	423206	564	9.4	1411
1st stage pinion	2826	5652	360406	366057	488	8.13	1220.2
2nd stage gear	17662.5	35325	360406	395731	527.64	8.79402	1319.1
2nd stage pinion	961.6	1923.25	360406	362329	483.1055	8.051759	1207.77
Shink disk	70650	141300	360406	501706	668.9412	11.15	1672.35

Table 19.Amount of dry ice in CO_2 blasting cleaning of steel gears. Govetto, S. 2008

For the spray washing process, it is estimated that 4 kWh/ton of energy is employed. Therefore, 38 kWh for the 9.5 tons of gears and 2006L of water are used in a Uniwashing machine (Govetto, S. 2008). Finally, the energy use in vapor degreasing process is 30.4 kWh for the 9.5 tons of gears and 888L of water use. In conclusion, it can be seen from Table 18 that CO_2 blasting is the most energy and material consuming and vapor degreasing is the less intensive cleaning process of all. Vapor degreasing is the one included in the LCA.

Two approaches can be analyzed in gear remanufacturing. The first one is the use of Plasma Spray. The volume of steel added is of 11cm^3 or 86gr of steel, leading to energy consumption between 190 kWh/ton and 370kWh/ton for steel gears. Here there is a high-energy consumption but it is small compared to the energy required to manufacture the gear from scratch or using recycled material (Govetto, S. 2008). The second approach is using a machining process; the type of machining considered is a finishing phase. Before analyzing the finishing for gears remanufacturing, the amount of volume removed for roughing is calculated. In table 20 is referred the amount of energy required for machining a

gear, which will be useful for the final calculations. R is given, so assuming R1 is 13% greater than R', r1 and e is given. Then the volume of steel removed is:

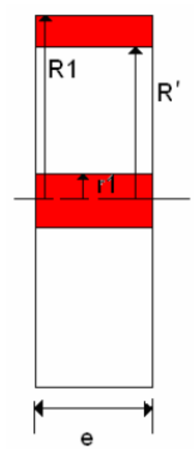


Figure 16. Dimensions considered for Gears remanufacturing. Govetto, 2008

$$Vsteel = \pi * \left(r_1^2 - 0.5 * \left(R_1^2 - R'^2\right)\right) * e = \pi * (7.06^2 + 0.5 * (56.5^2 - 50^2) * 6^2 = 39{,}790 cm^3$$

Material	R[cm]	R'[cm]	r1 [cm]	Energy requirement [kWh/cm^3]	Volume removed from planet gear [cm^3]	kWh/planet gear	Energy consumption per gear [kWh/ton]
Steel	50	56.5	7.06	0.0027	39,790	107.43	213.58

Table 20.Steel roughing machining energy consumption. Govetto, S. 2008

Table 20 shows the energy consumption per ton of gear remanufactured. According to Govetto, the total energy consumption from remanufacture a gear is 1/5 of the energy used on machining a new gear.

$$En\ machining\ remanufacturing = \frac{EN\ machining\ roughing}{5} = \frac{213.58}{5} = 42.716\ kWh/ton$$

The following are the processes in detail regarding the remanufacturing of a gearbox with new gears and bearings.

Process	Input	Value	Source/Comments
Gears	Planet gears	1.513 Tons	Calculation of weight for parts of a V80 2.0 MW wind turbine gearbox. Canadian Wind Energy Industry, 2011. Seekpart.com, Gear Ring - wind power machinery Ring, 2011.
	Helical gears	8.327 Tons	
	Rings gears	1.146 Tons	
Bearings	New bearings	1.665 Tons	Gebauer and Ruhl. 2001
Gearbox test	Electricity, production mix, US/US U	$2MW \times 12h \times (1-0.7) \times (1-0.9) = 0.72\ MWh$	12 hours in a testing bench, energy recovered and losses are included. Gearboxexpress, 2011.
Gearbox disassembly	Electricity, production mix, US/US U	1 kWh	Mostly manual process
Vapor degreasing gearbox case	Electricity, production mix, US/US U	$13.25\ \text{kW/Ton} \times 4.1\ \text{Ton} = 112\ \text{kWh}$	Govetto, S. 2008
	Tap water, at user/RER U	386.98 Kg	Govetto, S. 2008
Painting gearbox	Automotive painting, pretreatment/RNA	7 m^2	
	Automotive painting, top coat, per m^2/RNA	7 m^2	
Gearbox assembly	Electricity, production mix, US/US U	1 kWh	Mostly manual process

Table 21. Inputs for remanufacturing a gearbox from a V80 2.0MW. 2011

According to Table 21, for the gearbox remanufacturing analysis in SimaPro, the only processes that change are whether the gears or bearings are new or remanufactured.

4.2.2.6.9 Transformer

The kind of problems that can be present in a remanufacturing process for a transformer may have three different origins: dielectric problems caused by overvoltage and insulation ageing, thermal problems as a result of thermal overheating, and electro-mechanical problems due to short-circuit faults. One company that performs remanufacturing for transformers is ABB. They not only rely on physical testing, but also on reverse engineering techniques to locate possible defects prior to inspection. In order to avoid short-circuit faults, they perform better than original improvements in aspects like ampere-turn balancing, winding support, work hardening, epoxy coatings of conductors, and rigid clamping for windings (ABB, 2005).

Dry-type transformers are generally used for wind turbines. The transformer initially is cleaned, disassembled, and inspected before knowing the degree of damage to the equipment. The core steel and tank are repaired if they present considerable damage, but this is not considered in the analysis since is not a usual situation in a wind turbine; core steel and tank represents most of the monetary value and carbon footprint of the transformer (Steigermeier, 2011).

Energy and material used during inspection tests performed over the transformer are not considered in the analysis. After disassembly, a baking process for 8 hours at 275 ^{O}F is used to remove water and dirt from the tank. All the organic material is removed as insulation and tape contained in the individual conductors, also the cellulose (wood and paper) within the winding. ABB has assembled winding kits using techniques as winding cylinders to avoid the windings to pop out of the transformer. The copper and aluminum winding is removed, recycled, and replaced for new winding of the same material; 80% of the winding is made of copper and 20% of aluminum (Vito NV, 2010).

The coiling system is divided into low voltage (LV) and high voltage (HV) coils. The LV coil winding machines are used to rewind the transformer in a pre-impregnated insulation process, where winding sheet conductors are winding in parallel with epoxy pre-impregnated sheet of insulation, and compacting forces are applied to the winding at room temperature. Afterwards, the winding sheet conductors are dried out to form a solid block. The HV coils are wound using foil strips or rectangular magnet wire, and the winding stacking can be done by layer, disk, or pancake construction. The windings are immersed in a vacuum casting process with mineral epoxy for 8.25 hours (Titus, W. 2010). Additional

fiber glass is impregnated afterwards to reinforce the coil (ABB, 2005). Bushings and gaskets are replaced (Garrett & Sons, 2008). The advantage of remanufacturing is that the company in charge of the remanufacturing process can take advantage of the technology improvements in new materials years after the transformer was initially manufactured. Figure 17 shows the remanufacturing process for a transformer.

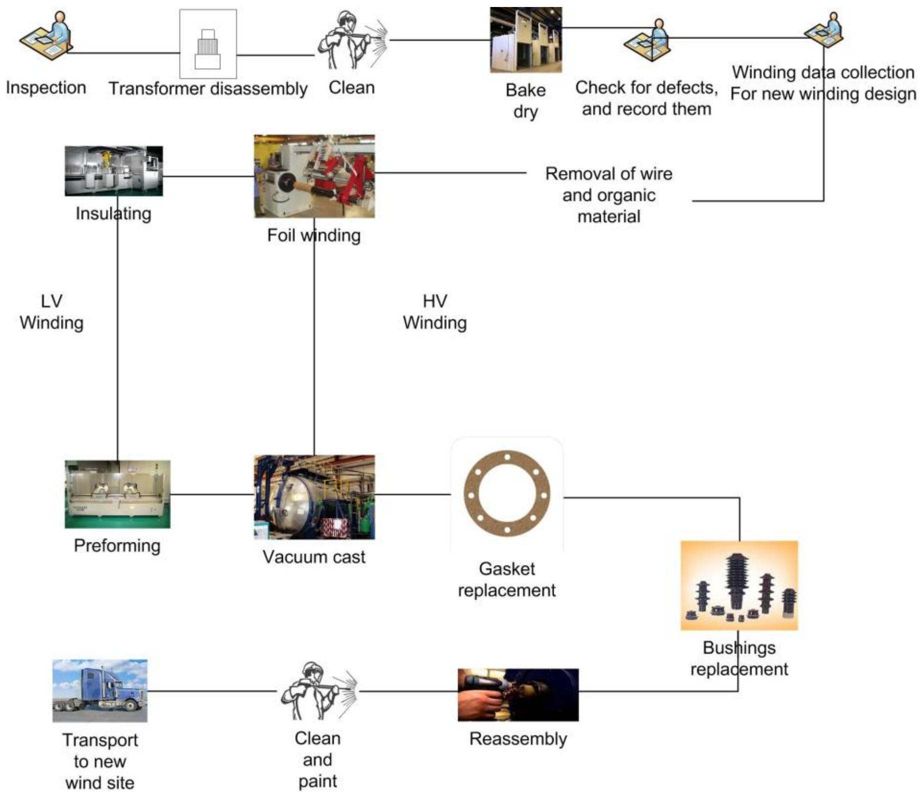


Figure 17. Transformer remanufacturing processes

Process	Input	Value	Source/Comments
Transformer disassembly	Electricity, production mix, US/US U	10 kWh	Assumed value, mostly manually disassembled
Steam cleaning for transformer	Gasoline, combusted in equipment/US	8.327 L	Assuming fuel consumption of 1.1 GPH for the 18hp engine of the steam machine
	Tap water, at user, /RER U	1146 Kg	1h cleaning with 5GPM of water usage for steam cleaning, assumed value
Dry baked for transformer	Heat, natural gas, at boiler atmospheric non-modulating<100kW/RER U	$38\ \text{kWh} \times 8\ \text{h} = 304\ \text{kWh}$	Using info from the same oven as for the dry baked generator
	Polychlorinated biphenyls	15 Kg	
Wire and organic material removal from transformer	Electricity, production mix, US/US U	0.297 kWh	Strip wire from the transformer can be done using an 800 W electric hoist. Refer to process "wire removal from generator"
LV rewinding for transformer	Copper wire for coil	1696.8 Kg	Total weight of winding 2121Kg, 80% of that is copper.
	Compressed air, optimized installation, >30kW, 6 bar gauge, at supply network	$0.018\frac{\text{m}^3}{\text{sec}} \times 60\frac{\text{sec}}{\text{min}} \times 60\frac{\text{min}}{\text{h}} \times 3\text{h} \times \frac{2121}{5000} = 82.5\text{m}^3$	Refer to process: Rewinding process for large generator
	Epoxy resin I	50Kg	Assumed value
	Aluminum for winding	$20\ \% \times 2121\ \text{Kg} = 424\ \text{Kg}$	Aluminum weight in winding of transformer is 20% of 2121Kg

	Electricity, production mix, US/US U	$\frac{7.45\ kWh * 2121\ Kg}{5000\ Kg} =$ 3.16 kWh	Preforming 7.45 kWh =Energy to preforming a generator (5tons of copper) 2121 Kg=quantity of copper from transformer 5000 Kg =quantity of copper from generator
	Electricity, production mix, US/US U	$\frac{112\ kWh * 2121\ Kg}{5000\ Kg} =$ 47.5 kWh	Rewinding 112 kWh=Energy to rewind a generator (5tons of copper) 2121 Kg =quantity of copper from transformer 5000 Kg =quantity of copper from generator
HV windings	Electricity, production mix, US/US U	55.95 kW x 2 h = 112 kWh	Rewinding machine can handle up to 9T generator. Broomfield USA
Vacuum cast for transformer	Dry baked for transformer	0.25 of dry baked for generator	Used to eliminate moisture before Vacuum process: The original "Dry baked for transformer" process uses 8 hours for baked dry the transformer, for this is only needed 2 hours

Table 22.Inputs for remanufacturing a transformer from a V80 2.0MW. 2011

Chapter V - Results

5.1 Manufacturing scenario

There are different LCAs performed for the manufacturing of 2.0MW wind turbines, but the one performed by Martinez et al in 2008 is the only one that shows results of the environmental impacts in Ecopoints (Pt.). The paper analyses a LCA for a Gamesa G8X 2.0MW, and offers two pieces of valuable data in order to make a fair comparison between their manufacturing and remanufacturing scenarios. The data displayed in Figure 18 refers to the environmental impacts in kPt. for each major component using the input information for the production of the components of the wind turbine. In the interest of this work, only the impacts resulting from the production of components inside the nacelle are considered for comparison purposes. The data detailed in Table 23, displays the total amount of materials and energy used for the manufacturing of the main components of the G8X 2.0MW wind turbine.

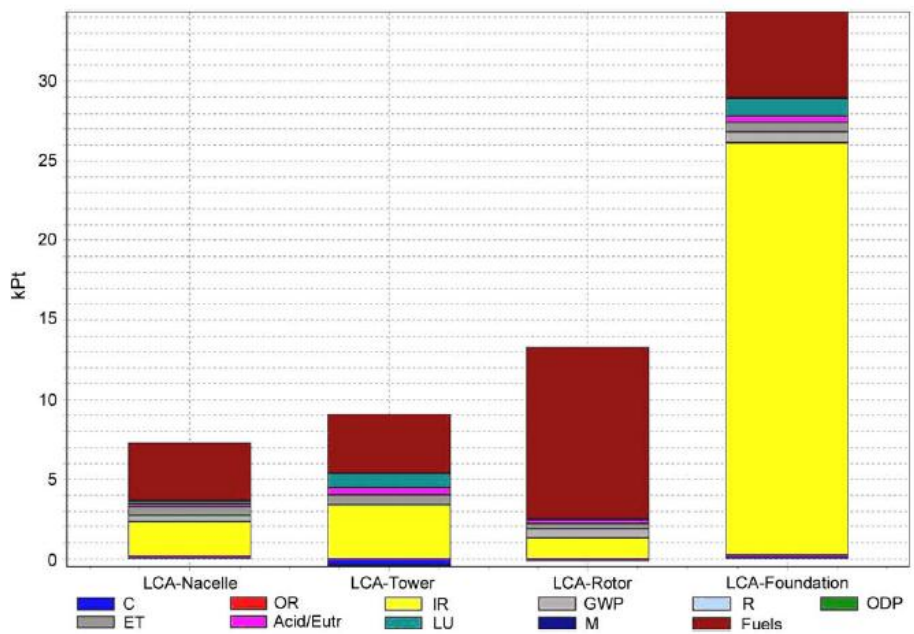


Figure 18. Eco profile for the four main components of a G8X 2.0MW wind turbine. Martinez et al, 2008.

According to Figure 18, the components inside the nacelle account for close to 7,500 Pt. This number should be close to the results of a LCA developed using the inputs from Table 23.

Component	Sub-component	Weight	Materials	Energy
Rotor	Three blades	19.5 t	11.7 t resin 7.8 t fibre glass	20, 15 MWh
	Blade hub	14 t	14 t cast iron	12 MWh
	Nose-cone	310 kg	0.124 t fibre glass 0.186 t resin	0.95 MWh
Foundation	Footing	725 t	700 t concrete 25 t iron	0.4 MWh
	Ferrule	15 t	15 t steel	17,000 MJ
Tower	Three sections	143 t	143 t steel	170,000 MJ
Nacelle	Bed frame	10.5 t	10.5 t iron	9 MWh
	Main shaft	6.1 t	6.1 t steel	5.3 MWh
	Transformer	5 t	0.149 t silica 1.5 t copper 3.3 t steel	200,000 MJ
	Generator	6.5 t	0.195 t silica 2 t copper 4.29 t steel	265,000 MJ
	Gearbox	16 t	8 t iron 8 t steel	495,000 MJ
	Nacelle cover	2 t	0.8 t fibre glass 1.2 t resin	6.2 MWh

Table 23.Energy use, type and quantity of materials employed for the manufacturing of the four main components of a G8X 2.0MW wind turbine. Martinez et al, 2008.

Table 24 shows the results that were obtained from running SimaPro using the input data for the nacelle from Table 23.

Eco-indicator 99, Manufacturing scenario		
E [Pt.]	H [Pt.]	I [Pt.]
40,468	37,219	462,200

Table 24. Results obtained from SimaPro for the manufacturing of the components inside the nacelle of a G8X 2.0MW wind turbine using input data from table 23.

It can be seen that the results of 7,500 Pt. originally obtained in the paper were not consistent with the results obtained using the inputs from Table 23. The closest value is 37,219 Pt. obtained from the Eco-indicator 99 hierarchist scoring system. Nevertheless, that result is five times higher than the result reported in the original paper. It is difficult to establish the reasons behind these differences. Therefore, in order to obtain a comparative value against our remanufacturing scenarios, we have to consider the materials and energy used, because they are the greatest contributors to the manufacturing impacts of the

components inside a wind turbine nacelle. The other wind turbine parts of the LCA from Martinez et al. were also analyzed in order to have a sense of the source of discrepancies for the nacelle manufacturing.

	Martinez et al	Sosa		
	Eco-indicator 99 [Pt.]	E [Pt.]	H [Pt.]	I [Pt.]
Nacelle	7,500	40,468	37,219	462,200
Rotor	13,200	10,392	16,580	2,944
Foundation	34,500	23,235	23,582	48,210
Tower	9,000	13,966	10,405	15,601

Table 25. Results obtained from SimaPro for the manufacturing of the components inside the nacelle for a G8X 2.0MW wind turbine using input data from table 25. (Eco-indicator 99).

The results from Martinez et al for the rotor, the foundation, and the tower (Table 25) are consistent with the LCA results using the data from Table 23. This means that other parameters affecting the results for the nacelle manufacturing in Martinez et al were not explained in that paper. Given these results, for comparative purposes, the nacelle manufacturing input data from Table 24 was used in order to understand the environmental impacts obtained in the LCAs for remanufacturing scenarios explained in the following section.

5.2 Remanufacturing scenarios

The configuration of the different remanufacturing scenarios will influence the results. The scenarios presented are:

Scenario 1: Remanufacturing, using new bearings and gears.

Scenario 2: Remanufacturing, using remanufactured bearings and gears.

Scenario 3: Remanufacturing, using new bearings and remanufactured gears.

Scenario 4: Remanufacturing, using remanufactured bearings and new gears.

These four scenarios, shown in Table 26, were configured depending on whether the bearings (inside the main shaft, the gearbox, and the generator) and the gears (inside the gearbox) are to be

replaced by new ones or remanufactured. Remanufacturing procedures remain the same on each scenario for the bedframe, the nacelle cover, and the transformer.

	Description of each scenario			
Parts	**Scenario 1: New bearings and gears**	**Scenario 2: Remanufactured bearings and gears**	**Scenario 3: New bearings and remanufactured gears**	**Scenario 4: Remanufactured bearings and new gears**
Transformer, Nacelle cover, Bedframe	Typical Remanufacturing	Typical Remanufacturing	Typical Remanufacturing	Typical Remanufacturing
Main shaft, Generator	New bearings	Remanufactured bearings	New bearings	Remanufactured bearings
Gearbox	New bearings and gears	Remanufactured bearings and gears	New bearings and Remanufactured gears	Remanufactured bearings and new gears

Table 26.Differences in remanufacturing scenarios for a typical remanufacturing process of components inside the nacelle.

5.2.1 Remanufacturing scenarios in Eco-indicator 99

This section compares the results of Martinez et al and the inputs for remanufacturing in Eco-indicator 99.

		LCA using Eco-indicator 99					
		E [Pt.]	**E [%]**	**H [Pt.]**	**H [%]**	**I [Pt.]**	**I [%]**
	Base scenario: new wind turbine manufacturing	40,468	100%	37,219	100%	462,200	100%
Remanufacturing	**Scenario 1: New bearings and gears**	36,349	90%	35,663	96%	423,742	92%
	Scenario 2: Remanufactured bearings and gears	7,513	19%	7,440	20%	39,062	8%
	Scenario 3: New bearings and remanufactured gears	20,105	50%	20,057	54%	201,016	43%
	Scenario 4: Remanufactured bearings and new gears	23,757	59%	23,047	62%	261,787	57%

Table 27. SimaPro results of the impacts from the new wind turbine manufacturing and the remanufacturing scenarios, and comparison expressed in percentages (Eco-indicator 99).

Table 27 displays a summary of the impacts obtained in SimaPro for each scenario and version of the Eco-indicator 99. Scenario 1 represents the greatest environmental impacts among the four scenarios. In this case, the individualist (I) normalization version accounts for the greatest impacts among the three evaluation methods for the remanufacturing scenarios.

Scenario 1 has most of the impacts, with between 90 and 96% of the total impacts from the original manufacturing scenario. In the individualist version the impacts for scenario 1 are 423,742 Pt., almost 200,000 Pt. over the scenario 4, because scenario 1 uses new bearings and scenario 4 uses remanufactured bearings. Furthermore, the environmental impacts of scenario 1 in the egalitarian and hierarchical versions are between 181 and 178% of scenario 3, and five times higher than scenario 2; it is important to notice that scenario 2 and 3 use remanufactured gears.

From an environmental impacts perspective, scenarios 2 and 4 offer an interesting outlook on whether to use remanufactured gears or not. The Scenario 2 are only 32 and 15% of the impacts associated with scenario 4, in which the old gears were replaced by new ones. In addition, all the versions in scenario 2 show only between 20 and 8% of the impacts from manufacturing new components inside the nacelle. That is the lowest among the gears remanufacturing scenarios.

The common characteristic between scenario 3 and 4 is that either the gears or the bearings are remanufactured, but the impacts are greater for scenario 4. The impacts of the individualist evaluation in scenario 4, the one that corresponds to new gears and remanufactured bearings, are 261,787Pt. Scenario 3, which analyzes new bearings and remanufactured gears, has an impact of 201,016 Pt. On the other hand, the difference between the impacts in scenario 3 and 4 for the egalitarian and hierarchist version is 9 and 8% respectively. The comparison between these two scenarios helps to understand the influence in the impacts of using new gears and bearings.

The differences in the results between the manufacturing and remanufacturing scenarios are not related to the weight of the wind turbine analyzed in this LCA or the Martinez et al study. The total weight of the components represented in the input data for the remanufacturing scenarios corresponding to the Vestas V80 2.0MW (46.1 Tons) wind turbine, was only 5.9% less than the total weight of the input data for the manufacturing scenario belonging to the GAMESA G8X 2.0MW (48.99 Tons) wind turbine.

The following is a more detailed analysis of final results using ReCIPe Endpoint, which is the most up-to-date weighting method in SimaPro.

5.2.2 Remanufacturing scenarios in ReCIPe Endpoint

Here the remanufacturing scenarios are compared using the ReCIPe Endpoint method, which was not available to Martinez et all. Given the differences in how Eco-indicator 99 and ReCIPe Endpoint were weighted, for these calculations different results can be noticed. Before explaining the results in detail, the weightings of each impact in the analysis for the egalitarian, hierarchist, and individualist versions of ReCIPe are described (Pre, 2012):

- In the default hierarchist perspective, the contribution of Human Health and Ecosystem Quality is 40% each. Respiratory effects and greenhouse effects dominate Human Health damages. Land use dominates Ecosystem Quality; Resources is dominated by fossil fuels

- In the Egalitarian perspective, Ecosystem Health contributes 50% to the overall result. The relative contributions within the damage categories are about the same as in the hierarchist perspective, except for carcinogenic substances. A hierarchist would consider a substance as carcinogenic if sufficient scientific proof of a probable or possible carcinogenic effect is available (International Association for Research on Cancer (IARC) class 3 and up)
- In the individualist perspective, Human Health is by far the most important category. Carcinogenic substances however play virtually no role. The individualist would only include those substances for which the carcinogenic effect is fully proven (IARC class 1). The individualists would also not accept (based on experience) that there is a danger fossil fuels can be depleted. This category is left out. For this reason Minerals become quite important

The impact assessment determines and quantifies the environmental impact of gathering and processing materials, transportation, operation, and retirement. The Figure 19 shows the impact categories analyzed:

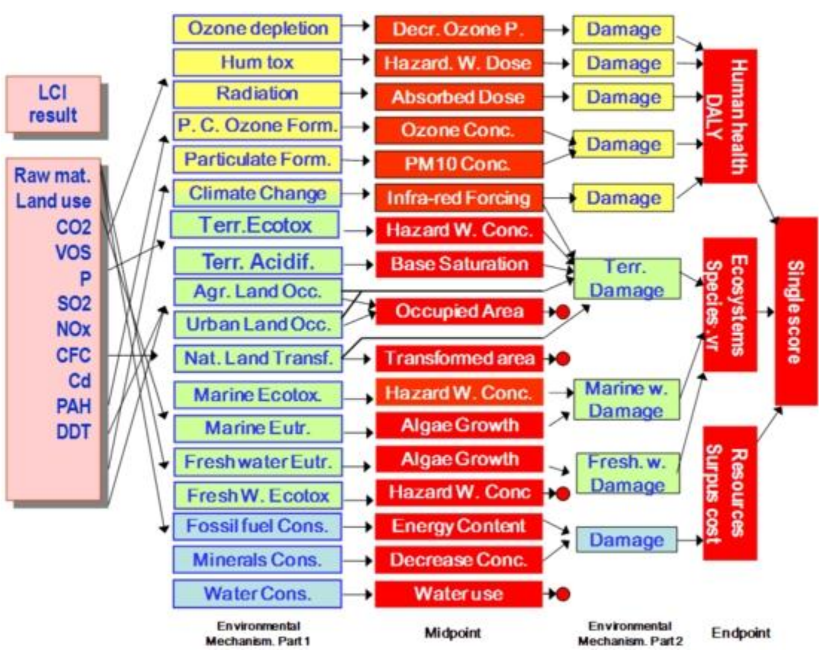


Figure 19. Impact categories analyzed in ReCIPe. Pre consultants, 2008.

	RECIPE - End point - Original condition A

		E [Pt.]	E [%]	H [Pt.]	H [%]	I [Pt.]	I [%]
	Base scenario: new wind turbine manufacturing	**46,489**	**100%**	**39,139**	**100%**	**29,441**	**100%**
Remanufacturing	**Scenario 1: New bearings and gears**	29,401	63%	19,703	50%	14,507	49%
	Scenario 2: Remanufactured bearings and gears	9,659	21%	2,937	8%	2,617	9%
	Scenario 3: New bearings and remanufactured gears	18,107	39%	10,633	27%	10,316	35%
	Scenario 4: Remanufactured bearings and new gears	20,774	45%	12,006	31%	12,366	42%

Table 28. SimaPro results of the impacts from the new wind turbine manufacturing and the remanufacturing scenarios, and comparison expressed in percentages (ReCIPe Endpoint).

According to Table 28, the egalitarian version for scenario 1 shows greater impacts among the three ReCIPe End-point versions, but much less than the impacts for the new wind turbine manufacturing scenario. This is because both bearings as gears were included as new components. All hierarchical and individualist versions for each remanufacturing scenario had less than 50% of the impacts than the manufacturing scenario. This occurs because the egalitarian version displays long term impacts than hierarchical and individualist versions of ReCIPe End-point.

Scenario 2, corresponding to remanufactured gears and bearings, had the lowest scores among the four scenarios. The hierarchical and individualist showed impacts with 8% and 9% compared to the manufacturing scenario, respectively. On the other hand, the egalitarian perspective, showed higher scores than the two versions, but only 21% of the impacts relative to manufacturing a new wind turbine.

In scenario 3, the impacts are fewer than in scenarios 4 and 1. The individualist version has impacts of 35% relative to the base manufacturing scenario. The hierarchical version has 27% of the impacts compared to the same version in the base manufacturing scenario, and the egalitarian version accounts only for 39% of the impacts.

The scores for scenario 4 were the second closest to the impacts of the base manufacturing scenario. The egalitarian version has 45% of the impacts from the base case manufacturing scenario. But

again, as shown in the other three scenarios, the hierarchical and individualist version had less than half of the impacts compared to the base manufacturing scenario; for the hierarchical version the impacts were 31% and for the individualist the impacts for manufacturing were 42%.

According to Pre Consultants, the hierarchical version should receive more attention for the analysis of results since it is generally the setup used to perform the analysis in the ReCIPe Endpoint method. Therefore, the following sections are focused on the hierarchist perspective of the ReCIPe method.

5.3 Sensitivity and impact analysis

An analysis was conducted on copper and steel materials for the most relevant remanufacturing scenarios, in order to determine if remanufacturing remains as an environmentally sound option for wind turbine retirement. Three remanufacturing scenarios were analyzed individually and then compared to each other.

The 1st, 2nd, and 3rd remanufacturing scenarios were chosen because, according to the results in Table 28, the first scenario had the highest impact scores, and the second scenario had the lowest scores. In addition, the third scenario is included because it is the most likely to occur.

The sensitivity analysis is divided in three conditions: condition A (original input data) uses recycled copper and a mix of virgin and recycled steel, condition B uses recycled copper and steel, and condition C is employed virgin copper and virgin steel.

A summary of the impacts using ReCIPe Endpoint – H is displayed in Table 29.

	ReCIPe Endpoint - H method. Comparison versus new wind turbine manufacturing scenario (39,139Pt.)						
	Sensitivity condition	**Condition A**		**Condition B**		**Condition C**	
	Base scenario: new wind turbine manufacturing	Pt.	%	Pt.	%	Pt.	%
Remanufacturing	**Scenario 1: New bearings and gears**	19,703	50%	19,050	49%	21,781	56%
	Scenario 2: Remanufactured bearings and gears	2,937	8%	2,937	8%	5,005	13%
	Scenario 3: New bearings and remanufactured gears	10,633	27%	10,633	27%	12,710	32%
	Scenario 4: Remanufactured bearings and new gears	12,006	31%	11,354	29%	15,225	39%

Table 29. Sensitivity analysis for each remanufacturing scenario (ReCIPe Endpoint –H).

The following sections analyze the impacts in detail of those scenarios using RECIPE Endpoint H analysis method.

5.3.1. Sensitivity and impact assessment for1st remanufacturing scenario

5.3.1.1 Condition A

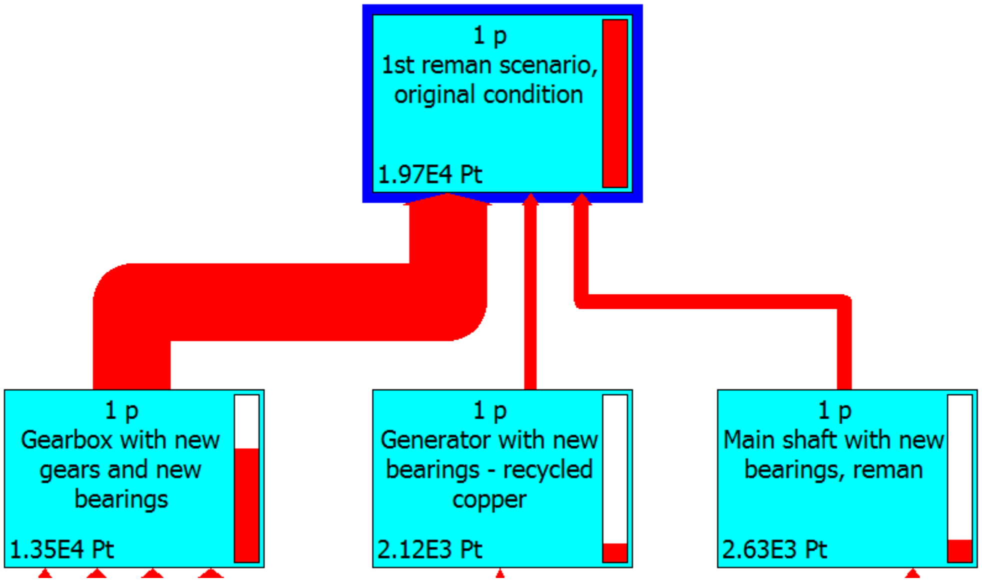


Figure 20. Network of impacts resulting from the 1st remanufacturing scenario (ReCIPe Endpoint –H, 9.6% threshold).

In Figure 20 the processes that contribute at least 9.6% of the impacts for the remanufacturing scenario 1 are displayed, this threshold was chosen because is not possible to show here a greater level of detail. The gearbox remanufacturing has the greatest environmental impacts with 13,494 Pt. The top ten processes that contribute at least 1% of the impacts are included in Table 30, because the complete network diagram is too complex to show. The results for the bedframe, the nacelle cover, and the generator bedframe are not displayed in Table 30 because their impacts are fewer than 52 Pt. each.

No	Process	Total	Gearbox with new gears and new bearings	Generator with new bearings - recycled copper	Main shaft with new bearings, reman	Transformer - recycled copper
	Total of all processes	19,703	13,494	2,117	2,631	1,390
1	Energy from LPG in bearing manufacturing	1,462	790	224	448	X
2	Electricity from hard coal, used in steel making	1,373	1,099	91	180	2
3	Hard coal, burned in industrial furnace for gears and bearings	1,373	1,037	126	171	38
4	Raw Ferrochromium, high-carbon, 68% Cr, used in steel making	1,168	937	77	154	0
5	Electricity from hard coal, mostly steel making	903	660	94	109	41
6	Electricity gas, various processes	831	578	103	91	55
7	Ferronickel, 25% Ni, used in steel making	822	659	54	108	0
8	Lignite electricity, for various processes	683	384	137	55	106
9	Natural gas, burned in industrial furnace, mostly for steel making	449	349	33	65	2
10	Electricity from hard coal, mostly steel making	437	190	30	89	123

Table 30. Impacts resulting from the ten processes that represent at least 1% of the impacts in 1st remanufacturing scenario, condition A (ReCIPe Endpoint –H).

Most of the high-impact processes are raw material extraction or energy related processes. However, the focus of the sensitivity analysis was centered only in the origin of the materials employed because the type of energy consumed by the machines is not assumed to change. Also, the energy mix employed by the utilities will remain the same. According to Table 30, among the processes that have significant impacts are raw ferrochromium (1,168Pt.) and raw ferronickel (822 Pt.). Those steel materials were used in the manufacturing of the bearings and gears.

For this sensitivity case, other important contributors to the total impacts are energy from LPG in bearing manufacturing (1,462 Pt.), and the electricity from gas and coal to manufacture gears and bearings (5,367 Pt. total). This shows that the manufacturing of new bearings and gears has significant influence on the impacts of remanufacturing a wind turbine. In terms of impacts, Figures 21, 22, and 23 display the impacts resulting from this condition.

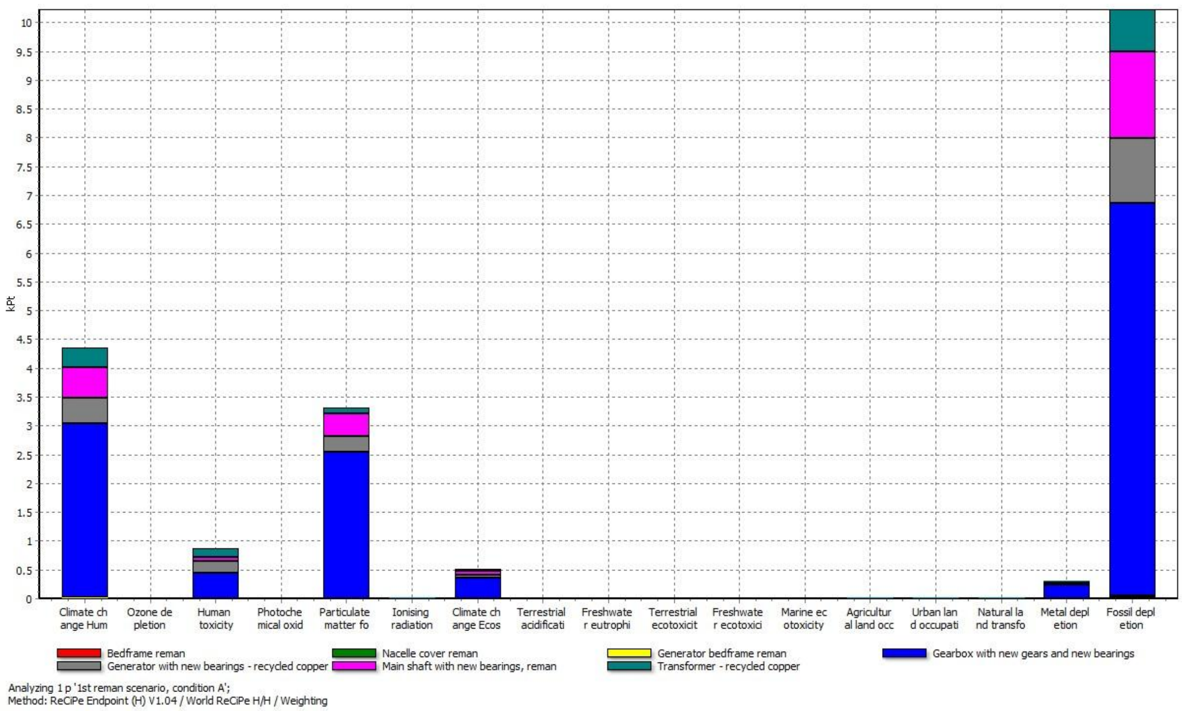


Figure 21. Weighting analysis resulting from the 1st remanufacturing scenario, original condition (ReCIPe Endpoint –H)

Figure 21 provides a picture of the damages incurred. It can be noticed that the Fossil Fuels Depletion category had the greatest impacts, accounting for 10,500 Pt. That score had similarity with the results from the gearbox in Table 30, in which the top impact contributors were related to energy consumption from fossil fuels.

In this weighting analysis, the impact from Fossil Fuels Depletion category is more than double the impact from Climate Change Human Health category, reporting 4,400 Pt. The impact for the Particulate Matter Formation category follows (3,400 Pt.). The other two categories that are relevant are Human Toxicity (900 Pt.) and Climate Change Ecosystem (500 Pt.) In all the categories except Human Toxicity, the gearbox has the biggest influence due to the manufacturing of new bearings and gears.

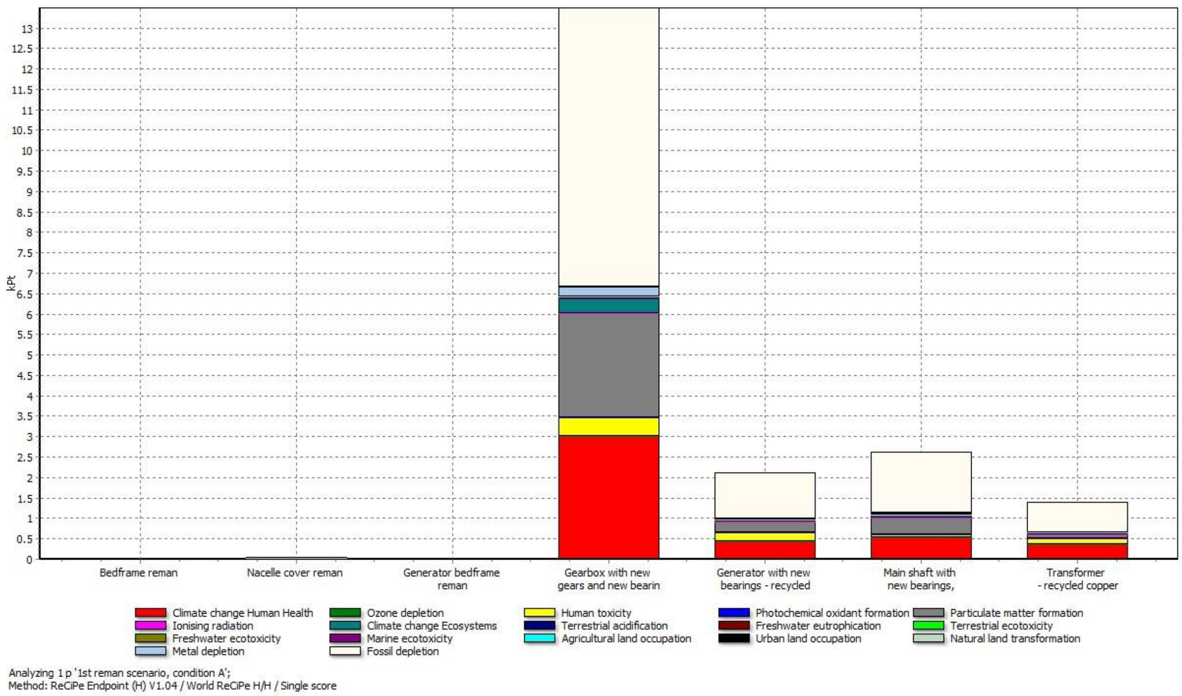


Figure 22. Single score analysis, Impact assessment resulting from the 1st remanufacturing condition A, (ReCIPe Endpoint –H).

Figure 22 displays the Single Score analysis, which corresponds to the impact contribution per component. It can be seen that the gearbox accumulates just over 13,000 Pt. mainly from the Fossil Fuel Depletion category. The rest of the impacts belong to the Climate Change Human Health and the Particulate Matter Formation categories. The main shaft has impacts just over 2,500 Pt. particularly from the Climate Change Human Health and the Fossil Fuel Depletion categories. The other component that has an important contribution for the impacts is the generator, with a value close to 2,100 Pt. The transformer has 1,500 Pt. of impacts. It can also be noticed that the contribution from the bedframe, nacelle cover, and generator bedframe is very small.

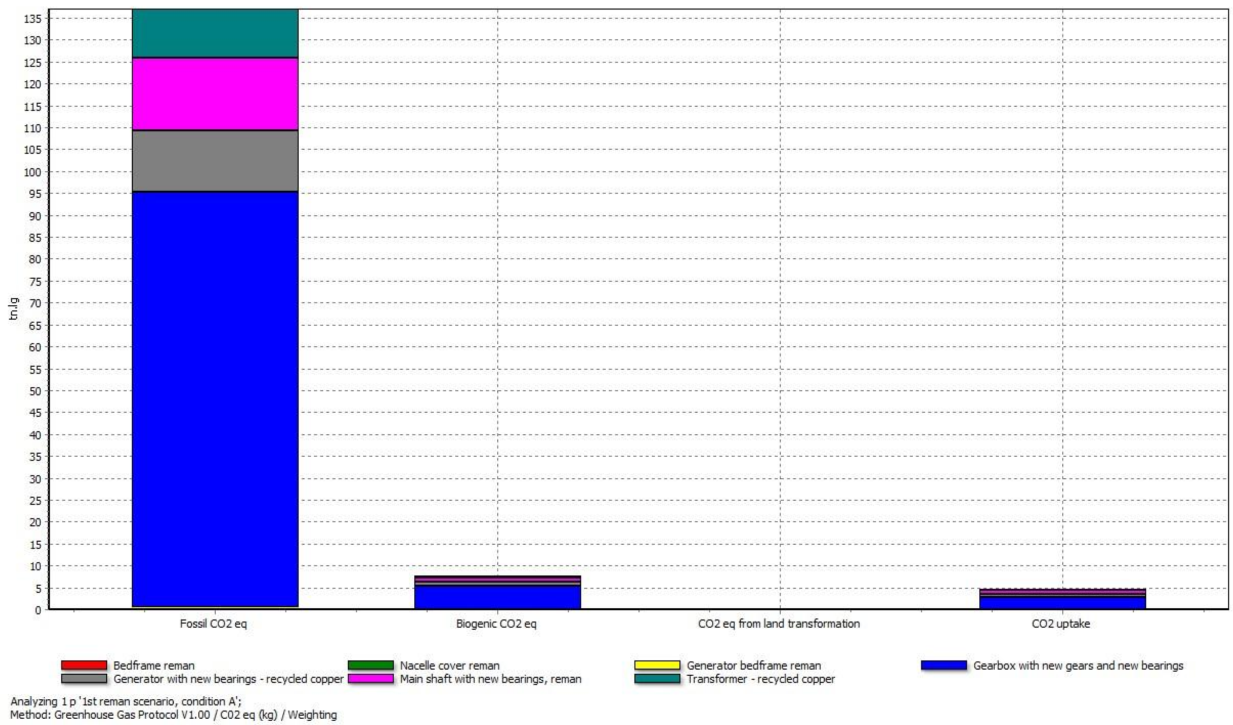


Figure 23. GHG analysis, Impact assessment resulting from the 1st remanufacturing condition A, (ReCIPe Endpoint –H).

According to the results in Figure 23, almost 140 Long Tons of equivalent CO2s are released to the atmosphere. As found in Figure 22, they mostly come from the gearbox, generator, main shaft, and transformer remanufacturing. 8 Long Tons of Biogenic CO2 equivalent is mainly consequence of the gearbox remanufacturing. 5 Long Tons corresponds to the CO2 uptake, mostly from gearbox remanufacturing. CO2 from land transformation is almost neglected in the results.

5.3.1.2 Condition B

This condition is defined by the use of recycled copper for windings in the generator and the transformer, and the use of recycled steel for the manufacturing of gears and bearings.

No	Process	Total	Generator with new bearings - recycled copper	Main shaft with new bearings, reman	Transformer - recycled copper	Gearbox w/ new gears and bearings - recycled steel
	Total of all processes	19,050	2,117	2,631	1,390	12,841
1	Energy from LPG in bearing manufacturing	1,462	224	448	x	790
2	Hard coal, burned in industrial furnace for gears	1,372	91	180	2	1,097
3	Raw Ferrochromium, high-carbon, 68% Cr, used in steel making	1,168	77	154	0	937
4	Electricity from hard coal, used in steel making	1,154	126	171	38	819
5	Electricity gas, various processes	844	103	91	55	591
6	Ferronickel, 25% Ni, used in steel making	822	54	108	0	659
7	Electricity from hard coal, mostly steel making	781	94	109	41	537
8	Lignite electricity, for various processes	706	137	55	106	407
9	Natural gas, burned in industrial furnace, mostly for steel making	436	33	65	2	335
10	Electricity natural gas, various processes	431	57	45	31	296

Table 31. Impacts resulting from the ten processes that represent at least 1% of the impacts in the 1st remanufacturing scenario, condition B (ReCIPe Endpoint – H).

From the results obtained the Table 31, the total impacts were reduced by about 2,000 Pt. compared to the remanufacturing scenario 1, condition A. This means that the use of recycled steel or copper does imply a large decrease in the impacts. Recycled copper appears to be especially helpful in reducing impacts from sulfidic tailings disposal, which accounted from 1,477 Pt., in the previous condition. On the other hand, this condition confirms that the use of energy related processes had most of the impacts in the LCA.

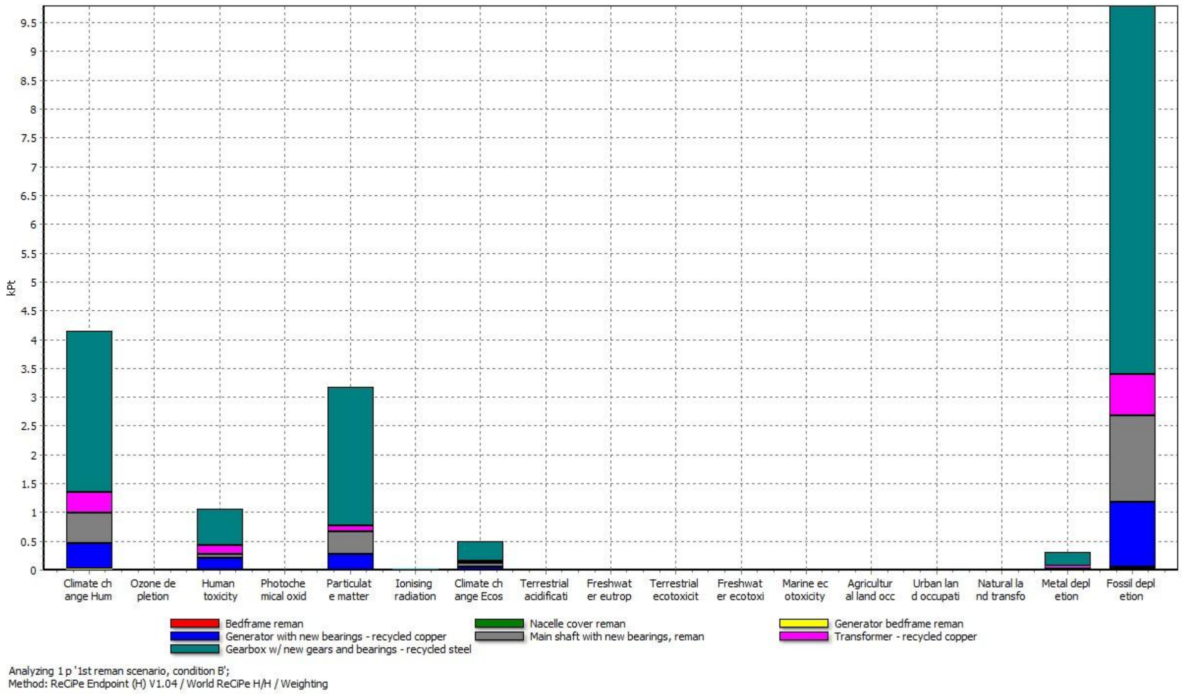


Figure 24. Weighting analysis resulting from the 1st remanufacturing scenario, condition B (ReCIPe Endpoint –H)

The weighting analysis for the condition B, according to Figure 24, has the same distribution compared to the two previous conditions. The Fossil Fuels Depletion category has impacts of 10,000 Pt., 6,500 Pt. coming from the gearbox remanufacturing. The Climate Change Human Health category generates 4,300 Pt. of the impacts, most of it coming from the gearbox remanufacturing. For the Particulate Matter Formation and Human Toxicity category the impacts of the gearbox remanufacturing are greater than any other part. In the Climate Change Ecosystems and Metal Depletion categories the impacts are much lower, less than 500 Pt. each.

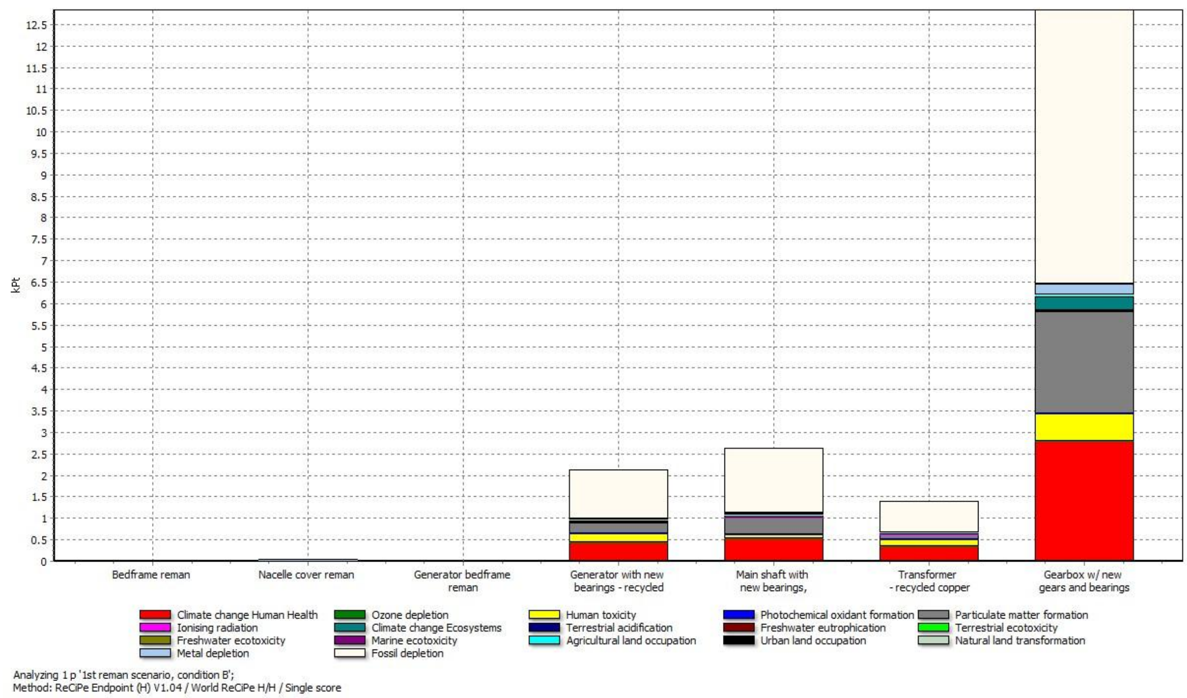


Figure 25. Single score analysis, Impact assessment resulting from the 1st remanufacturing, condition B (ReCIPe Endpoint –H).

The single score analysis for the condition B again shows that the gearbox remanufacturing has the greatest impacts of all the components with 13,000 Pt. As displayed in Figure 25 Fossil Fuel Depletion, Climate Change Human Health, and Particulate Matter Formation carry most of the impacts in the gearbox remanufacturing. The generator totals 3,200 Pt., and has its greatest impact in the Human Toxicity category. Fossil Fuel Depletion and Climate Change Human Health have some relevant impacts, but are less significant. The main shaft has 2,600 Pt., and those impacts mainly come from the Fossil Fuel Depletion and the Climate Change Human Health categories. The transformer has impacts of 2,300 Pt.

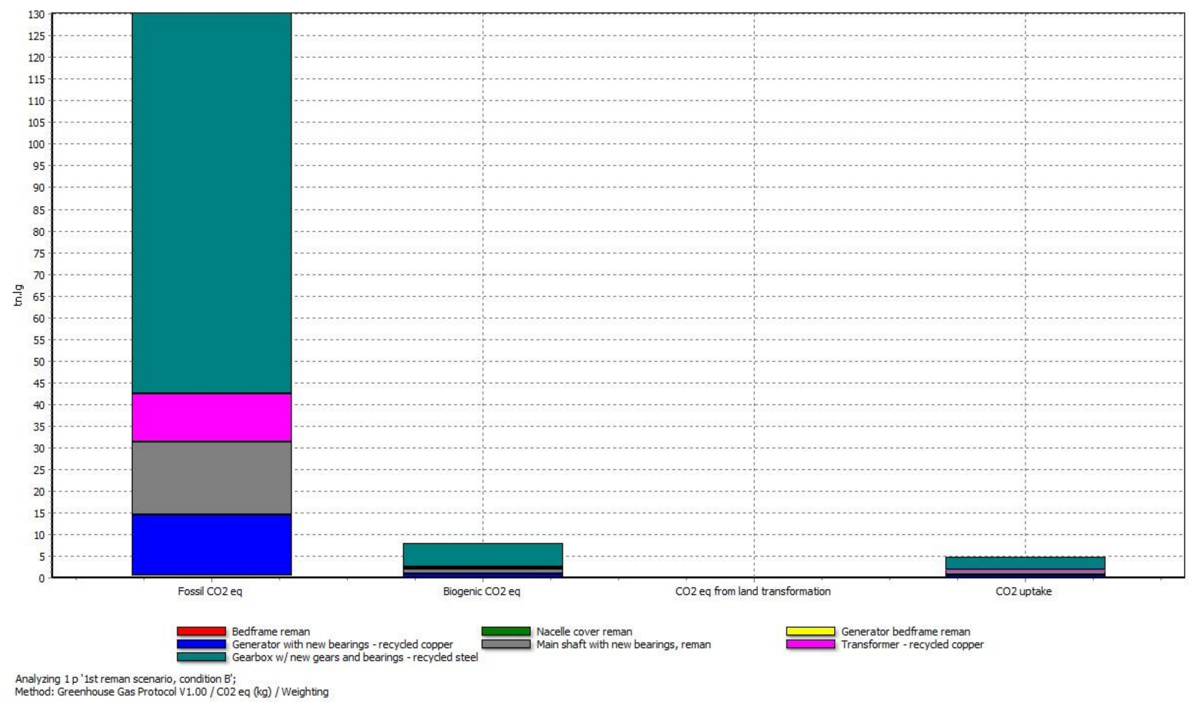


Figure 26. GHG analysis, Impact assessment resulting from the 1st remanufacturing scenario, condition B. (ReCIPe Endpoint –H).

Figure 26 displays 130 Long Tons of Fossil CO_2 equivalents, most of them coming from the generator, the gearbox, the transformer, and the main shaft remanufacturing. Eight Long Tons of Biogenic CO_2 equivalents are a consequence of the gearbox remanufacturing, and in a lesser way from the transformer remanufacturing. The CO_2 uptake, defined as the CO_2 captured by components during the material transformation, is approximately 5 Long Tons.

5.3.1.3 Condition C

This condition reflects the total impacts from using virgin copper and a mix of recycling and raw steel.

No	Process	Total	Transformer	Main shaft with new bearings, reman	Gearbox with new gears and new bearings	Generator with new bearings
	Total of all processes	21,781	2,304	2,631	13,494	3,281
1	Disposal, sulfidic tailings, virgin copper for windings production	1,477	625	8	53	791
2	Energy from LPG in bearing manufacturing	1,462	X	448	790	224
3	Hard coal, burned in industrial furnace for gears	1,382	6	180	1,099	96
4	Electricity from hard coal, used in steel making	1,381	42	171	1,037	131
5	Raw Ferrochromium, high-carbon, 68% Cr, used in steel making	1,170	1	154	937	78
6	Electricity from hard coal, mostly steel making	910	44	109	660	97
7	Electricity gas, various processes	842	59	91	578	110
8	Ferronickel, 25% Ni, used in steel making	823	1	108	659	55
9	Lignite electricity, for various processes	692	110	55	384	142
10	Natural gas, burned in industrial furnace, mostly for steel making	454	4	65	349	36

Table 32. Impacts resulting from the ten processes that represent at least 1% of the impacts in the 1st remanufacturing scenario, Condition C (ReCIPe Endpoint –H)

In Table 32, the total impacts from remanufacturing compared to the original condition A went from 21,645 to 21,781 Pt. The change in the total impacts was not important despite the fact that recycled copper was used. In summary, all the processes and the amount of impacts remained the same compared to the remanufacturing scenario 1, condition A.

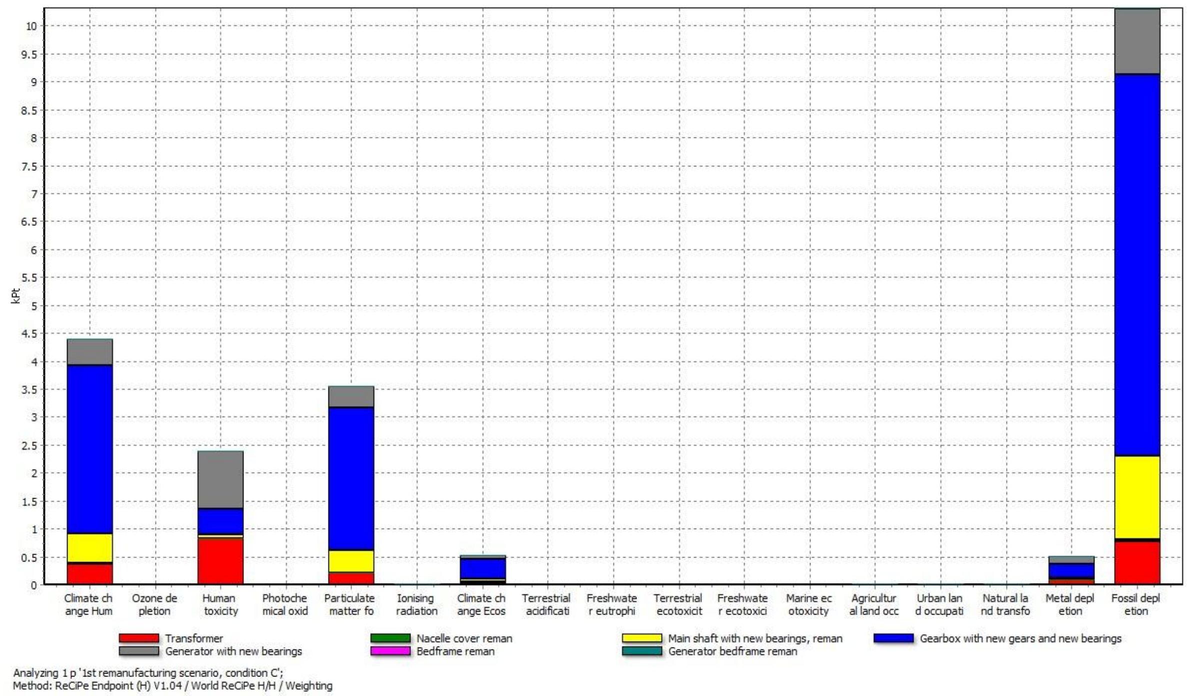


Figure 27. Weighting analysis resulting from the 1st remanufacturing scenario, Condition C, (ReCIPe Endpoint –H).

Figure 27 shows how the proportion of the impacts is similar to what was found in Condition A, remanufacturing scenario 1. The 11,000 Pt. impacts from the Fossil Fuel Depletion arise primarily from gearbox remanufacturing. The remaining impact mainly belongs to the transformer, the generator and the main shaft. Again, this shows the influence of the use of new gears and bearings over the final results. Climate Change Human Health category, as for the original condition A, is the second greatest impact from remanufacturing. The gearbox, the transformer, the generator, and the main shaft also have most of the contributions for this category (4,400 Pt.). Particulate Matter Formation follows with 3,500 Pt. primarily from the generator and the transformer remanufacturing. For those parts copper rewinding is the main remanufacturing process. The biggest contributor to the impacts in the Human Toxicity category is the generator.

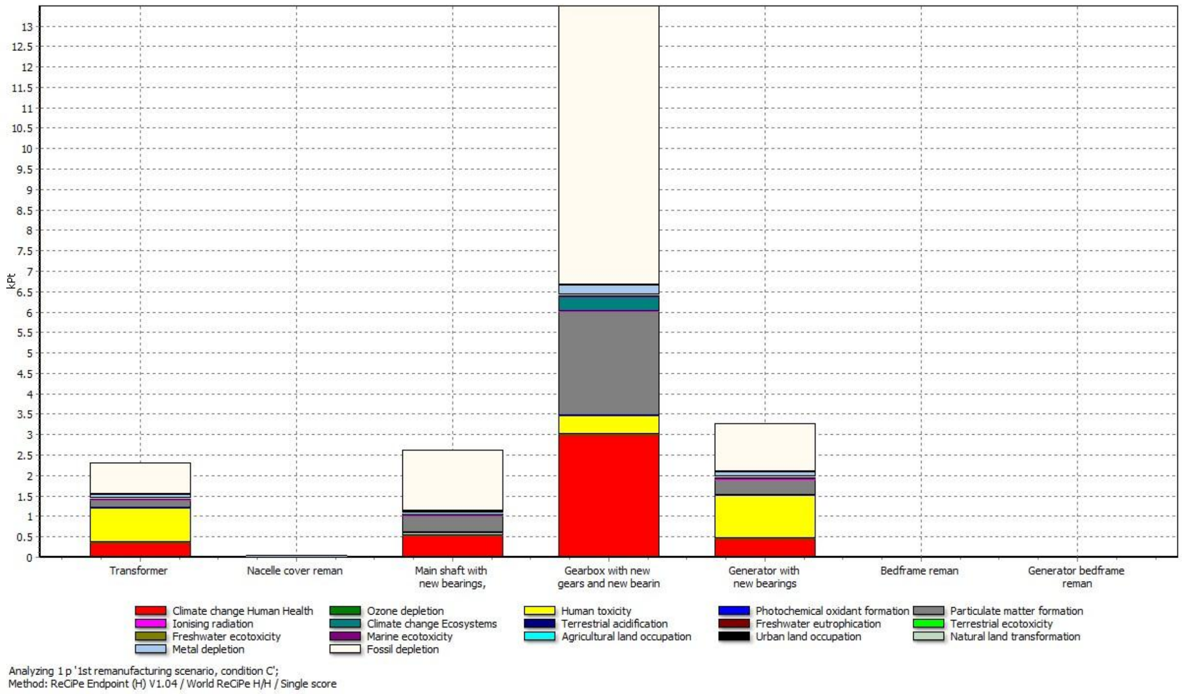


Figure 28. Single score analysis, Impact assessment resulting from the 1st remanufacturing scenario, Condition C, (ReCIPe Endpoint –H).

Figure 28 as well as Figures 25 and 22, shows that the majority of the single score impacts evaluation come from the gearbox remanufacturing. The gearbox is responsible for more than 50% of the total impacts with 14,000 Pt. For the gearbox, the three greatest impacts come from Fossil Fuel Depletion, Climate Change Human Health, and Particulate Matter Formation categories. The generator and the transformer have a similar contribution to the impacts in the Climate Change Human Health, Fossil Depletion, and Human Toxicity categories with a value close to 3,200 Pt. The main shaft is responsible for substantial impacts in the Climate Change Human Health, and Fossil Fuel Depletion categories. The transformer is responsible for impacts that total to 2,300Pt.

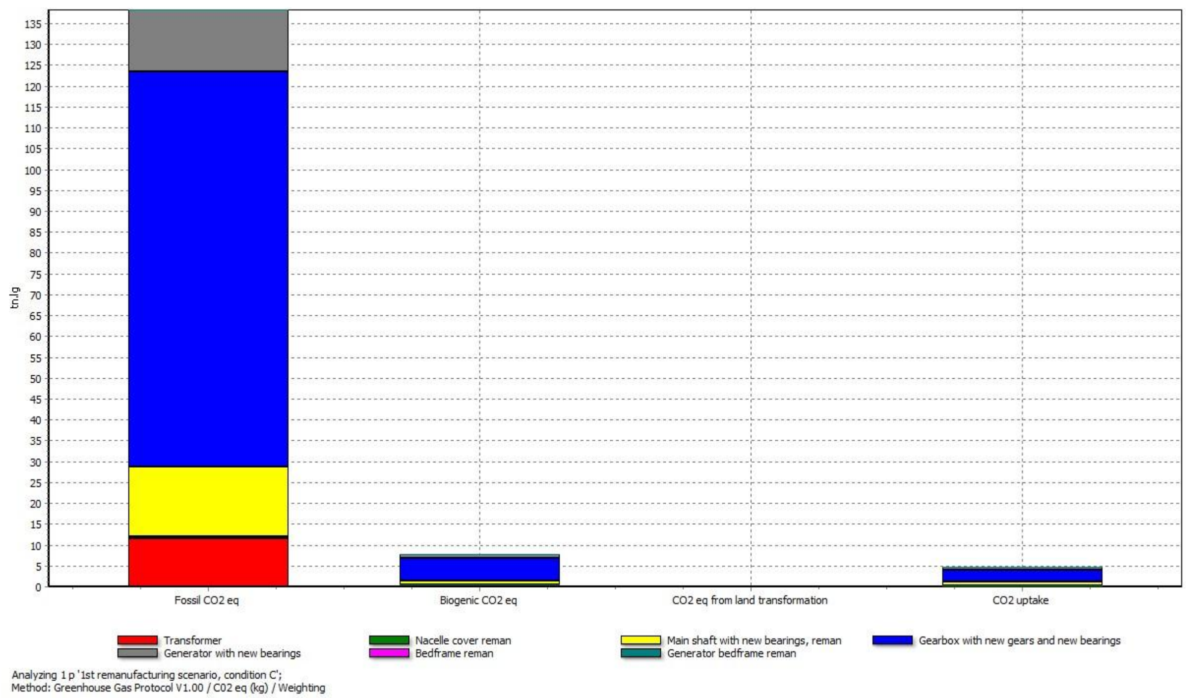


Figure 29. GHG analysis, Impact assessment resulting from the 1st remanufacturing scenario, Condition C. (ReCIPe Endpoint –H).

According to Figure 29, this remanufacturing condition (condition C) releases approximately the same Long Tons of Fossil CO_2 equivalents than the original condition A. Most of the impacts are related to the gearbox remanufacturing, with approximately 60 Long Tons of Fossil CO_2 equivalents released. In addition, the main shaft, the generator, and the transformer release between 10 to15 Long Tons of Fossil CO_2 equivalents each. 7 Long Tons of Biogenic CO_2 equivalents are mostly consequence of the gearbox remanufacturing. CO2 uptake has a value close to 5 Long Tons of CO2 equivalents, mostly from the gearbox remanufacturing. CO2 from land transformation is almost neglected in the results.

5.3.2. Sensitivity and impact assessment for 2nd remanufacturing scenario

This remanufacturing scenario has the least of the impacts due to use of remanufactured gears and bearings. Only two different cases for sensitivity analysis are analyzed, since the use of remanufactured gears and bearings in scenario 2 does not imply adding virgin or recycled steel. Therefore, the Condition C is discarded.

5.3.2.1 Condition A

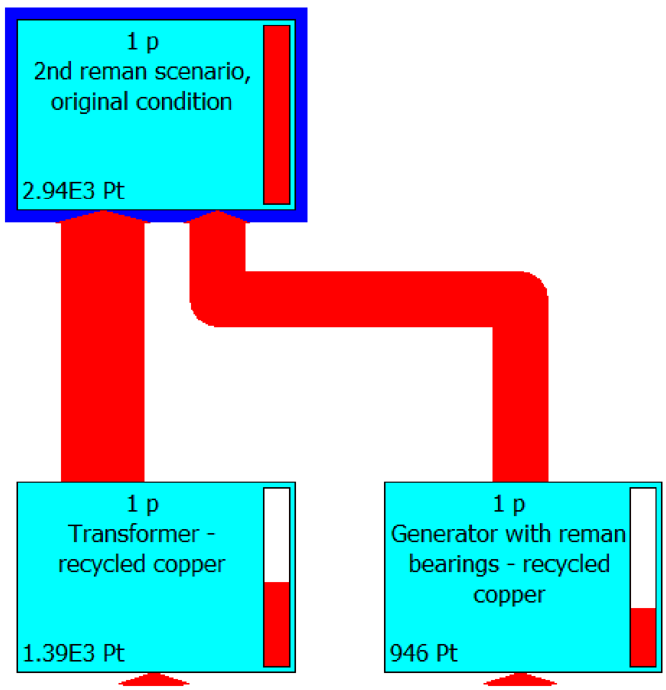


Figure 30. Network of impacts resulting from the 2nd remanufacturing scenario, original condition A (ReCIPe Endpoint –H, 18% threshold)

Figure 30 displays the impacts resulting from those processes that contribute at least 18% of the impacts in wind turbine remanufacturing. The 18% threshold was chosen because is not possible to show here a greater level of detail. The transformer remanufacturing process carries most of the impacts with approximately 1,390 Pt. of the 2,940 Pt. In addition, the generator makes a contribution to the total impacts of 946 Pt. Since this figure displays only a small part of the total contributions, the top impact contributors are shown in Table 33.

No	Process	Total	Transformer - recycled copper	Gearbox with reman gears and reman bearings	Generator with reman bearings - recycled copper	Main shaft with reman bearings, reman
	Total of all processes	2,937	1,390	260	946	270
1	Hard coal, at mine/RNA U	297	123	65	25	79
2	Lignite electricity, for various processes	234	106	7	113	7
3	Disposal, sulfidic tailings, virgin copper for windings production	220	97	1	121	1
4	Natural gas, for production of copper windings	125	55	3	61	2
5	Electricity natural gas, for various processes	122	42	34	8	35
6	Hard coal, mostly for electricity in copper winding	87	41	3	40	2
7	Hard coal, mostly for electricity in copper winding	86	38	3	42	3
8	Oil for lubricant and light fuel	79	33	9	30	6
9	Electricity hard coal, for various processes	73	30	17	4	21
10	Natural gas, for production of copper windings	77	34	2	39	1

Table 33. Impacts resulting from the ten processes that represent at least 1% of the impacts in the 2nd remanufacturing scenario, condition A, (ReCIPe Endpoint – H).

In Table 33, it is observed that the transformer contributes almost half of the impacts in this condition with 1,396 Pt., mainly from the energy intensive processes in copper rewinding. The generator has important impacts in this remanufacturing condition with 946 Pt. The use of virgin copper, from processing and disposal (220 Pt.) is a key element in the final result of 2,937 Pt. Energy related processes, from the use of fossil fuels, have considerable impacts for each operation. This is because the most important process in this remanufacturing scenario is the copper rewinding in the generator and the transformer.

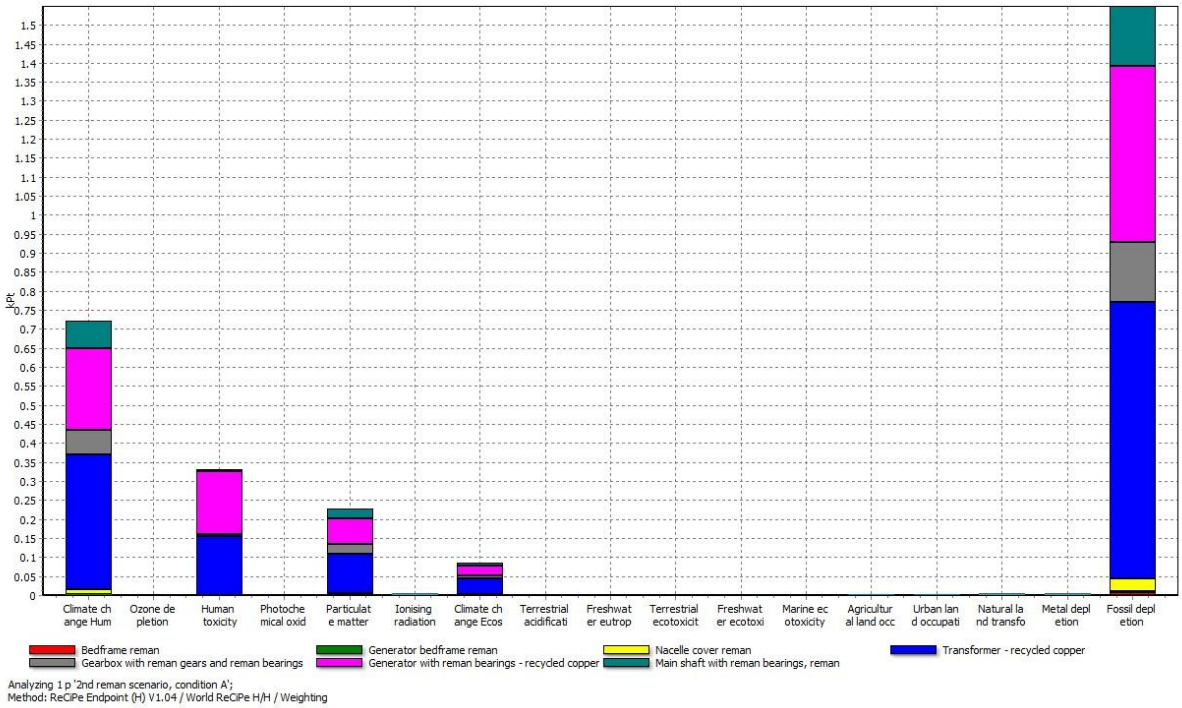


Figure 31. Weighting analysis, Impact assessment resulting from the 2[nd] remanufacturing, condition A, (ReCIPe Endpoint –H).

In Figure 31, the Fossil Fuel Depletion category leads the impacts on this condition with approximately 1,600 Pt., mostly from the remanufacturing of the transformer and the generator. Next in importance is Climate Change Human Health. Here the transformer takes half of the impacts with 350 Pt. As with the two previous categories, the Human Toxicity category is dominated by transformer remanufacturing with 150 Pt. out of the 350 Pt. in total. Transformer remanufacturing also has most of the impacts in the Particulate Matter Formation and the Climate Change Ecosystem categories, with 240 and 80 Pt., respectively. The generator also creates almost half of the impacts for both categories.

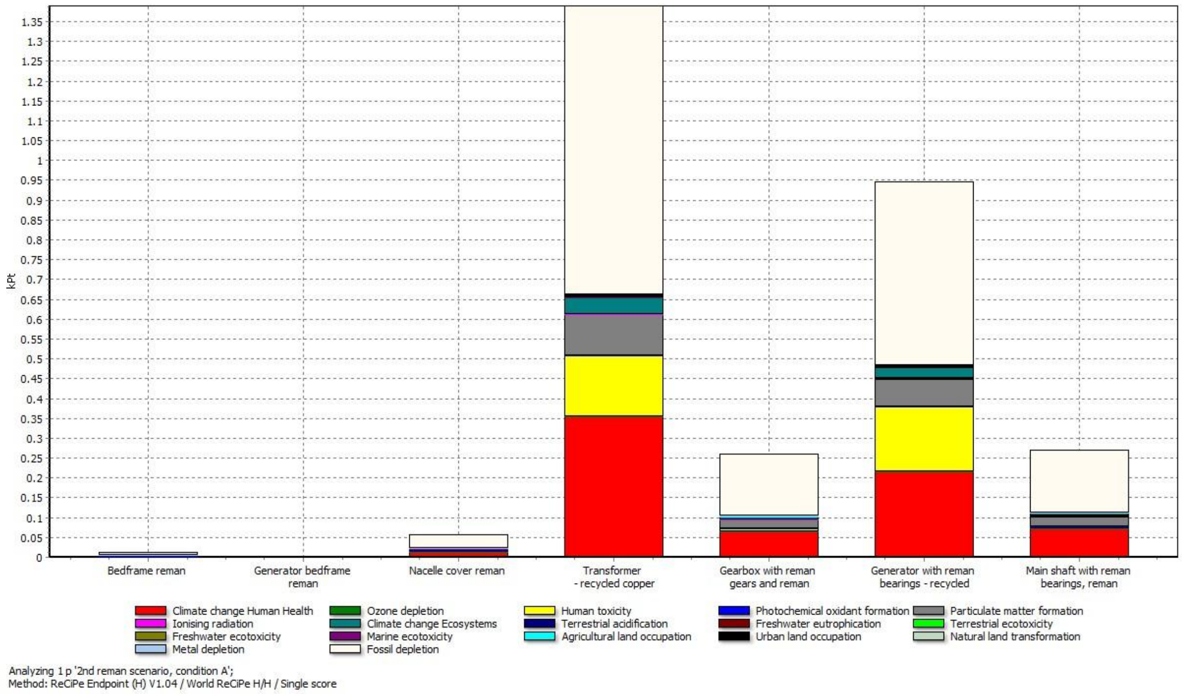


Figure 32. Single score analysis, Impact assessment resulting from the 2nd remanufacturing scenario, condition A (ReCIPe Endpoint –H).

According to Figure 32 transformer remanufacturing has 1,400 Pt. Fossil Fuel Depletion, Human Toxicity, and Climate Change Human Health categories make up most of the impacts from transformer remanufacturing. Generator remanufacturing carries 950 Pt. of the impacts. The proportions per impacts categories are similar for transformer and generator remanufacturing, since the copper rewinding process dominates the total impacts for both parts. The rest of the impacts are headed by the main shaft and the gearbox remanufacturing with just above 250 Pt.

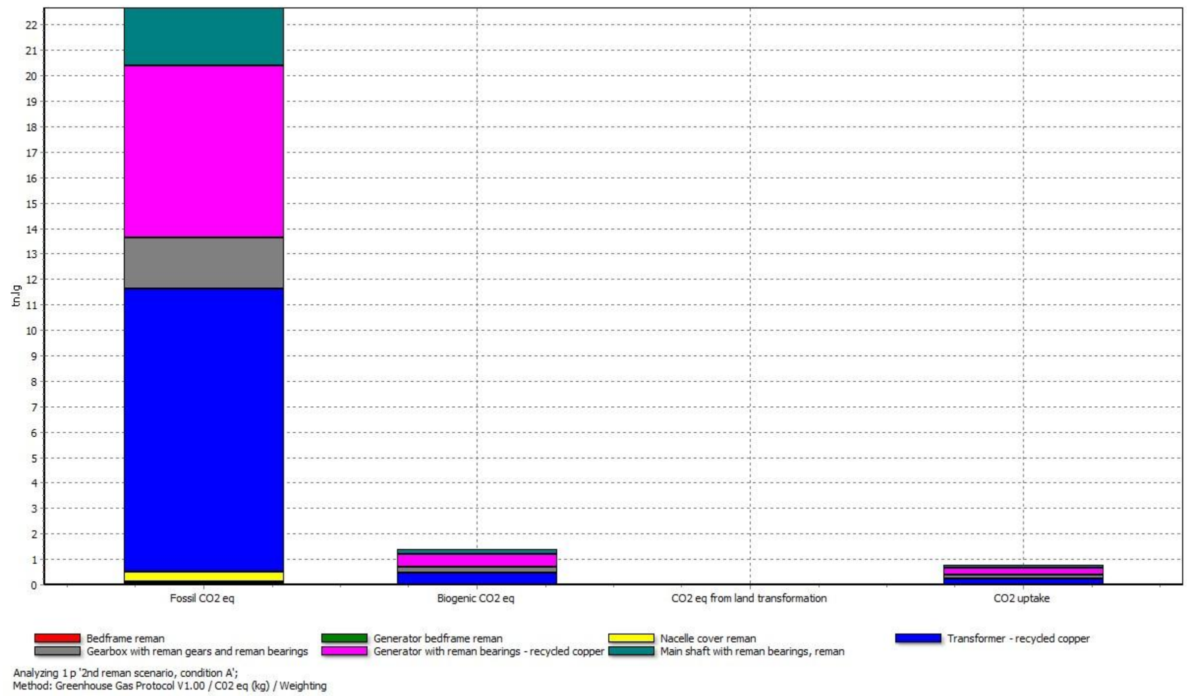


Figure 33. GHG analysis, Impact assessment resulting from the 2nd remanufacturing scenario, condition A, (ReCIPe Endpoint –H).

According to Figure 33, this condition generates 23 Long Tons of CO_2 equivalents from fossil fuels, with over 11 Long Tons coming from the transformer remanufacturing. The generator is also an important contributor with 6 Long Tons of CO_2 equivalents. The main shaft and the gearbox are the other components with an important contribution to the release of CO_2 from fossil fuels. In addition, CO_2 emissions from Biogenic CO_2 equivalents are less than 1.5 Long Tons for all the parts.

5.3.2.2 Condition C

Similar to the 1st remanufacturing scenario, the use of virgin copper and steel are the main factors that drive the results in this condition. The impacts are indicated in Table 34.

No	Process	Total	Transformer	Main shaft with reman bearings, reman	Generator with reman bearings	Gearbox with reman gears and reman bearings
	Total of all processes	5,005	2,304	270	2,101	260
1	Disposal, sulfidic tailings, virgin copper for windings production	1,415	625	1	788	1
2	Virgin copper	363	161	0	202	0
3	Hard coal, at mine/RNA U	298	124	79	26	65
4	Lignite electricity, for various processes	243	110	7	118	7
5	Copper wire for coil	160	71	x	90	X
6	Natural gas, for production of copper windings	134	59	2	66	3
7	Electricity natural gas, for various processes	122	42	35	8	34
8	Hard coal, mostly for electricity in copper winding	95	42	3	47	3
9	Hard coal, mostly for electricity in copper winding	93	44	2	44	3
10	Oil for lubricant and light fuel	88	37	6	35	9

Table 34. Impacts resulting from the ten processes that represent at least 1% of the impacts in the 2nd remanufacturing scenario, condition C (ReCIPe Endpoint – H)

The total impacts for the condition C in remanufacturing scenario 2 totals 5,005 Pt. Most of the impacts come from the disposal of the sulfidic tailings when the copper is mined, the extraction of the virgin copper, and the processing of the copper into copper wire. The rest of the impacts come from the energy used for the remanufacturing process. Almost 90% of the impacts in this scenario come from the transformer and the generator remanufacturing.

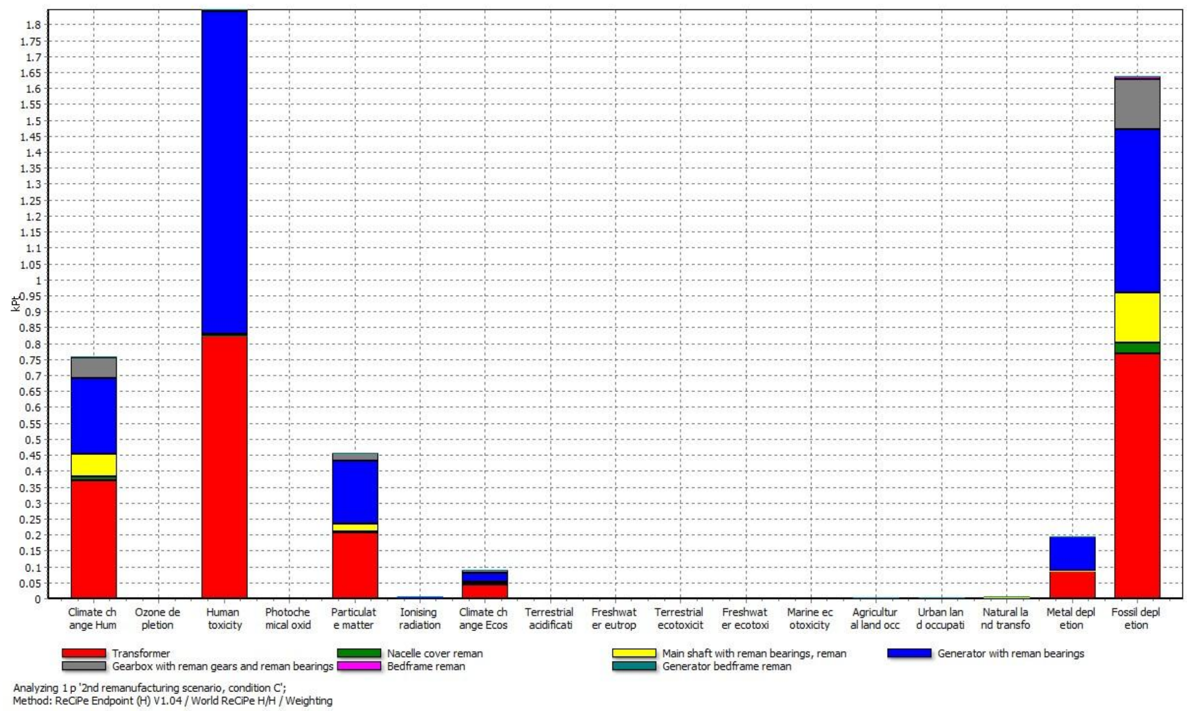


Figure 34. Weighting analysis, Impact assessment resulting from the 2nd remanufacturing scenario, condition C, (ReCIPe Endpoint –H).

The Human Toxicity category has the biggest impact from the results shown in Figure 34, accounting for 1,900 Pt. This category is nearly equally divided between the transformer and the generator remanufacturing. The next largest source of impacts is from the Fossil Fuel Depletion category (1,650 pt.). Particulate Matter Formation, Metal Depletion, and Climate Change Ecosystems categories generate very few impacts compared to the first two categories, with less than 750 Pt. each.

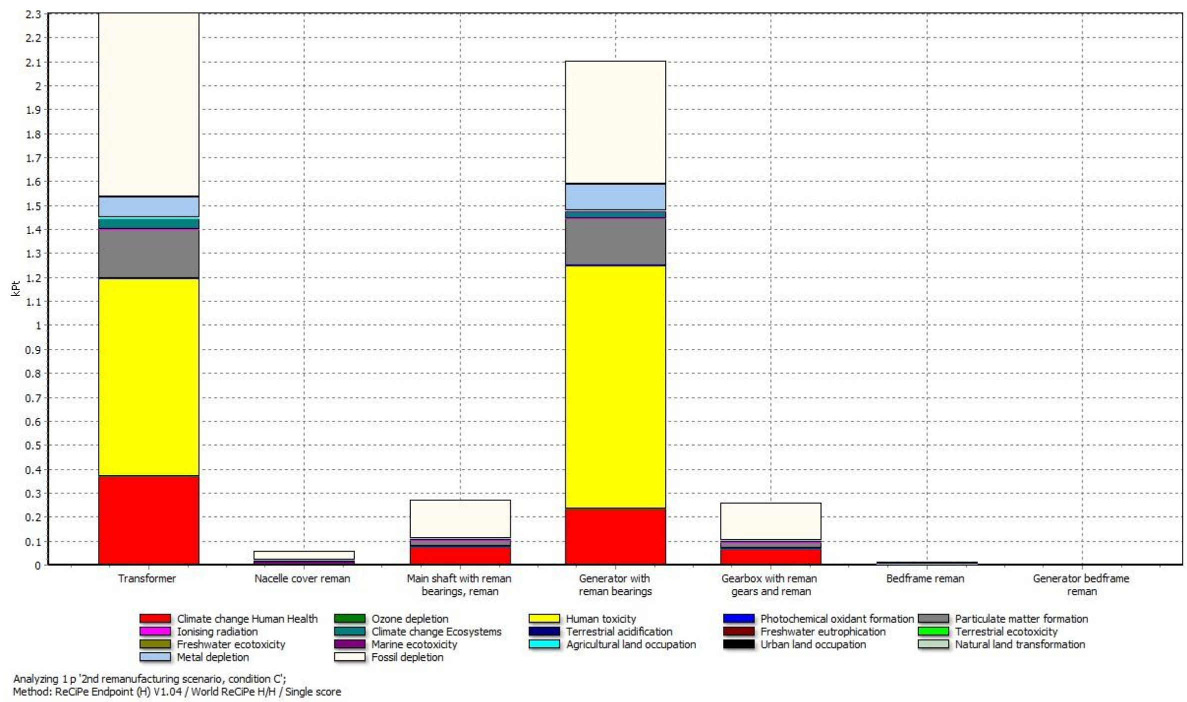


Figure 35. Single score analysis, Impact assessment resulting from the 2nd remanufacturing scenario, condition C, (ReCIPe Endpoint –H).

Using the information from Figure 35, condition C for the 2nd remanufacturing scenario shows similar impacts from the transformer (2,300 Pt.) and the generator (2,100 Pt.) remanufacturing. Both show the same pattern in which the Human Toxicity has most of the impacts, followed by the Fossil Fuel Depletion. To a lesser extent Climate Change Human Health and Particulate Matter Formation also influence the total impacts. Metal Depletion accounts for about 100 Pt. for the generator and the transformer. The gearbox, the main shaft and the nacelle cover generates fewer than 300 Pt. of impacts, mostly from Fossil Fuel Depletion.

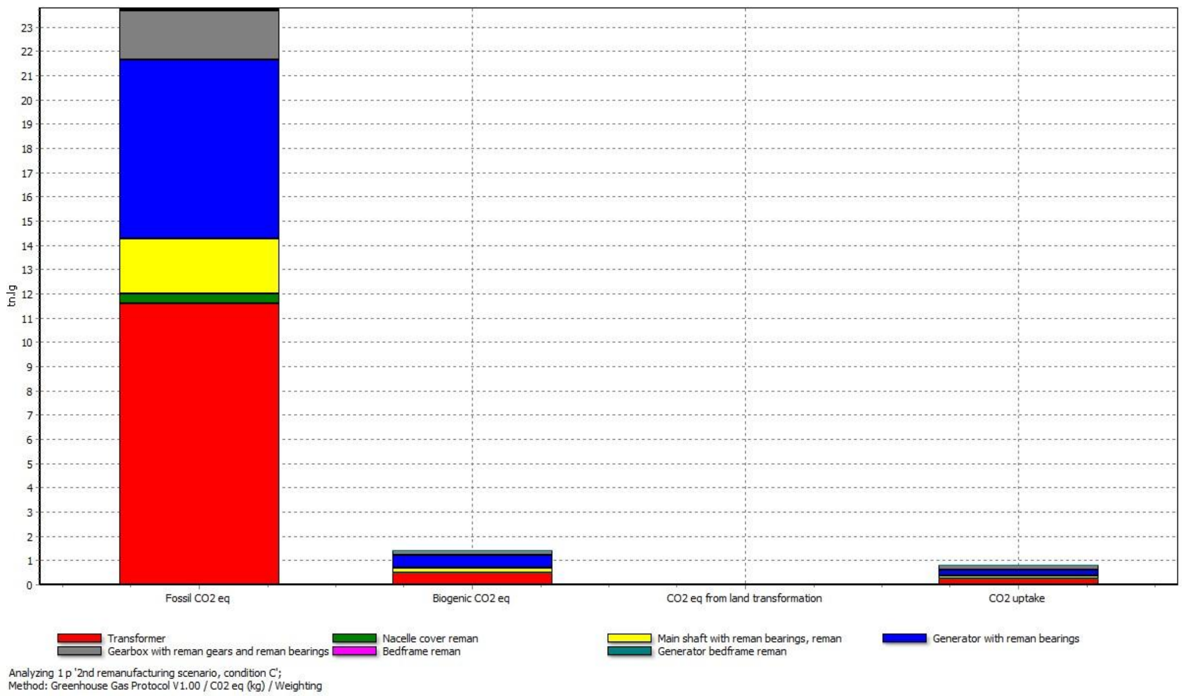


Figure 36. GHG analysis, Impact assessment resulting from the 2nd remanufacturing scenario, condition C, (ReCIPe Endpoint –H).

In Figure 36, 24 Long Tons of CO_2 equivalents from fossil fuels are released, mostly arising from transformer and the generator remanufacturing. To a lesser degree, the gearbox and the main shaft also contribute to those 24 Long Tons. Biogenic CO_2 equivalents account for 1.5 Long Tons and the CO_2 uptake for almost 1 Long Ton.

5.3.3. Sensitivity and impact assessment for 3rd remanufacturing scenario

This remanufacturing scenario is the most likely to occur. Gear remanufacturing can be a very common procedure if the gears do not suffer catastrophic damage, and the bearings are replaced by new ones. The installation of new bearings is the safeties procedure taken by remanufactures. Two different cases for sensitivity analysis are analyzed. The results follow.

5.3.3.1 Condition A

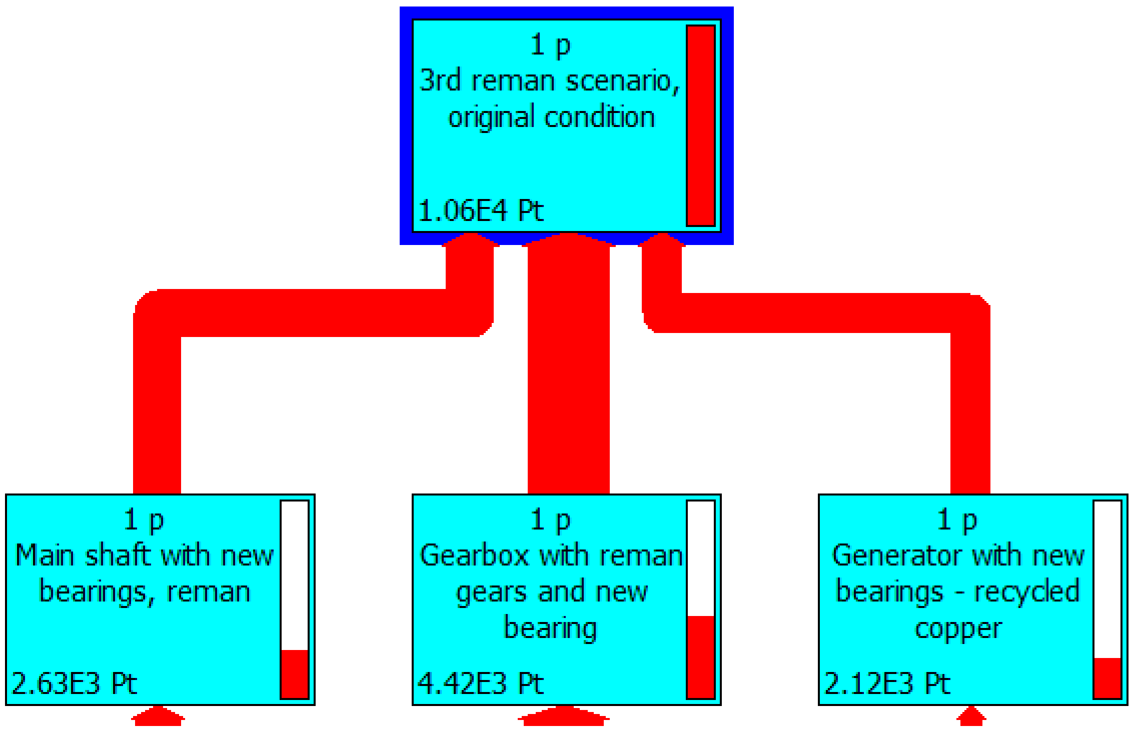


Figure 37. Network of impacts resulting from the 3rd remanufacturing scenario, condition A (ReCIPe Endpoint –H, 19% threshold)

For this sensitivity analysis, in Figure 37 the gearbox has the greatest impacts among all the components with 4,424 Pt. Followed by the main shaft remanufacturing with 2,631 Pt. The generator is responsible for significant impacts with 2,117 Pt. In Table 35 the processes that have the greatest impact in this condition are shown.

No	Process	Total	Transformer - recycled copper	Main shaft with new bearings, reman	Gearbox with reman gears and new bearing	Generator with new bearings - recycled copper
	Total of all processes	10,633	1,390	2,631	4,424	2,117
1	Energy from LPG in bearing manufacturing	1,462	X	448	790	224
2	Electricity coal, mostly new bearings manufacturing and gears reman	635	38	171	299	126
3	Electricity hard coal, steel making for bearings	592	2	180	317	91
4	Raw Ferrochromium, high-carbon, 68% Cr, used in steel making	502	0	154	271	77
5	Electricity hard coal, various processes	434	41	109	190	94
6	Electricity natural gas, for various processes	413	55	91	160	103
7	Lignite electricity, for various processes	391	106	55	92	137
8	Ferronickel, 25% Ni, used in steel making	353	0	108	190	54
9	Electricity hard coal, various processes	331	123	89	84	30
10	Raw Steel	268	X	82	145	41

Table 35. Impacts resulting from the ten processes that represent at least 1% of the impacts in the 3rd remanufacturing scenario, condition A (ReCIPe Endpoint – H)

The energy from LPG in bearing manufacturing is the biggest contributor to the impacts with 1,462 Pt. mainly due to new bearing manufacturing for the gearbox, the main shaft, and the generator remanufacturing. The generation of electricity from gas and coal for the manufacturing of bearings is another important contributor for the impacts of this sensitivity condition. The use of raw materials for steel making is a very important contributor with a total of 1,123Pt. related to the production of chromium for steel bearings.

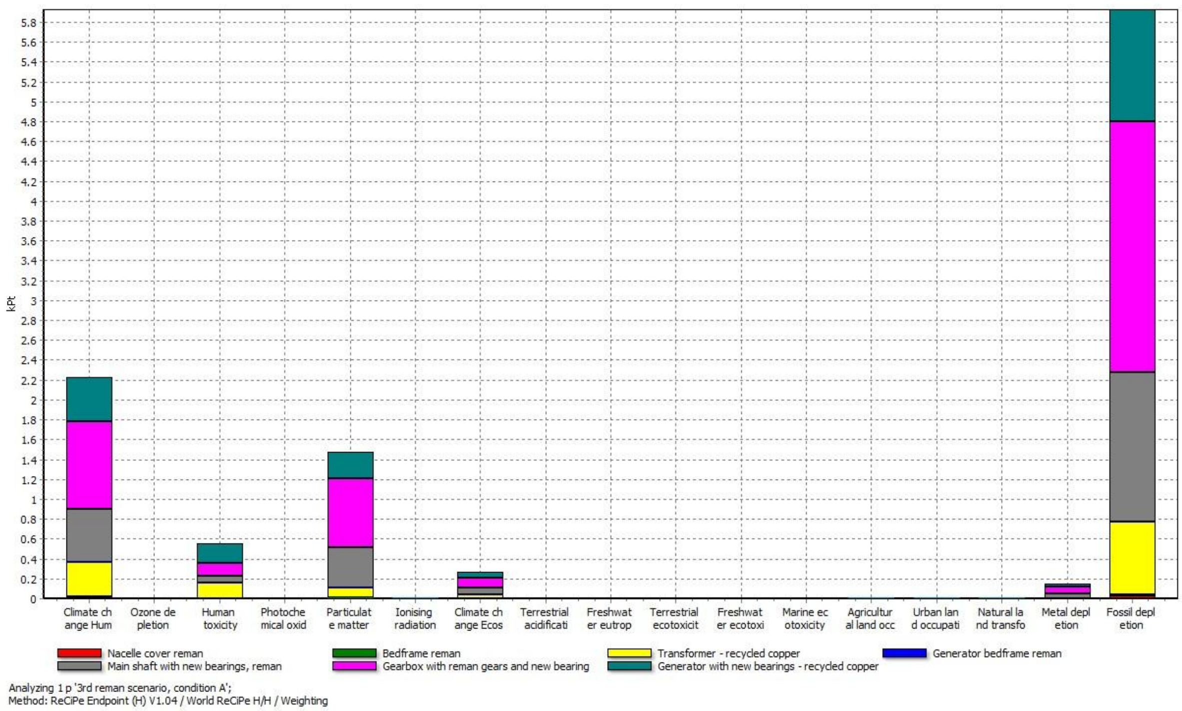


Figure 38. Weighting analysis, Impact assessment resulting from the 3rd remanufacturing scenario, condition A, (ReCIPe Endpoint –H).

According to Figure 38, the gearbox and the main shaft remanufacturing have more of the impacts in this condition. Fossil Fuel Depletion has a big impact in this case (5,900 Pt.), mostly divided between the remanufacturing of the transformer and the generator. Climate Change Human Health category follows in importance with 2,200 Pt. mainly due to the gearbox remanufacturing. Particulate Matter Formation is also a big part of the impacts for this condition with 1,500 Pt. distributed also mainly between the gearbox and the main shaft. Human Toxicity category occupies a minor importance relative to the impacts of other categories with approximately 600 Pt. Climate Change Ecosystem category has very few impacts, less than 300 Pt., compared to the previous three impact categories.

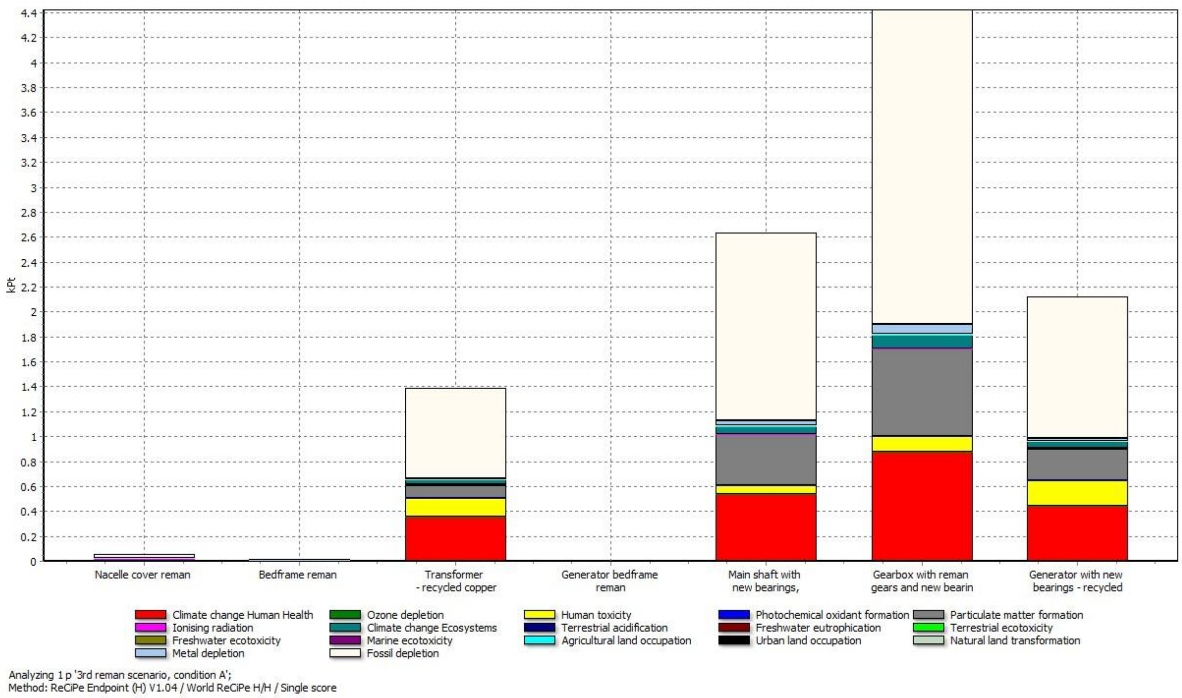


Figure 39. Single score analysis, Impact assessment resulting from the 3rd remanufacturing scenario, condition A, (ReCIPe Endpoint –H).

In Figure 39, the greatest impacts come from the gearbox remanufacturing with 4,424 Pt., the three most important impact categories that contribute to this value are Particulate Matter Formation, Fossil Fuel Depletion, and Climate Change Human Health. The main shaft remanufacturing follows with 2,631 Pt. with Particulate Matter Formation, Fossil Fuel Depletion, and Climate Change Human Health as the most important contributors. The generator follows with 2,117 Pt. distributed between Particulate Matter Formation, Fossil Fuel Depletion, and Climate Change Human Health. Finally, the transformer has 1,390 Pt. mostly from Climate Change Human Health and Fossil Fuel Depletion.

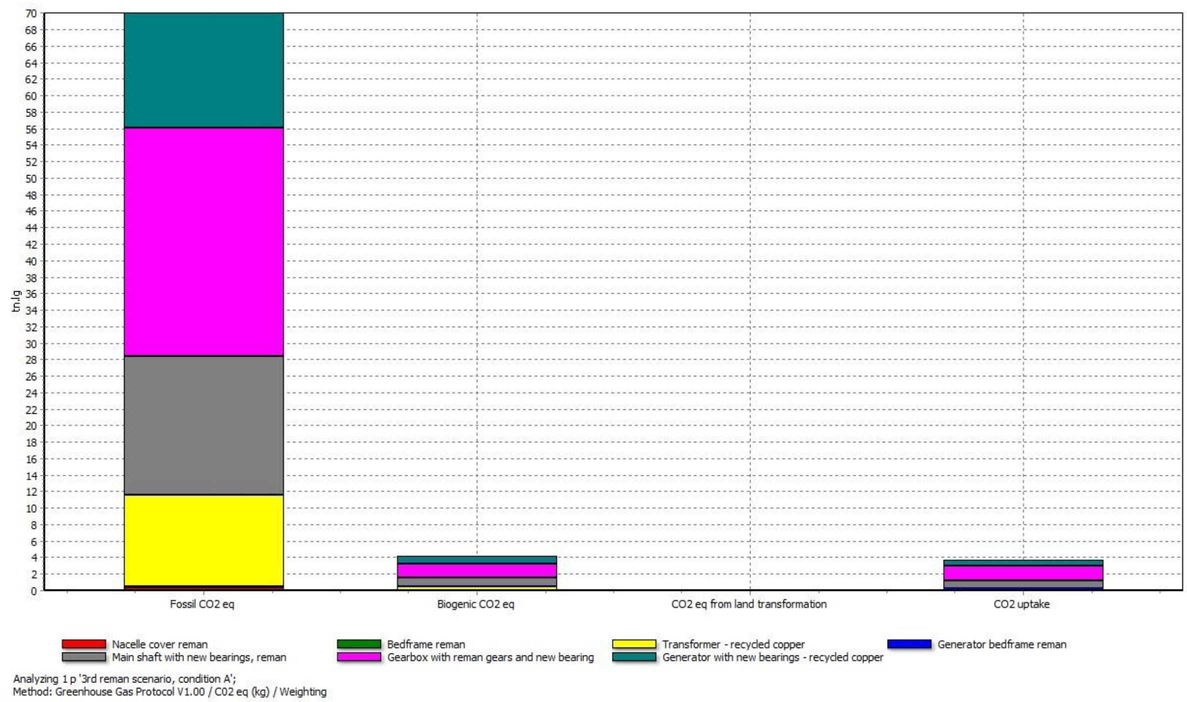


Figure 40. GHG analysis, Impact assessment resulting from the 3rd remanufacturing scenario, condition A, (ReCIPe Endpoint –H).

Figure 40 shows 70 Long Tons of CO_2 emissions equivalents, coming mainly from the gearbox and the rest nearly equally distributed between the transformer, the generator, and the main shaft remanufacturing. The Biogenic CO_2 emission equivalents contribute 4 Long Tons and the CO_2 uptake is also 4 Long Tons.

5.3.3.2 Condition C

This condition corresponds to the use of virgin steel and copper for remanufacturing using new bearings and remanufactured gears. In Table 38, the processes that contribute the top 1% of the impacts are displayed.

No	Process	Total	Main shaft with new bearings, reman	Gearbox with reman gears and new bearing	Generator with new bearings	Transformer
	Total of all processes	12,710	2,631	4,424	3,281	2,304
1	Energy from LPG in bearing manufacturing	1,462	448	790	224	x
2	Disposal, sulfidic tailings, virgin copper for windings production	1,438	8	13	791	625
3	Electricity coal, mostly bearings manufacturing	644	171	299	131	42
4	Electricity hard coal, mostly bearings manufacturing	600	180	317	96	6
5	Raw Ferrochromium, high-carbon, 68% Cr, used in steel making	504	154	271	78	1
6	Electricity hard coal, various processes	440	109	190	97	44
7	Electricity natural gas, for various processes	424	91	160	110	59
8	Lignite electricity, for copper rewinding	400	55	92	142	110
9	Raw copper	369	2	3	203	161
10	Ferronickel, 25% Ni, used in steel making	354	108	190	55	1

Table 36. Impacts resulting from the ten processes that represent at least 1% of the impacts in the 3rd remanufacturing scenario, condition C, (ReCIPe Endpoint – H).

The greatest impact comes from the copper processing, among those processes are the disposal of sulfidic tailings (1,438 Pt.), raw copper (369 Pt.), and electricity for copper processing (400 Pt.). The use of electricity from coal and gas for the manufacturing of roller bearings also has an important impact, both accounts for 2,706 Pt. The use of raw materials for steel making contributes 858 Pt. Other processes related to electricity generation also have important impacts in this scenario.

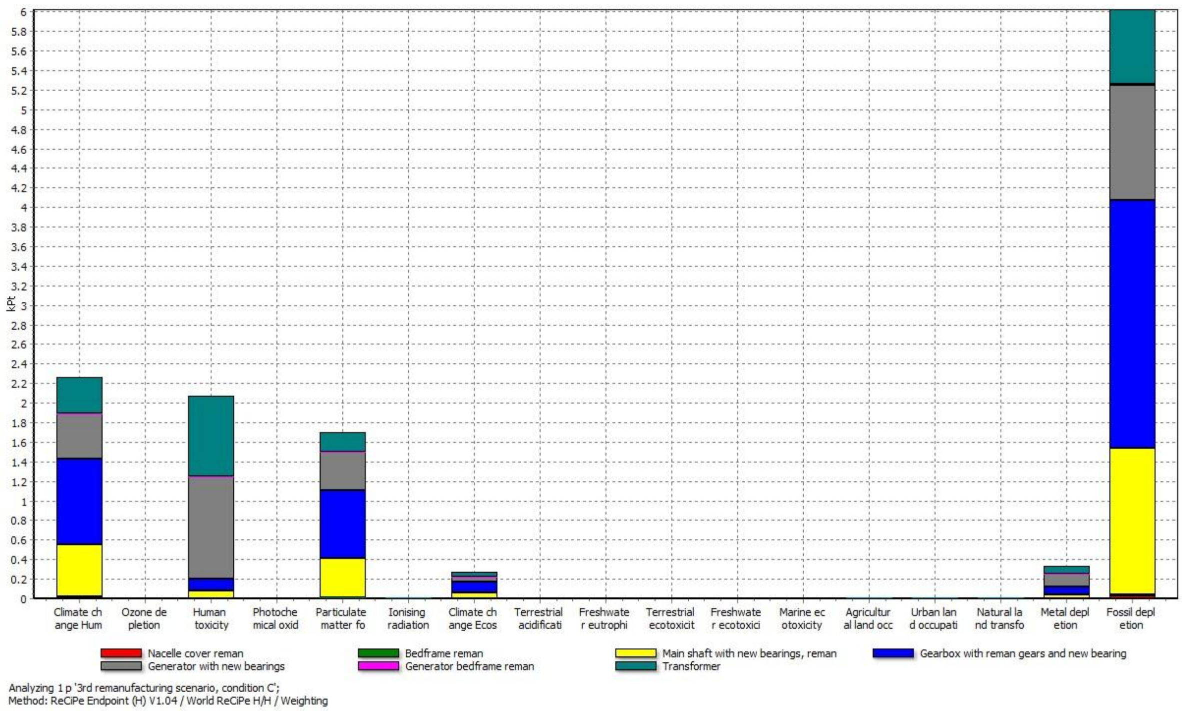


Figure 41. Weighting analysis, Impact assessment resulting from the 3rd remanufacturing scenario, condition C, (ReCIPe Endpoint –H).

In Figure 41, the impacts from the Fossil Fuel Depletion category (6,000 Pt.) are distributed between the gearbox, the generator, the transformer and the main shaft remanufacturing. The Climate Change Human Health category follows with 2,300 Pt. in which the gearbox has most of the impacts, followed by an equal contribution from the main shaft, the transformer, and the generator. Human Toxicity category accounts for 2,100 Pt., mostly from the generator and the transformer. Particulate Matter Formation category has 1,700 Pt. Climate Change Ecosystems and Metal Depletion have impacts less than 400 Pt.

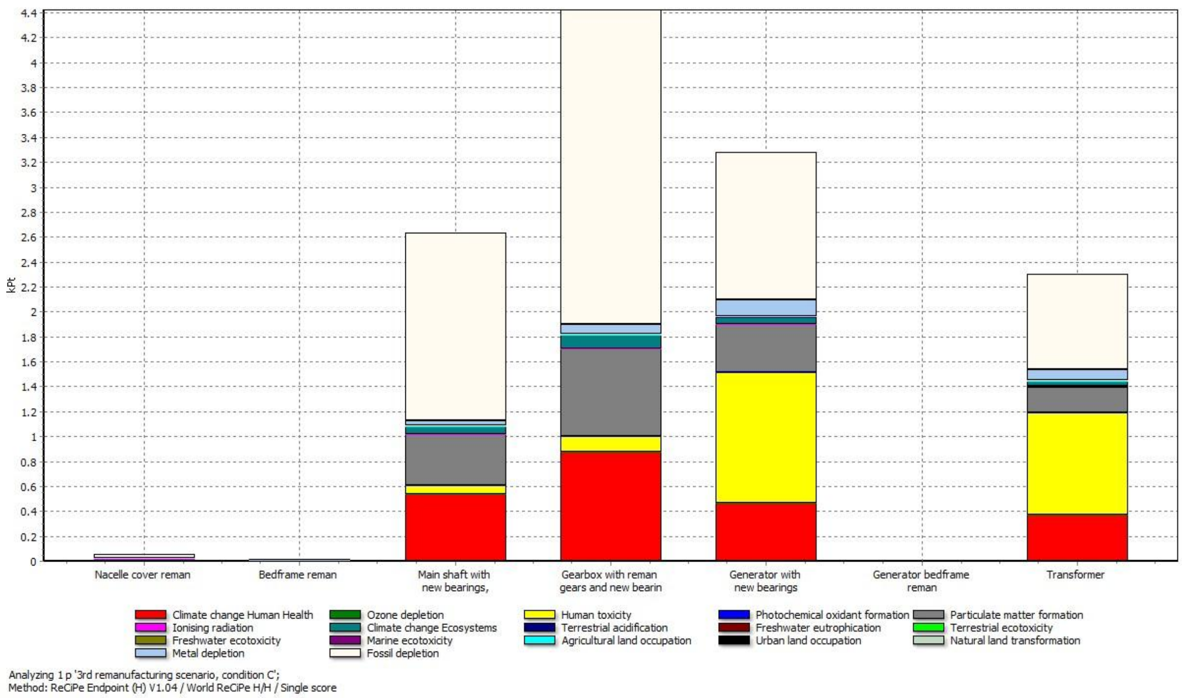


Figure 42. Single score analysis, Impact assessment resulting from the 3rd remanufacturing scenario, condition C, (ReCIPe Endpoint –H).

In the single score analysis shown in Figure 42, the gearbox has the biggest impacts with 4,424 Pt. mostly from Particulate Matter Formation, Fossil Fuel Depletion, and Climate Change Human Health categories. The generator impacts of 3,281 Pt., mainly from the Fossil Fuel Depletion and Human Toxicity categories. The main shaft follows in the quantity of impacts with 2,631 Pt., having a similar distribution of impacts categories as for the generator. The transformer has a similar proportion in impacts as for the generator, but accounts for 2,304 Pt.

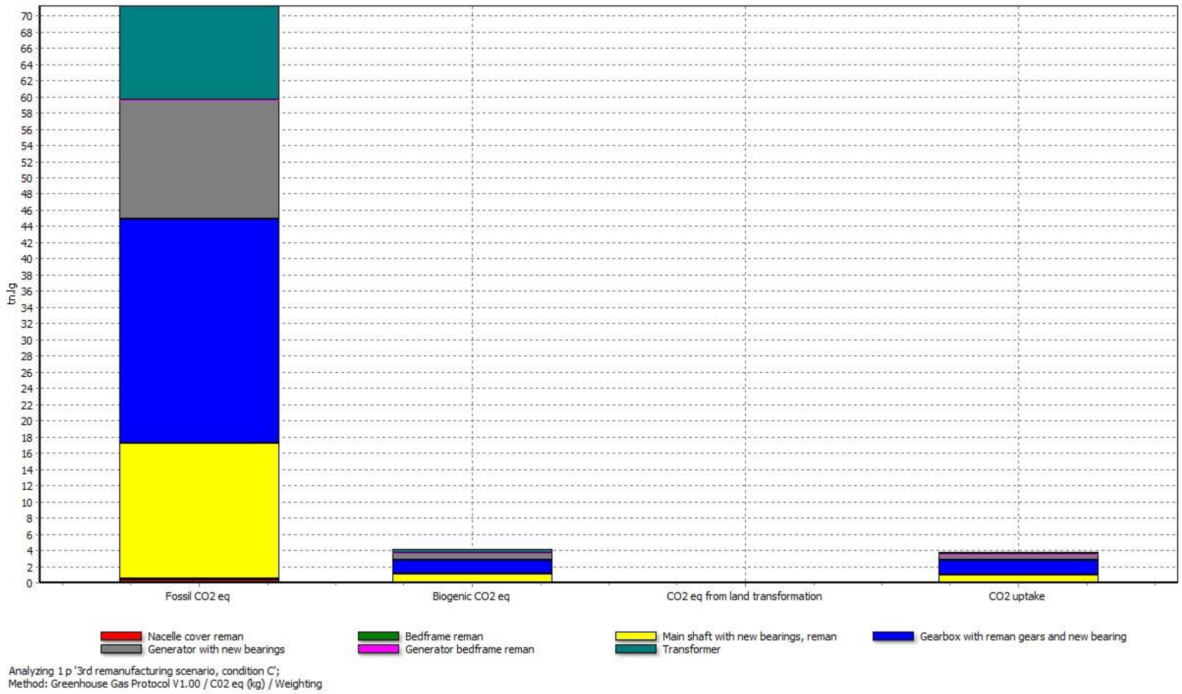


Figure 43. GHG analysis, Impact assessment resulting from the 3rd remanufacturing scenario. condition C, (ReCIPe Endpoint –H).

Condition C, displayed in Figure 43, accounts for 72 Long Tons of CO_2 equivalents. Most of the impacts come from the gearbox with 27 Long Tons of CO_2 equivalents, followed by the main shaft with 16 Long Tons and the generator with 15 Long Tons. The transformer also has an important contribution with 12 Long Tons of CO_2 equivalents. The entire operation only contributes 4 Long Tons of biogenic CO_2 equivalents, and the CO_2 uptake is 4 Long Tons as well.

5.3.4. Sensitivity and impact assessment for the comparison between conditions

This section shows a comparison between the remanufacturing scenarios of each sensitivity analysis condition. The purpose is to draft conclusions about the trade-offs between each condition.

5.3.4.1 Condition A

In Figures 44, 45, and 46 condition A over each remanufacturing scenario is compared.

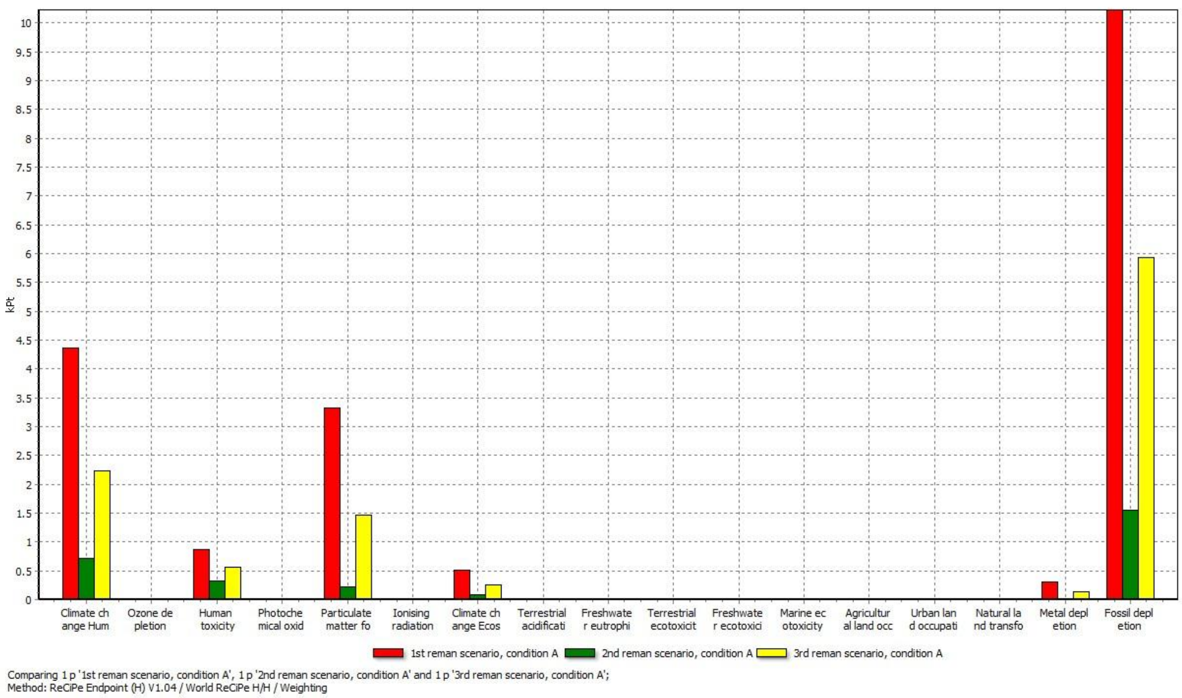


Figure 44. Impacts assessment comparison between remanufacturing scenarios using condition A sensitivity analysis. (ReCIPe Endpoint –H).

The greatest impact arises from the Fossil Fuel Depletion category. For this category, scenario 1 has most of the impacts with 11,000 Pt. Scenario 3 that has a value close to 6,000 Pt. These results verify again that the manufacture of new parts (bearings and gears) has an important effect over the final results. Scenario 2 has fewer of the impacts with just above 1,500 Pt.

Climate Change Human Health is another category in which scenario 1 has most of the impacts with a value of 4,400 Pt., those impacts are greater than the impacts from scenario 3 that has 2,200 Pt. Scenario 2 has very few impacts compared to scenario 1 and 3. Scenario 2 has impacts of only 700 Pt. on this category, which is the product of using few new materials and energy intensive processes.

The next greatest impact category is Particulate Matter Formation. Here again appears the tendency in which the impacts in scenario 1 are much greater than the impacts in scenario 2 and 3. The remanufacturing scenario 1 corresponds to an impact of 3,400 Pt., which is followed by scenario 3 with 1,500 Pt. As with the previous categories, scenario 2 has the fewer impacts with 200 Pt.

The distribution of impacts from the Human Toxicity category is very similar among the three remanufacturing scenarios. Again, scenario 1 has most of the impacts with 800 Pt. Scenario 3 has 600 Pt. Finally, scenario 2 has around 250 Pt. impacts.

The Climate Change Ecosystems category has very little influence compared to the other categories with 500 Pt. for scenario 1. As occurred for the previous categories, scenario 3 has the second largest impacts with just over 200 Pt., and scenario 2 has the fewest impacts with 100 Pt.

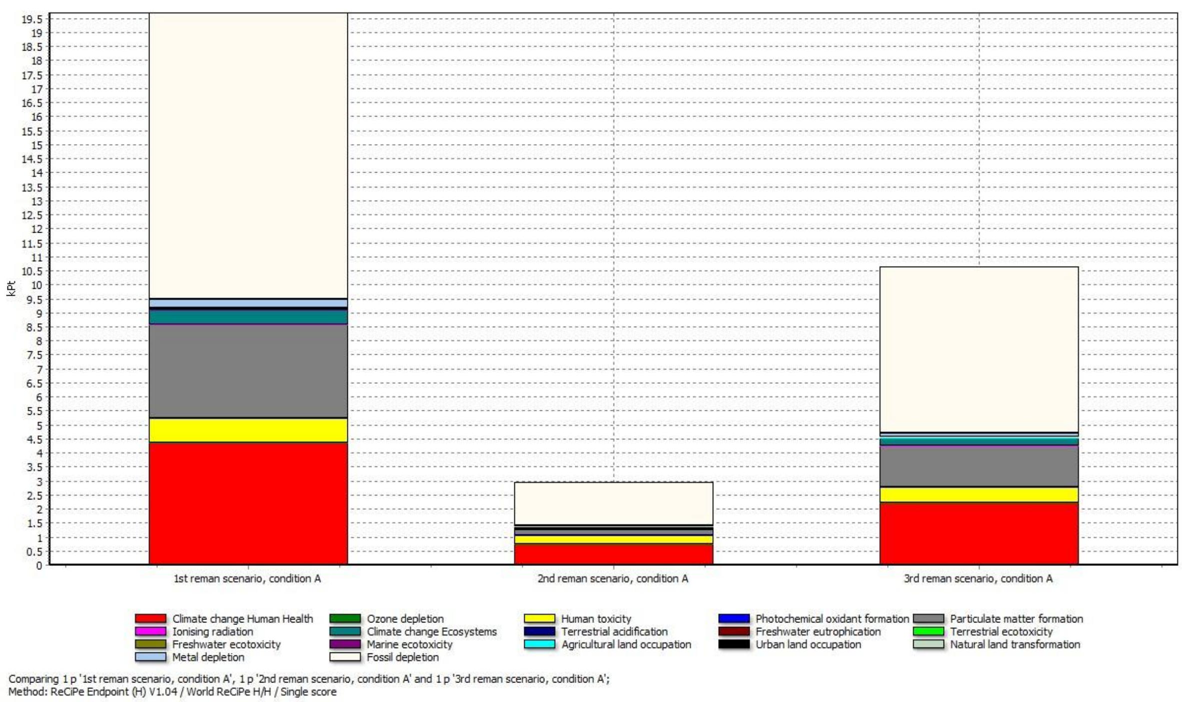


Figure 45. Single score impacts assessment comparison between remanufacturing scenarios using condition A sensitivity analysis. (ReCIPe Endpoint –H).

Figure 45 shows that remanufacturing scenario 1 has most of the impacts among the three scenarios with 19,703 Pt. Most of the impacts in this scenario come from the Fossil Fuel Depletion category which accounts for 10,000 Pt. As previously analyzed, the use of coal and gas for energy intensive processes drives this value. The Climate Change Human Health category has the second most

impacts in this scenario with 4,400 Pt. Particulate Matter Formation is the next greatest category that has important influence over the final results, with impacts of 4,000 Pt.

Scenario 3 has the second largest quantity of impacts, mostly from the Fossil Fuel Depletion, Climate Change Human Health, and Particulate Matter Formation categories. The total impacts for this scenario are 10,633 Pt.

Scenario 2 for this sensitivity analysis has the fewest impacts with 2,937 Pt., making this the best alternative when there is no need to replace bearings or gears by new ones. The two categories that have almost 70% of the impacts for this scenario are Fossil Fuel Depletion and Climate Change Human Health.

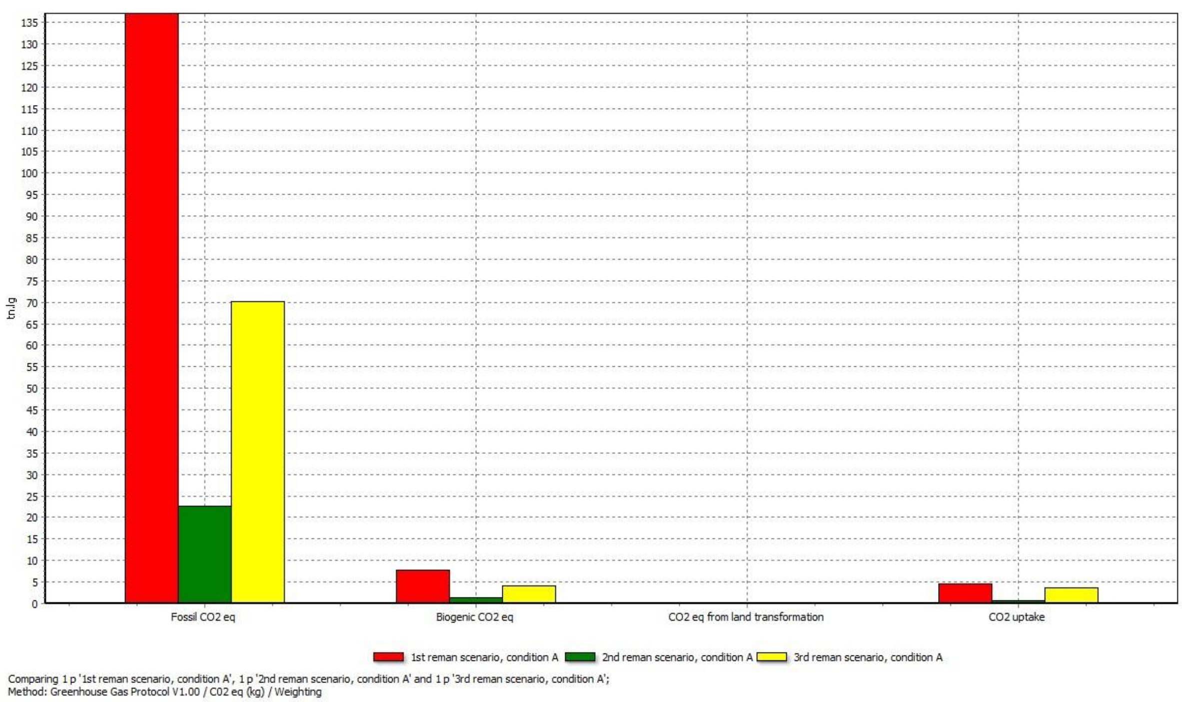


Figure 46. Green-house gasses emissions comparison between remanufacturing scenarios using condition A sensitivity analysis. (ReCIPe Endpoint –H).

For the condition A, according to Figure 46, the majority of the impacts come from scenario 1. In this GHG analysis scenario 1 has over 135 Long Tons of CO_2 equivalents released, which is the most damaging scenario of all. Scenario 3 has releases 70 Long Tons of CO_2 equivalents, which is 55 Long Tons less than scenario 1. Scenario 2 has only about 23 Long Tons of CO_2 equivalents released, which is almost a fourth of the Long Tons of CO_2 equivalents released in scenario 1.

5.3.4.2 Condition B

In Figures 47, 48, and 49 the remanufacturing scenarios is compared.

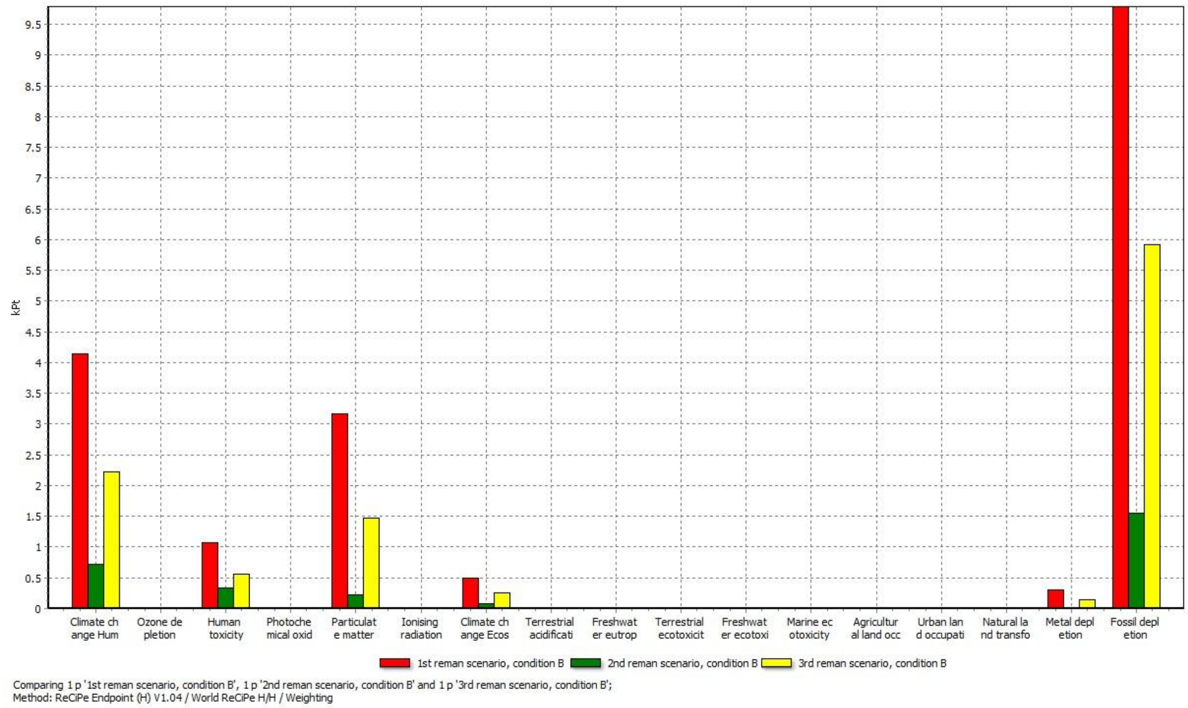


Figure 47. Impacts assessment comparison between remanufacturing scenarios using condition B sensitivity analysis. (ReCIPe Endpoint –H).

Figure 47 compares the results from the sensitivity analysis of condition B for the three remanufacturing scenarios analyzed in the previous section. Fossil Fuel Depletion dominates the results in Figure 47, with the impacts of scenarios 1and 3 over 5,500 Pt. each; both results are higher than any other impact category. Clearly the influence of the use of fossil fuels for energy production has an important impact over the wind turbine remanufacturing process. The impacts from scenario 2 is lower (1,500Pt) because is not processed new material for gear and bearing remanufacturing.

Climate Change Human Health has the second largest impact among all the categories. Again, the remanufacturing scenario 1 has greater impacts than the other two scenarios. The impacts in scenario 1 are over 40% compared to scenario 3, and seven times higher than scenario 2.

Particulate Matter is the category with the third largest quantity of impacts. Here scenario 1 has most of the impacts with 3,400 Pt., and scenario 3 has about 40% of the impacts of scenario 1. Scenario 2 with 200 Pt. has only a small fraction of the impacts of scenario1.

The Human Toxicity category has similar influence on results as the two previous categories, the values range between 1,000 Pt. and 400 Pt., being scenario 1 the one with the greatest impact, followed by scenario 3, and then by scenario 2.

Climate Change Ecosystems category has fewer impacts than the first three categories analyzed. Scenario 1 is the largest with 500 Pt., followed by scenario 3 with 325 Pt. Finally, the scenario 2 has the fewer impacts with less than a third of the impacts of scenario 1. The Metal Depletion category has impacts fewer than 200 Pt. for the scenario1, and for the other two scenarios the impacts are less than 100 Pt. each.

In summary, the remanufacturing scenario 1 has the greatest environmental impacts due to the manufacturing of new bearings and gears. On the other hand, scenario 2 has the fewer impacts of the three remanufacturing scenarios, due to the fact that the only new part included is the copper rewinding for the generator and the transformer, and the rest undergoes different machining processes.

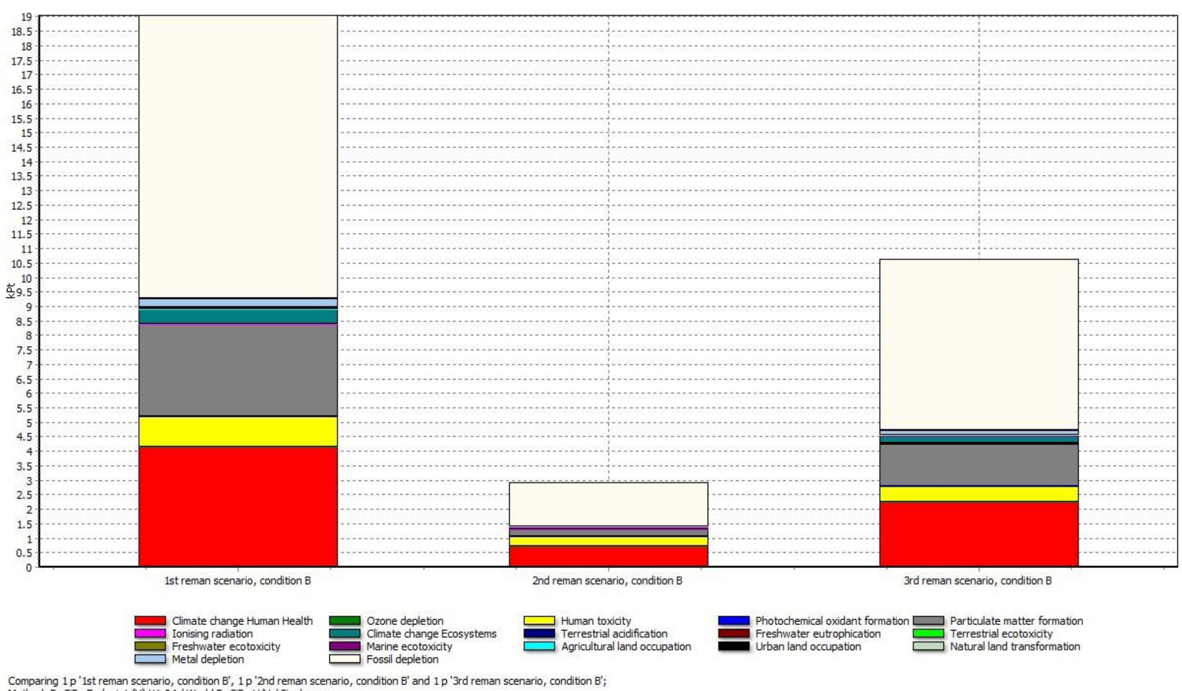


Figure 48. Single score impacts assessment comparison between remanufacturing scenarios using condition B sensitivity analysis. (ReCIPe Endpoint –H).

The single score analysis, shown in Figure 48, provides comparative results on the total impacts from each remanufacturing scenario. As was described earlier, scenario 1 has most of the impacts. In this sensitivity condition it accounts for 19,000 Pt., which is around 50% more than scenario 3. Again, the influence of the use of raw materials and important quantities of energy in the manufacturing of the bearings and the gears makes scenario 1 the one with the greatest impacts.

Most of the impacts in scenario 1 come from the Fossil Fuel Depletion category (10,000 Pt.), due to the amount of energy employed for processing the materials into new bearings and gears. Then the Climate Change Human Health and Particulate Matter Formation have similar impacts for this scenario, but both totalizing 40% of the total impacts. The impacts of other categories are very small compared to the categories previously mentioned.

Scenario 3 follows in terms of quantity of impacts with 10,937 Pt., more than half of them coming from the Fossil Fuel Depletion category. This value is highly influenced by the manufacturing of new bearings. In addition, Climate Change Human Health and Particulate Matter categories account for 4,000 Pt. Human Toxicity has around 500 Pt. in impacts. The other categories have very little influence over the final result.

Scenario 2 has fewer of the total impacts with 2,937 Pt. making this the most environmentally friendly procedure to remanufacture a wind turbine. To put the wind turbine again in operation in scenario 2, is only needed replacing of copper windings by new ones and applying minor machining procedures. These impacts are only 8% of the impacts corresponding to the manufacturing scenario performed over the Vestas wind turbine.

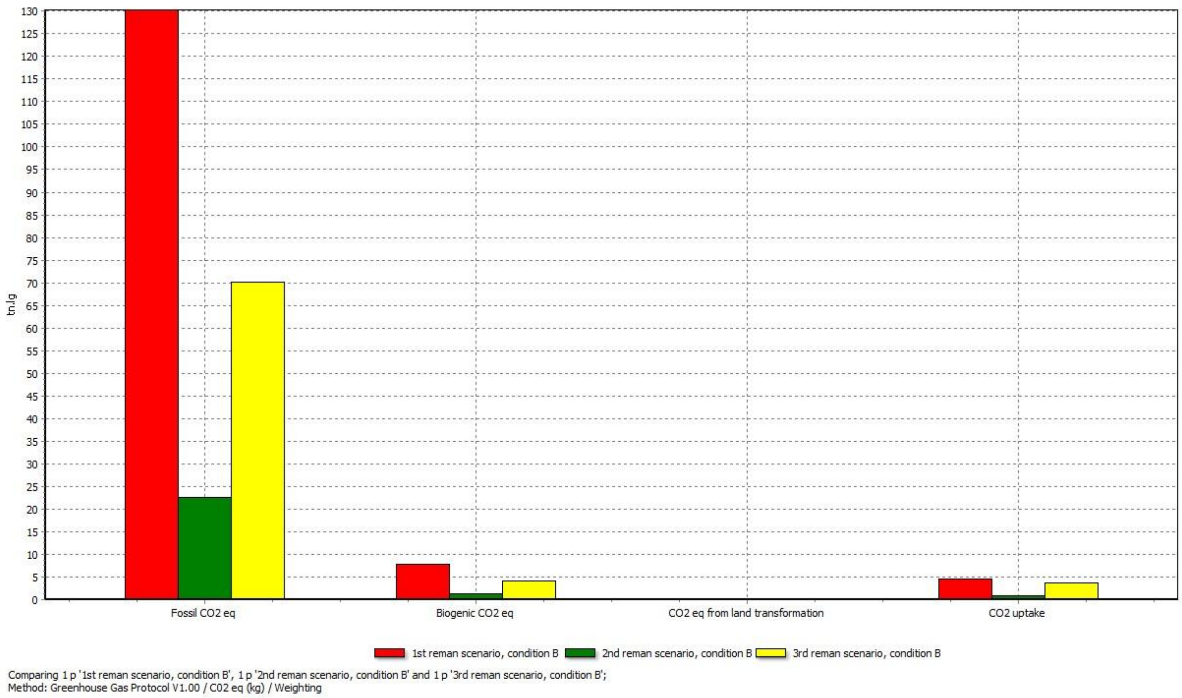


Figure 49. Green-house gasses emissions comparison between remanufacturing scenarios using condition B sensitivity analysis. (ReCIPe Endpoint –H).

Scenario 1 generates the greatest GHG impact accounting for 130 Long Tons of CO_2 emissions equivalent. This is compared to the 70 Long Tons of CO_2 equivalent released by scenario 3, and the 23 Long Tons of CO_2 equivalent for scenario 2. Therefore, scenario 1 has the most harmful effect on global warming. Again, the use of new components puts pressure over the requirement of new materials and the use of intensive energy processes.

5.3.4.3 Condition C

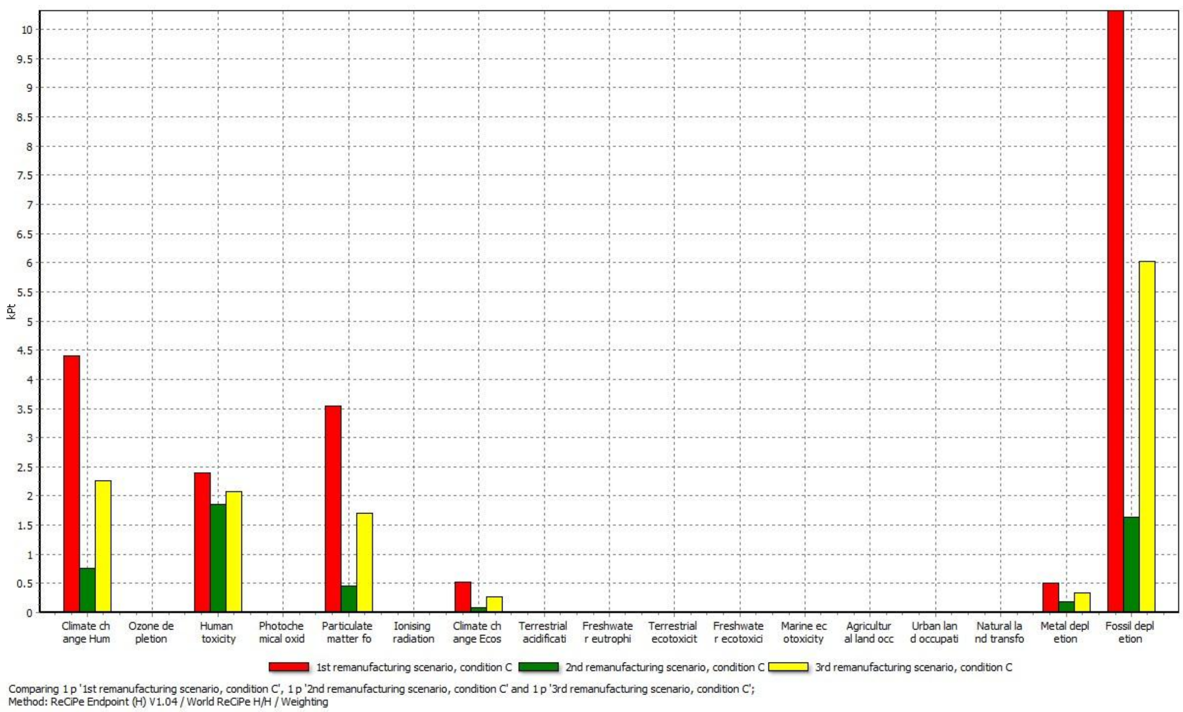


Figure 50. Impacts assessment comparison between remanufacturing scenarios using condition C sensitivity analysis. (ReCIPe Endpoint –H).

In Figure 50 the Fossil Fuel Depletion category carries most of the impacts. The remanufacturing scenario 1 has the greatest impact with 11,000 Pt. followed by the scenario 3 that accounts for 6,000 Pt. scenario 2 has the fewer of the impacts with 1,600 Pt.

Climate Change Human Health follows in quantity of impacts for scenario 1 (4,400Pt.); again, scenario 3 has almost half of the impacts of scenario 1 with 2,250 Pt. Scenario 2 has the fewest impacts with 700 Pt. in this category.

Particulate Matter Formation category is the third largest impact category in this analysis, followed by Human Toxicity category. Both of them account for a similar total amount of impacts with 6,000 Pt. Human Toxicity has more impacts in this condition than for condition A and B, because of the use of raw copper for copper rewinding. Consequently, more impacts are produced from the disposal of sulfidic tailings in the mining of copper ore. Climate Change Ecosystems and Metal Depletion have fewer than 500 Pt. for each remanufacturing scenario.

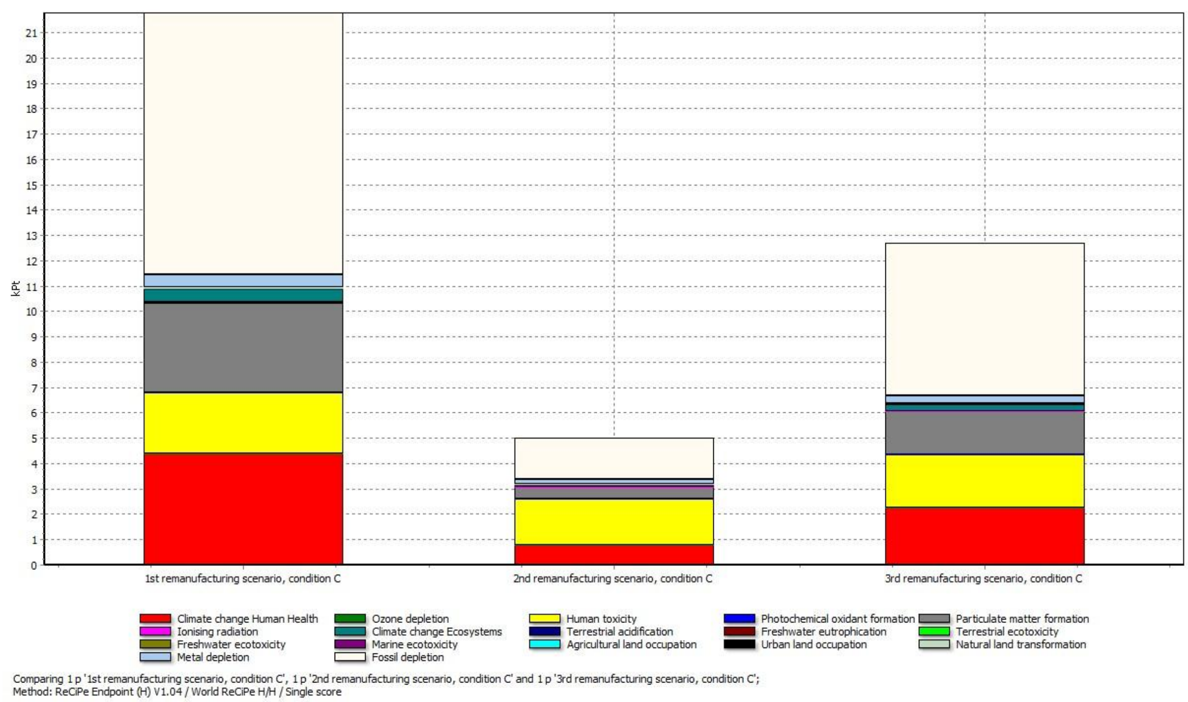


Figure 51. Single score impacts assessment comparison between remanufacturing scenarios using condition C sensitivity analysis. (ReCIPe Endpoint –H).

In Figure 51 scenario 1 also accounts for the greatest impacts among the three remanufacturing scenarios with 21,781 Pt. Fossil Fuel Depletion category carries about half of the impacts for this scenario. Climate Change Human Health category has considerable impacts with 4,000 Pt. Particulate Matter Formation has also an important contribution with 3,500 Pt. Scenario 3 has 12,710 Pt. which is almost half of the impacts of the remanufacturing scenario 1.

These results clearly show that the manufacturing of new gears has important impacts over the final results. For condition C, remanufacturing scenario 2 again has the fewest impacts with 5,005 Pt. Therefore, the application of a remanufacturing strategy in which the addition of new components is minimized, decreases the total impacts from remanufacturing. The impacts in this condition from each individual category are bigger than for the other two conditions previously analyzed.

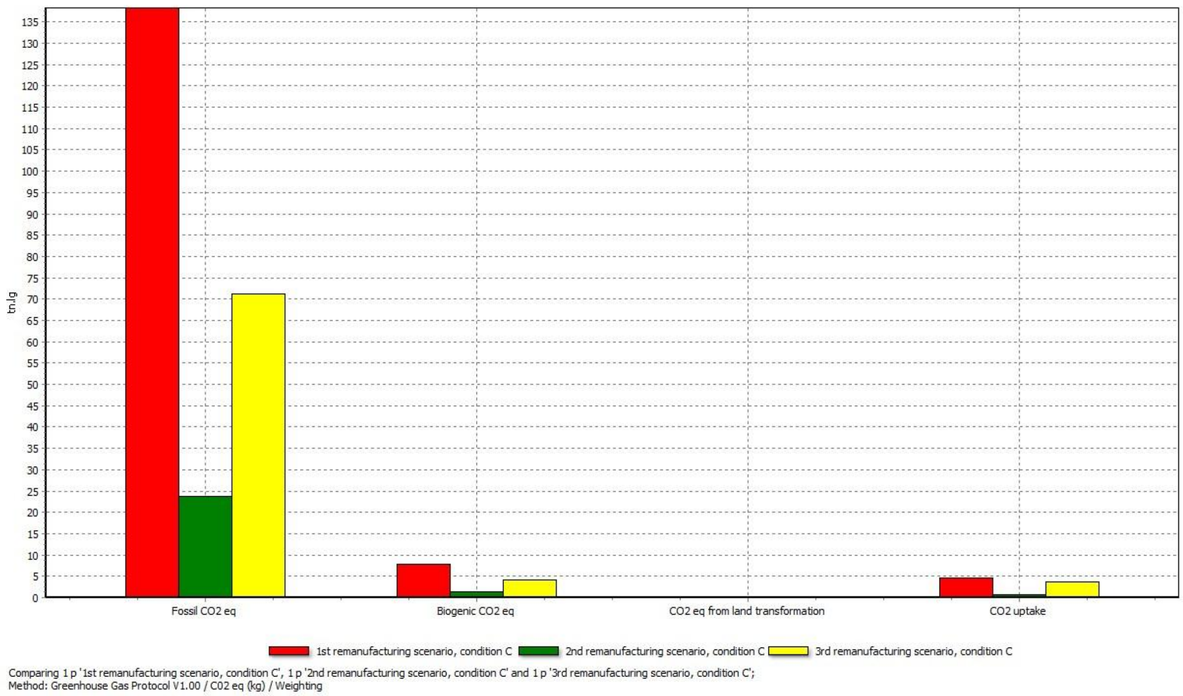


Figure 52. Green-house gasses emissions comparison between remanufacturing scenarios using condition A sensitivity analysis. (ReCIPe Endpoint –H).

In Figure 52 remanufacturing scenario 1 carries most of the impacts. In this case, 140 Long Tons of CO_2 equivalents are released. That result is almost two times bigger than the results for the remanufacturing scenario 3. Again, the decision of whether to remanufacture or to install new gears has an important impact over the final results. Remanufacturing scenario 2 has fewer of the CO_2 releases with a quantity equivalent to 24 Long Tons, which is nearly six times less than remanufacturing scenario 1. The Long Tons of Biogenic CO_2 equivalents released are less than 8 Long Tons for each scenario.

5.3.5. Embodied energy for scenarios and conditions

An additional element employed to analyze environmental impacts is the calculation of the embodied energy. This refers to the amount of energy units, in our analysis Mega Joules equivalents (MJeq.), employed to complete a given process. The results displayed on Table 37 correspond to the Cumulative Energy Demand method applied for the new wind turbine manufacturing and the different remanufacturing scenarios and conditions.

	Cumulative Energy Demand method. Comparison versus new wind turbine manufacturing scenario (3,909,654 MJeq.)						
	Sensitivity condition	**Condition A**		**Condition B**		**Condition C**	
	Base scenario: new wind turbine manufacturing	MJeq.	%	MJeq.	%	MJeq.	%
Remanufacturing	**Scenario 1: New bearings and gears**	1,969,179	50%	1,885,865	48%	1,987,496	51%
	Scenario 2: Remanufactured bearings and gears	295,960	8%	295,960	8%	312,984	8%
	Scenario 3: New bearings and remanufactured gears	1,146,945	29%	1,146,945	29%	1,165,261	30%
	Scenario 4: Remanufactured bearings and new gears	1,118,068	29%	1,034,888	26%	1,265,669	26%

Table 37. Sensitivity analysis for each remanufacturing scenario using the Cumulative Energy Demand Method.

These results are similar on percentage per scenario compared with the new wind turbine manufacturing case to the ones obtained in Eco-Points (Table 27). The new wind turbine manufacturing scenario also has the greatest impact with 3,909,654 MJeq.

Scenario 1 remains the remanufacturing scenario with the greatest impact, accounting for between 51% and 48% of the cumulative energy demand compared to the new wind turbine manufacturing scenario. Scenario 2 represents the least energy demanding scenario with only 8% of the established baseline. Finally, scenarios 3 and 4 have cumulative energy demands of between 26 and 30% compared to the new wind turbine manufacturing scenario.

5.3.6. Effects of transportation on the impact assessment sensitivity analysis for scenarios and conditions

The remanufactured wind turbine could operate and be installed not only in the U.S., but in any country where good winds are available for its operation. The transportation stage of the remanufactured equipment may offset environmental benefits of the total impacts of remanufacturing, compared to the manufacturing of a new wind turbine. Therefore, in this section a comparison between the total impacts of wind turbine remanufacturing is performed, including the transportation to different continents, versus the manufacturing of a new wind turbine with no transportation included.

The use of a lorry for inland transportation will be employed in the analysis, since it has bigger impacts than the use of rail road transportation, and its existence anywhere in the World is more common. Oceanic freight ship is used for water transportation.

Distance traveled by the remanufactured wind turbine				
Via	South Africa	China	NYS, U.S.A.	Venezuela
Lorry 32Tons>, inland U.S.A.	503 Km	2,080 Km	2,506 Km	503 Km
Lorry 32Tons>, inland destination	3,000 Km	2,000 Km	N/A	N/A
Ocean freight	14,322 Km	10,445 Km	N/A	4,051 Km

Table 38. Description of each of the transportations methods used to haul a remanufactured wind turbine. (ReCIPe Endpoint – H). Distancefromto.net, 2012.

Those countries, shown in Table 38, were chosen as an example of what developing countries may use the remanufactured wind turbine. The transportation to South Africa starts by transporting the remanufactured wind turbine using a lorry from the north of Texas to the port in Corpus Christi, Texas. Then ocean freight is used for delivering the machine through the Gulf of Mexico, the Caribbean Sea, and the Atlantic Ocean to a port in South Africa located at a distance of 14,322 Km from Texas. Finally, the remanufactured wind turbine is transported using a lorry for 3,000 Km to a non-specified place in the African continent. The idea is to represent an inland location that requires some lorry transportation.

The transportation of the remanufactured wind turbine to Venezuela begins in the same way as explained in the South African example; delivering the machine to a port in Corpus Christi, Texas, and

then ocean freight (4,051 Km) through the Caribbean Sea. Inland transportation is not considered for this example, since the wind at Venezuela's shore is good enough to install it near the port.

Transportation to an unspecified location in New York State (NYS) can be done by lorry transportation for 4,051 Km.

For an inland location in China, lorry transportation from Texas to the port of Los Angeles it is considered (2,080 Km), ocean freight delivery for 10,445 Km, and inland transportation in China for 2,000 Km. The resulting impacts from transportation for each region analyzed are shown in Figure 53.

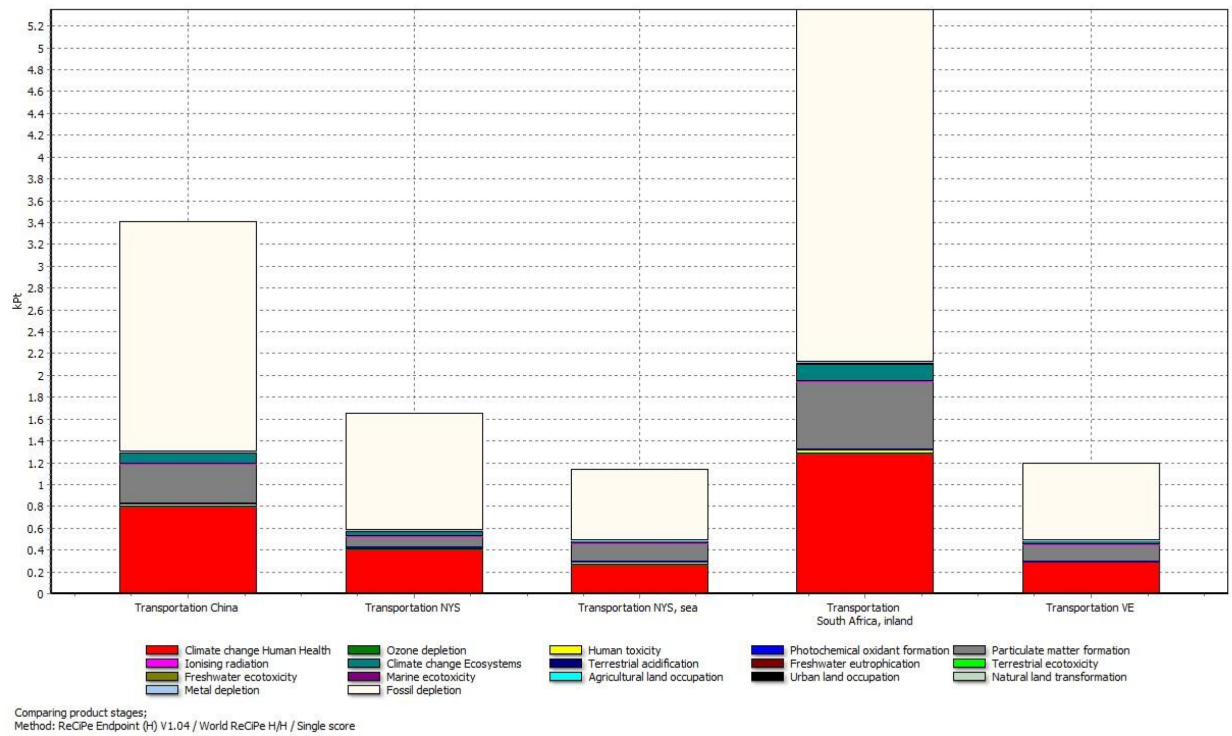


Figure 53. Comparison of transportation among different destinations for the remanufactured wind turbine. (ReCIPe Endpoint – H).

For the remanufacturing scenario 1, condition A, the difference on the environmental impacts between the new and the remanufactured wind turbine is of almost 20,000 Pt. Adding the highest impact resulting from transportation (5,300 Pt. to South Africa, inland) the total impacts are still significantly less than the manufacturing of a new wind turbine; this can be seen in Figure 54. Therefore, the additional transportation associated with a remanufactured wind turbine does not offset the environmental benefits of remanufacturing. The transportation and installation in coastal areas will make the environmental

impacts fewer, because the use of ocean freight is less damaging to the environment than using a lorry. For example, the transportation and installation in the coast of Venezuela, which is just 4,000 Km away from Texas' shore, opens a good possibility of investing in second-hand wind turbines in the Caribbean, if the finances are suitable for the operation of a wind turbine. If sea freight is considered as transportation to NYS, the impacts of transporting to Venezuela would be a bit higher compared to NYS.

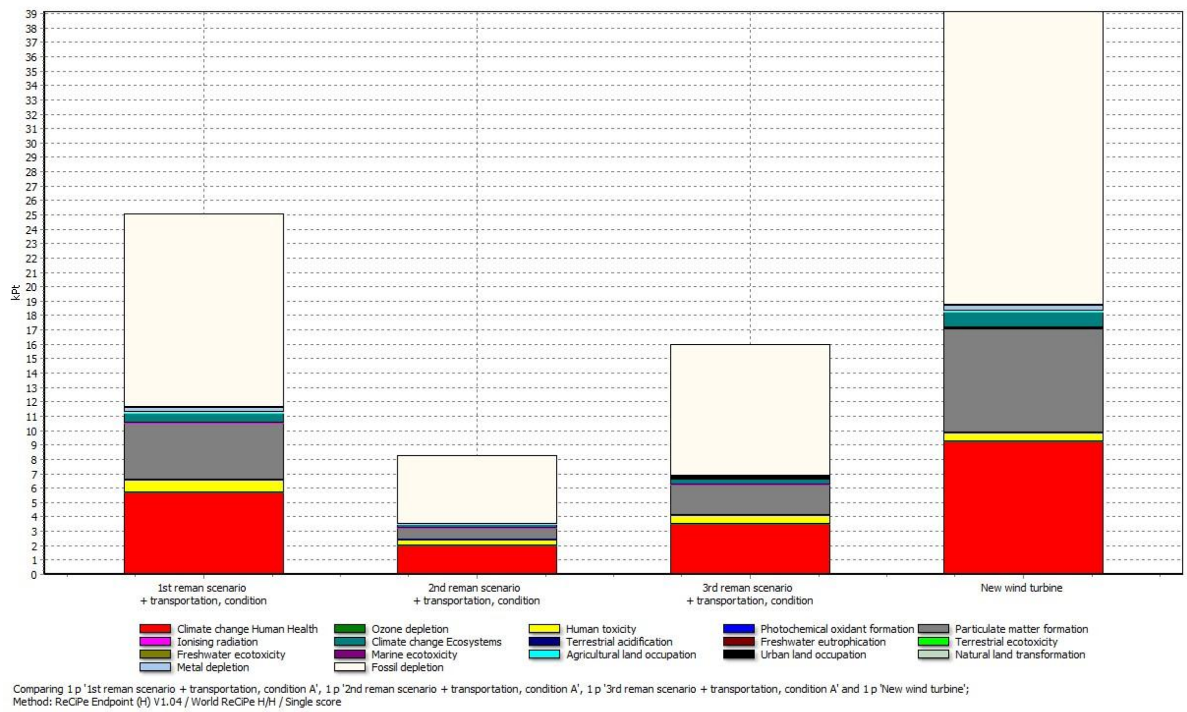


Figure 54. Comparison of the impacts from transportation South Africa, inland and remanufacturing scenarios versus the impacts of the manufacturing scenario of a new wind turbine. (ReCIPe Endpoint –H).

5.4 Technological trends for the future

This section addresses some of the technological changes in wind turbine technology that might influence remanufacturing procedures and their environmental impact in the following years.

One of the most important influences for future wind turbine technology is the role of transmission systems. As shown in this study, the new or remanufactured gearbox and generator have a big impact over the environment. According to Vath from Bosch Rexroth AG, experts agree that high-temperature superconducting direct drive generators with medium speed concept and hybrid drives will be commonly used in the future. Furthermore, "The amount of copper and permanent magnets leads to

huge investment costs and dependency of the availability for rare earth material" (Vath, 2012). Figure 55 shows different drive train concepts currently in use, and to be employed in the future.

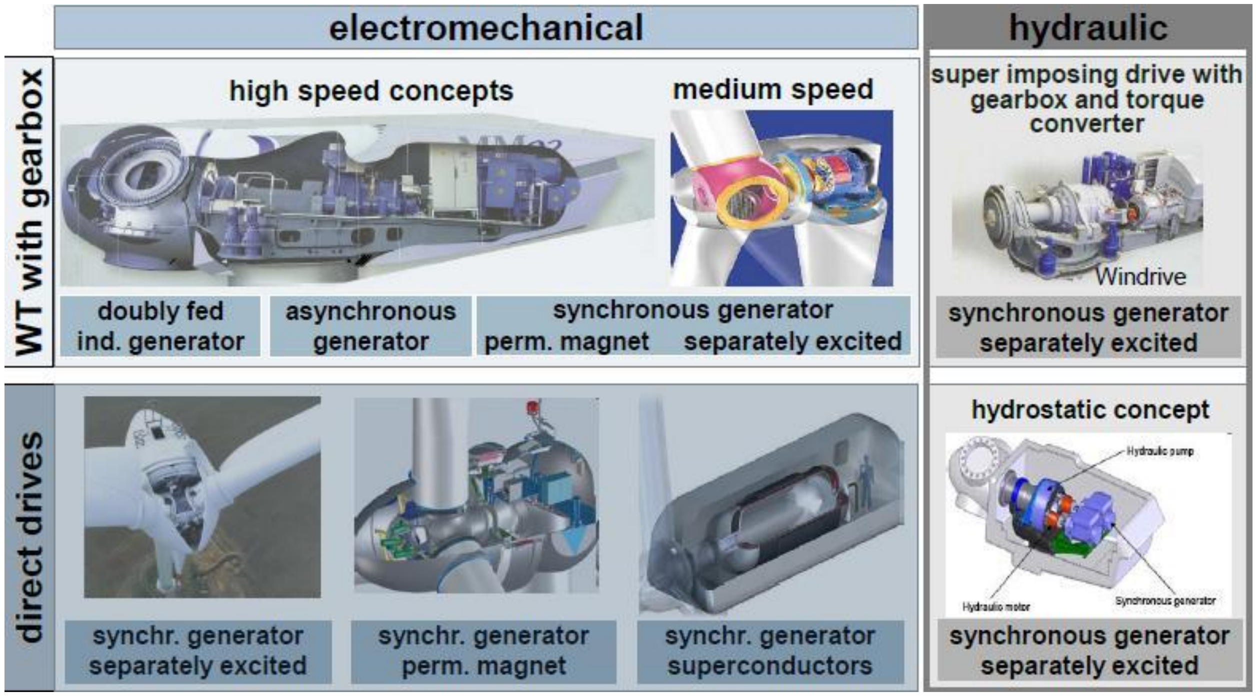


Figure 55. Overview: different train concepts. Andreas Veth, 2012.

Mining rare metals for permanent magnets has a greater environmental impact than mining copper or aluminum. Consequently, the environmental impact from the use of direct drive technology or hybrid systems for the manufacturing of new wind turbines might be greater than using the traditional gearbox approach. On a hybrid drive system, the weight of the permanent magnet material can be 710 Kg., whereas on a direct drive system the weight of the permanent magnet material for the same system can be 7020 Kg. (Li et all, 2009).

The use of generators made of superconductors represents a third and more technologically advanced option. A super conductor transmission system for the same power rating could weigh only 20 Kg., but it would be cost prohibitive (Zirngibl, 2012). Therefore, a factor that will influence the environmental impact of this equipment is how quickly these new technologies will be introduced.

5.5 Discussion and analysis of results

The discrepancies in the LCA results for the components inside the nacelle between the Martinez et all study and this work, lead to the use of the results obtained from using the input data of the Martinez et all work together with the ReCIPe Endpoint H methodology. The total of 39,139 Pt. from the manufacturing of the new wind turbine, at least doubles the environmental impacts obtained from every remanufacturing scenario. The input information used was exclusively materials and energy. Fossil Fuel Depletion category represents more than the 50% of the total impacts for the manufacturing of the new wind turbine, and Climate Change Human Health follows with just over 9,000 Pt.

Fossil Fuel Depletion category remains as the leading environmental impact category for all remanufacturing scenarios. The dominance of coal and gas in the energy mix for electricity production has an important influence on this result. The electricity mix is used for processing new materials as copper, steel, and aluminum, manufacturing of new parts like gears, bearings, and windings, and for mechanical and thermal processes during remanufacturing. Natural gas also dominates this category as it is employed for high thermal processes like bake dry and pyrolysis.

Climate Change Human Health category is the second largest impact for all remanufacturing scenarios. This category is linked to Fossil Fuel Depletion since the use of fossil fuels contributes to the effect of climate change over the health of humans. Therefore, the increase of the impacts for both categories is related to the electricity mix and the use of natural gas for the processes described before.

Scenario I has the greatest environmental impacts of all the remanufacturing scenarios. The processing of steel into new bearings and gears causes this scenario to have an important impact. For the new bearings 2.6 Tons of steel are added as well 10.9 Tons for the new gears. This amount of material represents almost a fifth of the total weight of the components inside the nacelle. As a result, many resources must be used to manufacture those new components. The mining, processing, and manufacturing of components made of ferrochromium and ferronickel are particularly damaging (for example, 1,990 Pt. for the scenario 1), since those materials are mainly used for bearings and gears.

Scenario 2 has the least environmental impacts of all remanufacturing scenarios. The remanufacturing of gears and bearings greatly decreases environmental impacts due to reduced energy and material consumption. Energy is used for both components on inspecting, cleaning and machining

operations, and materials are mainly employed when substituting rollers on the remanufactured bearings and windings on the generator and transformer. Rewinding operations for the generator and transformer, due to the replacing of copper and aluminum, have the greatest impacts on this remanufacturing scenario.

Scenario 3, according to remanufacturers, is the most likely scenario to occur because remanufacturing of the gears and replacing of bearings is a common practice in the industry. The greatest environmental impact comes from replacing bearings on the main shaft, gearbox, and generator. The LPG employed as energy source on the manufacturing of new bearings has the greatest influence on this scenario with 1,462 Pt., Followed by the use of ferrochromium, ferronickel, and raw steel with a total of 1,123 Pt.

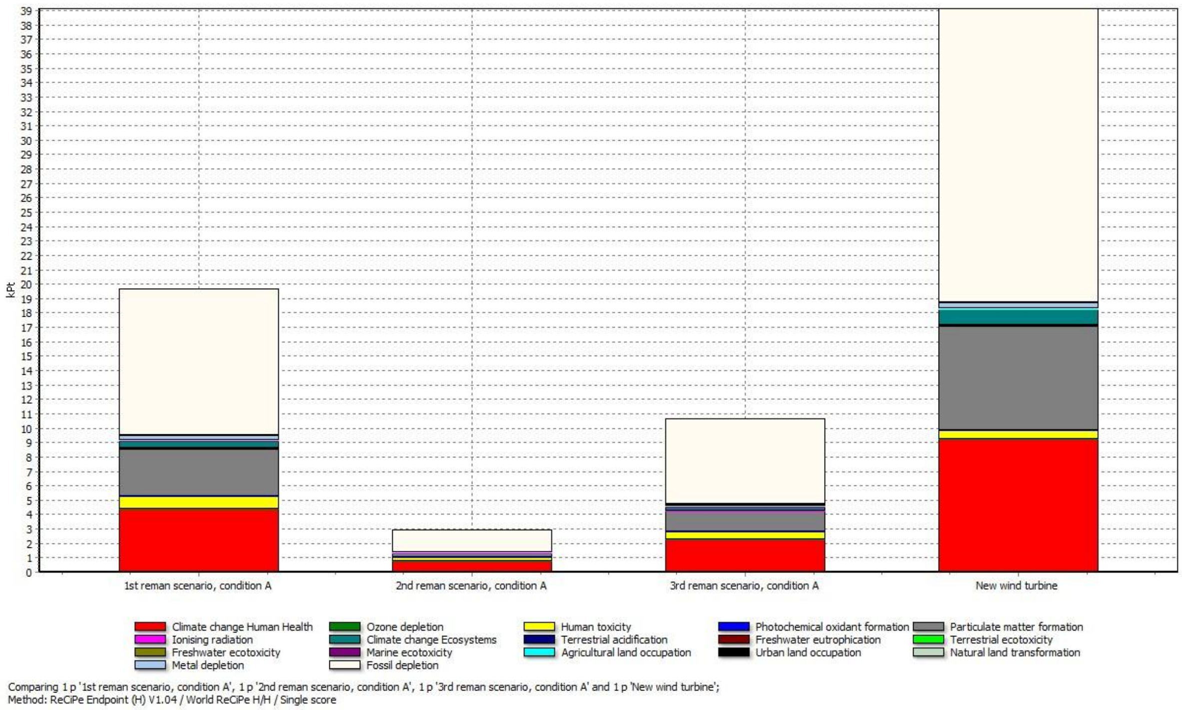
The mix of recycled and virgin materials has some influence on the variations of the environmental impacts shown on conditions A, B, and C. In scenario 1, the difference is 2,078 Pt. between condition A and C, the difference between condition A and C in scenario 2 is 2,068 Pt., and in scenario 3 the difference is 2,077 Pt. For scenario 1, in which the impacts are 21,781 Pt. in the worst case, the impact of the mix of recycled and virgin materials might not be of significance. On the other hand, in scenario 2 the type of condition chosen makes the impacts double. Therefore, depending on the scenario analyzed, the condition A, B, or C will have a different influence on the results.

The influence on transporting a remanufactured wind turbine to a new site is small compared to manufacturing a new wind turbine, which was demonstrated by choosing different installation sites around the world with no more than 3,000 Km. of inland transportation by truck.

In the future, the type of new technology for transmission systems will influence the overall environmental impacts for remanufacturing wind turbines. As new equipment is installed using new technologies the industry will search for ways, at the end of the wind turbine life time, to put this equipment back into service using a remanufacturing techniques. Prior to this, it would be advisable to understand the environmental impact of using permanent magnets or superconductor materials for transmission system.

Chapter VI – Conclusions and Recommendations

6.1. Conclusions



Comparison of the impacts of the remanufacturing scenarios, condition A versus the impacts of the manufacturing scenario of a new wind turbine. (ReCIPe Endpoint –H).

The use of remanufactured parts is a proven strategy in other industries for decreasing the environmental impacts over the life-cycle of a product. In large machines, such as commercial wind turbines, the total impacts are important. In previous works referenced in this thesis, it has been shown that the manufacturing stage has most of the environmental impacts from the life-cycle of a wind turbine. The results of this thesis research confirm that the remanufacturing of the components inside the nacelle has fewer impacts than the manufacturing of new components. Figure 55 shows that remanufacturing scenario 1, corresponding to the remanufacturing scenario with most of the environmental impacts, has only 50% of the impacts of the manufacturing of new components inside the nacelle.

The main reason fewer impacts under these circumstances is because raw materials are not mined, processed and manufactured into large components that contain most of the weight. This comment

corresponds to the following components: bedframes, nacelle cover, main shaft, and external case for gearbox, transformer, and generator. The savings from preventing the use of energy and materials for those components make the remanufacturing of wind turbines an excellent alternative from an environmental point-of-view compared to the manufacturing of new wind turbines. Other authors have explained that a remanufactured wind turbine can be cheaper than a new one, and that the acquisition of a new wind turbine could take months from the moment the costumer requested it to an OEM. Therefore, the decrease in lead times, cheaper price, and the environmental benefits accompanying remanufactured wind turbines makes them an attractive investment.

In remanufacturing scenario 1, the manufacturing of new gears and bearings makes the total impacts nearly double compared to other remanufacturing scenarios. The use of energy from coal and gas has an important share of the impacts when processing the raw materials for the gears and the bearings. Therefore, if renewable energies can be used as electricity sources the impacts would be fewer. This conclusion goes hand in hand with the impact analysis which demonstrates that the Fossil Fuel Depletion category is by far, the one that generates most of the impacts from remanufacturing a wind turbine. The Climate Change Human Health category is the one with the second largest impacts. However, this category accounts only for half of the impacts of the Fossil Fuel Depletion category. Nevertheless, the total impacts are fewer than for the scenario where the components inside the nacelle are manufactured as new.

The use of recycled or raw steel has a small difference over the final impacts if the worst, original, and best conditions for each remanufacturing scenarios are compared. But the act of remanufacturing those components implies huge impacts reductions compared to manufacturing new components. In addition, the proportion of the impacts remains the same for each category. Credits from recycling the copper and steel used for bearings, gears, and winding are not shown in this analysis; including this in the analysis could further decrease the total impacts of the remanufacturing scenarios.

Given that the gear remanufacturing can be a common procedure in the remanufacturing of a wind turbine, the key for the industry in terms of environmental impacts is to be able to use high quality remanufactured bearings. If the bearings are of the highest quality and suffer minimum damage during operation they can be remanufactured, and the total environmental impacts would be fewer for any condition. That is shown in the remanufacturing scenario 2, where the bearings and the gears are remanufactured and copper rewinding for the transformer and the generator is the only new material added. Scenario 2 represents, in the best circumstances, 8% of the total impacts compared to manufacturing a new wind turbine.

It is essential for the remanufacturing industry to show that this procedure can be used as carbon credits, under any of the world-wide or regional carbon trade mechanism. Because it will encourage economic savings to the owner of the project and it will encourage the first wind turbine owners to sell their wind turbines to other markets, and then install a newer wind turbine with better technology. Despite that the manufacturing of the new wind turbine would encourage use of additional energy and materials, the savings in carbon by using new wind turbines would be greater than the renovation of traditional energy plants that, in overall, have more long-term impacts over the environment.

Something worthy of mentioning, is that detailed input data for the new wind turbine manufacturing scenario was not included in the analysis. If more detailed information were included, the environmental impacts of manufacturing a new wind turbine would be larger than the one obtained in this work. Hence, the difference between the remanufacturing and the new wind turbine manufacturing scenarios would be greater. Conversely, given the educational nature of this work, if an industrial partner were interested in this research, more detailed information could be obtained and the results for remanufacturing would be more accurate.

The Particulate Matter Formation has also relevance on the final environmental impacts. Consequently, the installation of proper monitoring and mitigation systems in each industrial site related to the wind turbine remanufacturing business could decrease those values.

6.2. Recommendations

The fact that the impact of remanufacturing for the rotor and the tower was not analyzed in this work, does not make this work less relevant. The reason is towers and rotors rarely suffer considerable damage. Therefore, for the sake of this work, it was assumed that those impacts would not be significant compared to the remanufacturing of the components inside the nacelle, and future work could be focused on this area.

It is important to address the state of the components at the end of the wind turbine’s useful life in terms of environmental impacts. The greater the damage of a component, the more material and energy must be invested in order to be properly remanufactured. Future work can be centered on elaborating a model to understand the environmental impacts related to the wear out of the components.

The size of wind turbine has relevance over the total environmental benefits of wind turbine remanufacturing. Therefore, an analysis about the environmental impacts on remanufacturing smaller

(micro, residential, distributed) wind turbines and compare them to manufacturing a new wind turbine of the same class could be suggested.

The high environmental impact of mining permanent magnet materials might compromise the environmental benefits of using a clean technology as wind turbines. Therefore, is advisable to perform a comparison between current and future transmission technology on wind turbines.

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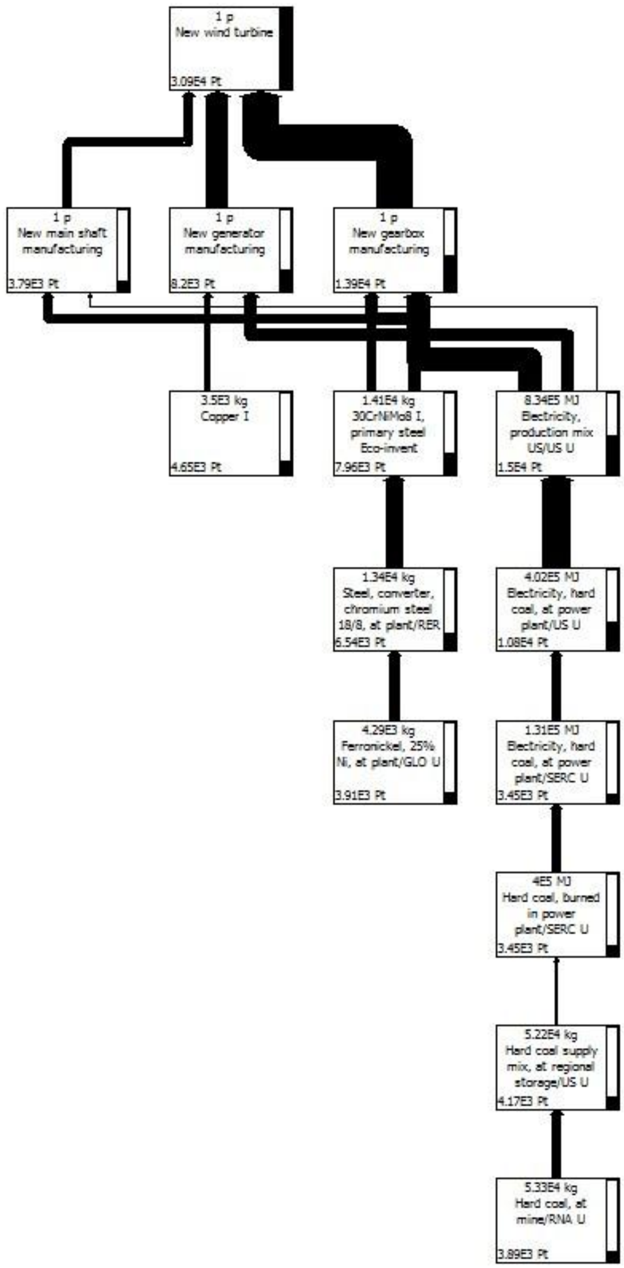
Chapter VIII - Appendix

Appendix A – New Wind Turbine Results

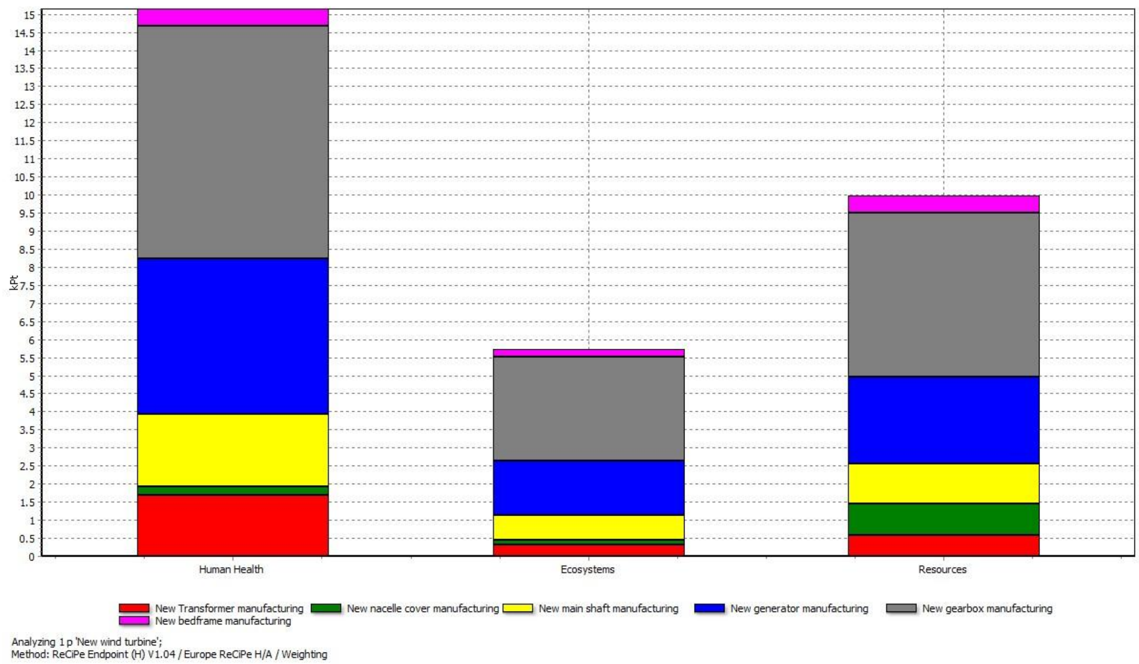
New Wind Turbine - Network 12% Threshold



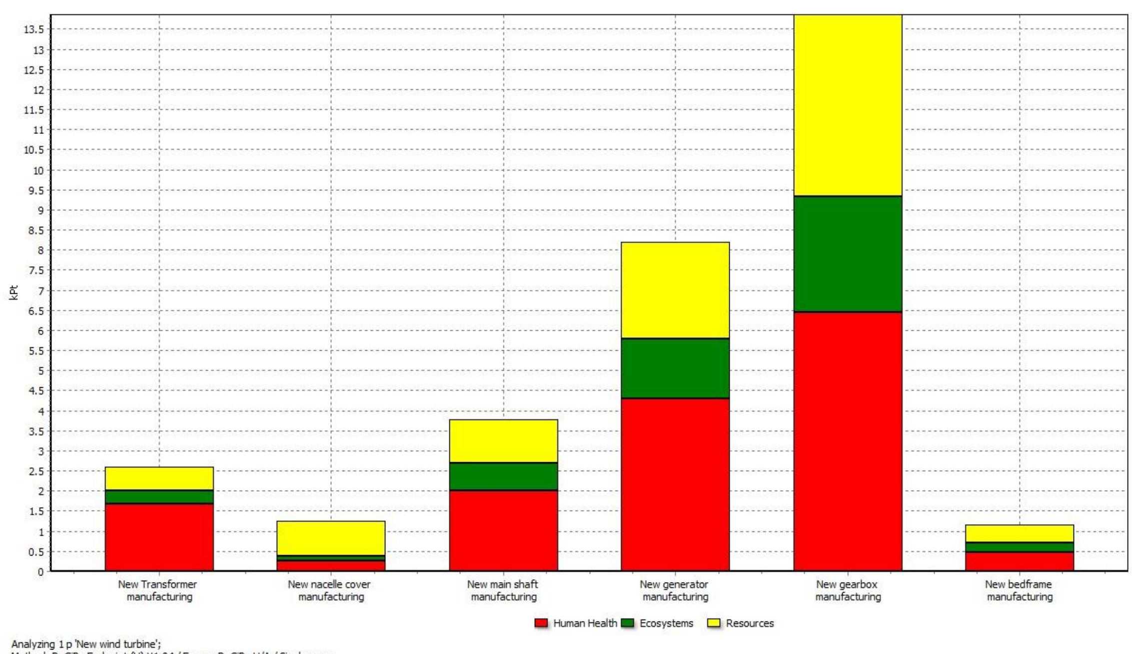
New Wind Turbine - Process Contribution 12% Threshold

No	Process	Unit	Total	New Transformer manufacturing	New nacelle cover manufacturing	New main shaft manufacturing	New generator manufacturing	New gearbox manufacturing	New bedframe manufacturing
	Total of all processes	Pt	30852.93	2592.69	1243.53	3788.84	8203.91	13863.33	1160.64
	Remaining processes	Pt	6893.99	117.64	318.10	1536.71	1022.59	3658.07	240.88
1	Lignite, at mine/RER U	Pt	316.95	0.00	5.20	57.56	61.71	184.93	7.54
2	Natural gas, burned in industrial furnace >100kW/RER U	Pt	341.49	0.00	0.17	145.15	2.01	193.92	0.25
3	Energy Asia I	Pt	399.73	52.31	x	120.88	68.01	158.53	x
4	Bulk carrier I	Pt	401.66	101.41	x	0.36	132.76	72.54	94.59
5	Hard coal, burned in power plant/SPP U	Pt	457.68	0.00	12.25	10.47	145.46	271.71	17.78
6	Ferronickel, 25% Ni, at plant/GLO U	Pt	463.45	0.00	0.02	200.15	0.27	262.97	0.03
7	Hard coal, at mine/EEU U	Pt	463.86	0.00	0.46	193.68	5.43	263.63	0.66
8	Hard coal, burned in power plant/MRO U	Pt	504.52	0.00	13.51	11.55	160.35	299.52	19.60
9	Crude iron I	Pt	521.81	x	x	x	x	225.65	296.16
10	Steel I	Pt	584.60	254.17	x	x	330.43	x	x
11	Crude oil N-sea(b) I	Pt	597.06	x	597.06	x	x	x	x
12	Nickel I	Pt	641.97	84.02	x	194.13	109.22	254.60	x
13	Ferrochromium, high-carbon, 68% Cr, at plant/GLO U	Pt	690.91	0.00	0.03	298.50	0.31	392.03	0.04
14	Hard coal, burned in power plant/WECC U	Pt	713.71	0.00	19.11	16.33	226.83	423.71	27.73
15	Energy US I	Pt	826.52	54.05	x	263.88	70.26	385.97	52.36
16	Natural gas, burned in power plant/US U	Pt	1024.22	0.00	27.42	23.44	325.51	608.05	39.80
17	Hard coal, burned in industrial furnace 1-10MW/RER U	Pt	1111.73	0.00	0.50	473.37	5.89	631.26	0.72
18	Natural gas, unprocessed, at extraction/RNA U	Pt	1388.95	0.00	37.18	31.79	441.43	824.57	53.97
19	Hard coal, burned in power plant/SERC U	Pt	2075.90	0.00	55.56	47.67	659.64	1232.38	80.65
20	Hard coal, burned in power plant/RFC U	Pt	2281.07	0.00	61.06	52.20	724.97	1354.20	88.64
21	Hard coal, at mine/RNA U	Pt	3649.98	0.00	95.91	111.02	1138.71	2165.11	139.22
22	Copper I	Pt	4501.19	1929.08	x	x	2572.11	x	x

New Wind Turbine - Weighting 12% Threshold



New Wind Turbine - Single Score 12% Threshold



Appendix B - Impact Assessment per Damage Category

New Wind Turbine - Impact Assessment per Damage Category Single Score

Damage category	Unit	Total	New Transformer manufacturing	New nacelle cover manufacturing	New main shaft manufacturing	New generator manufacturing	New gearbox manufacturing	New bedframe manufacturing
Total	Pt	30852.93	2592.69	1243.53	3788.84	8203.91	13863.33	1160.64
Human Health	Pt	15148.99	1679.95	253.23	2004.42	4293.54	6451.08	466.76
Ecosystems	Pt	5739.97	324.54	123.55	690.09	1492.79	2872.33	236.67
Resources	Pt	9963.98	588.20	866.75	1094.32	2417.58	4539.92	457.22

Reman Wind Turbine, Scenario 1, Condition A - Impact Assessment per Damage Category Single Score

Damage category	Unit	Total	New Transformer manufacturing	New nacelle cover manufacturing	New main shaft manufacturing	New generator manufacturing	New gearbox manufacturing	New bedframe manufacturing
Total	Pt	30852.93	2592.69	1243.53	3788.84	8203.91	13863.33	1160.64
Human Health	Pt	15148.99	1679.95	253.23	2004.42	4293.54	6451.08	466.76
Ecosystems	Pt	5739.97	324.54	123.55	690.09	1492.79	2872.33	236.67
Resources	Pt	9963.98	588.20	866.75	1094.32	2417.58	4539.92	457.22