ENVIRONMENTAL IMPACT OF ADDITIVE MANUFACTURING IN THE RENEWABLE ENERGY INDUSTRY: CASE OF WIND TURBINE

Lappeenranta–Lahti University of Technology LUT

Master’s thesis in Sustainability Science and Solutions

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ABSTRACT

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Increasing demand for goods and services is growing with the evident rise in population globally. To cater to the needs for the planet, manufacturing methods that are part of industry should be more sustainable, while giving major importance to the environmental performance of the products. The concern of diminishing resources and raw materials is driving scientists, researchers, governments, and industry stakeholders to adopt new technologies that can outperform traditional methods of manufacturing. Additive manufacturing is one such manufacturing method that is on the cusp of being largely integrated into the industries of today. It is a technique that benefits the three pillars of sustainably, namely the environment, economy, and society. It plays a crucial role in reducing waste by efficient resource consumption and reduced manufacturing waste, reduction of emissions during the life cycle of a product, promoting on-demand and localized manufacturing, and offers a high level of design freedom which can help manufacture complex parts. The renewable energy industry has challenges such as system reliability, energy security, environmental impacts, and reliability of the systems. However, with growing technology, these issues can be addressed, specifically by integrating additive manufacturing into the industry. Wind energy is one of the most promising types of renewable energy and it is growing globally in terms of capacity installed per year, and overall capacity available. AM is increasingly being used in the wind energy industry, but it is still yet to be made fully commercial and functional. The main benefits are repairs and remanufacturing, improved supply chain, and reduced environmental issues. Life cycle assessment is a powerful tool to study the environmental impacts for the life cycle of a product. It helps to identify the various impacts caused to the environment by addressing specific indicators such as global warming potential, depletion of resources, water consumption, etc. Life cycle analysis can be then further used to improve the product by developing them further, strategic developments, marketing opportunities, and better legislation.

The results of the thesis firstly indicate the environmental impacts caused by traditionally manufactured a 2 MW wind turbine during its life cycle. The findings were that the products, recurring, and transport stages contributed significantly to the greenhouse gas emissions. Steel, resins and adhesives, and concrete are the materials that contribute maximum to the emissions. Other significant indicators to the environmental performance for the life cycle of the wind turbine are ozone depletion potential, abiotic resource depletion, water footprint, and particulate matter emissions. For each of these indicators, the product and recurring stages contribute the most to the environmental impact. Secondly, a case study has been identified to use additive manufacturing to manufacture a rotating unit, which is a part of the hydraulic pitch system of a wind turbine. The results showed that significant material savings can be achieved by using AM, which can positively impact the environmental performance. The weight reduction and material savings for the assembly was approximately 44% and 72% respectively, in comparison to traditionally manufactured rotating unit. Finally, the results of the thesis from both experimental parts were analyzed and discussed to illustrate the environmental benefits gained by integrating additive manufacturing for the life cycle of the wind turbine.

SYMBOLS AND ABBREVIATIONS

A	Area swept of turbine blade	[m^2]
c	Chord length of blade	[m]
DSR	Direct solar radiation	[Wh/m^2/year]
E (Energy)	Watt hour/Terawatt hour	[Wh or TWh]
HR	Horizontal radiation	[Wh/m^2/year]
M	Mass	[kg]
P (Power)	Watt/ Megawatt	[W or MW]
T (Temperature)	Degrees Celsius	[°C]
U	Velocity of airfoil profile	[m/s]
V	Velocity of wind	[m/s]
v	Kinematic velocity	[m/s]
Y	Product life	[Years]
ρ	Density	[kg/m^3]

Dimensionless quantities

C_p	Power coefficient
Re	Reynolds number
%	Percentage

Abbreviations

2D	2 dimension
3D	3 dimension

ABS	Acrylonitrile Butadiene Styrene
AM	Additive manufacturing
ARD	Abiotic resource depletion (kg Sb-equivalent)
ASTM	American Society for Testing and Materials
BAAM	Big area additive manufacturing
BJ	Binder jetting
CAD	Computer aided design
Cd	Cadmium
CFC-11	Trichlorofluoromethane ($CFCl_3$)
CH_4	Methane
CNC	Computer numerical control
COP	Conference of Parties
CO_2	Carbon dioxide
DED	Directed energy deposition
DfAM	Design for additive manufacturing
DfM	Design for manufacturing
EIA	Environmental impact assessment
EU	European Union
FDI	Foreign direct investment
GDP	Gross domestic product
GHG	Greenhouse gases
GWP	Global warming potential (kg CO_2 equivalent)
HAWT	Horizontal axis wind turbine
HMA	Hypomethylating agents

I 4.0	Industry 4.0
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LCT	Life cycle thinking
LEED	Leadership in Energy and Environmental Design
L-PBF	Lased-based powder bed fusion
ME	Material extrusion
MJ	Material jetting
NO_x	Nitrogen oxides
N_2O	Nitrous oxide
ODP	Ozone depletion potential (kg CFC-11 equivalent)
ORNL	Oak Ridge National Laboratory
PBF	Powder bed fusion
PLA	Polylactic acid
PM	Particulate matter (kg PM 2.5 equivalent)
RE	Renewable energy
RU	Rotating unit
R&D	Research and development
Sb	Antimony
SHL	Sheet lamination
STL	Standard tessellation language
UNFCCC	United Nations Framework Convention on Climate Change

UV	Ultraviolet
VAT	Vat photopolymerization
VAWT	Vertical axis wind turbine
WCED	World Commission on Environment and Development
WF	Water footprint (m^3 water deprived equivalent)
WPD	Wind power density

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1 INTRODUCTION

The fourth industrial revolution (Industry 4.0, I 4.0) has been shaping the future of manufacturing to make the sector more efficient, simple, flexible, and cost effective with automation, manufacturing interoperability, and digital tools (Vaidya et al., 2018). Interoperability is the ability of two or more systems to exchange and use the information to obtain a specific function (Zeid et al., 2019). Industrial automation increases productivity by reducing labour costs and the speed of work. It allows the workforce to have access, monitor, operate, and maintain the related equipment safely with real time data analysis. Additionally, it also lowers the negative impacts on the environment by increasing energy efficiency and optimization of resources and products (Frei, 2022). The growing scarcity of available resources has driven scientists, decision makers, industrialists, consumers, etc., to move towards a circular model (Despeisse et al., 2017).

The term circular economy was introduced by the Ellen MacArthur Foundation in which resources are used to their maximum potential while minimizing the wastes associated with it (Deutz, 2020). A linear economy is where extraction of raw materials is done to manufacture products, after which the product is thrown away. By moving from a linear to a circular system, elimination of resources going into the system, and waste going out of the system can provide benefits to the economic system in which it is present, as well contribution of environmental and societal benefits (Geissdoerfer et al., 2017). Renewable energy (RE) generates minimal waste and needs less resource extraction compared to fossil fuels and is an important aspect of circular economy (Majeed and Luni, 2020). It is the energy obtained from natural sources such as the sun, wind, water, earth, and biomass (Mohtasham, 2015). The share of RE increased by 3% in 2020, and 8% in 2021 to reach 8,300 TWh, with solar and wind energy contributing to two-thirds of the growth (IEA, 2021). RE contributes to national sustainable development and positively impacts the gross domestic product (GDP) of a country (Abdullah et al., 2020). Innovation and country environment are the two variables that affect technological advances shown in Figure 1 (Wen et al., 2022).

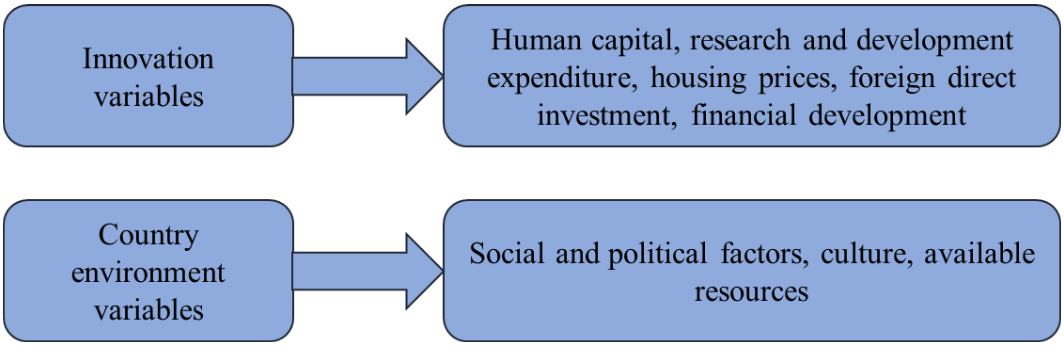


Figure 1: Variables affecting technological development (Adapted from (Wen et al., 2022))

As seen from Figure 1, advances in technology are impacted by factors such as human capital and the investments in research and development (R&D) of technologies. Foreign direct investment (FDI) in the RE industry is advised to reduce the effects of global warming, improve regional collaboration, integration, and business (Kang et al., 2021). Socio-cultural, political factors and the available resource of a country supports technical advancements such as RE, which is growing especially in regions with high consumption such as Asia, Europe, and the Americas (Wen et al., 2022).

Fossil fuels have provided opportunities and prosperity to mankind for over hundreds of years but have negative effects that damage the environment and human health. They are considered to be contingent resources, or reserves, as they cannot be replenished (Abas et al., 2015). The release of greenhouse gases (GHG) such as CO_2, methane (CH_4), ozone etc, has majorly polluted the atmosphere by causing global warming and air pollution. Large volume of GHGs in the atmosphere and earth make it difficult for current technologies to be able to clean all the emissions in the environment (Abas et al., 2015; Martins et al., 2019). RE provides advantages such as lower GHG emissions, reduces the negative impact on the environment, enables a diversification of fuel mixtures, promotes conservation of natural resources, provides more access to energy, etc. However, there a few challenges to be addressed such as high investment costs, dependence on location, variability of efficiencies, etc., (Maradin, 2021).

The rise of product demand and manufacturing activities, along with the need for sustainability must drive strategies that reduce the negative impact on the environment (Wiktorsson et al., 2011). Traditional manufacturing methods use subtractive methods such as machining, drilling, casting, etc., where material is removed a larger part. It allows for low cost and high-volume production, simplicity of products, more requirement of natural resources, raw material, and labour (Pereira et al., 2019). This manufacturing method causes more wastage, releases more emissions into the atmosphere and requires more energy (Javaid et al., 2021; Nörmann and Maier-Speredelozzi, 2016). Hence, the need for a novel method of manufacturing to address these problems is imperative to reduce stress on the environment, demand for products, and global supply chains. Additive manufacturing (AM) provides a new approach to manufacturing as it happens layer-by-layer and thus provides freedom of design. AM introduces a solution to reduce the amount of waste from manufacturing processes, reduce energy usage and localize manufacturing (Ghobadian et al., 2020). This can reduce worsening environmental conditions while also simplifying the manufacturing process (Duda and Raghavan, 2018).

Customized and complex products can be manufactured using AM for different technical requirements through product optimization, part orientation, material choice and quality, and system calibration. This can help to meet the growing demand RE technologies (Javaid et al., 2021). AM plays a crucial role in the current supply chain model by being able to rapidly manufacture and consolidate parts on demand and locally. Its integration to the wind energy industry could prove to provide several benefits (Kocsis and Xydis, 2021).

1.1 Background to the research

The increasing usage of resources for industry and personal use is growing with the increase in population and demand for goods and services. To meet these demands, manufacturing industries need to increase their production capabilities while employing sustainable manufacturing strategies to reduce environmental impacts (Nörmann and Maier-Speredelozzi, 2016). Sustainable manufacturing or green manufacturing aims to minimise pollution and drive innovation to continuously have the best practices (Javaid et al., 2021). Sustainability can be defined from the Brundtland Report as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development (WCED), 1987). The pillars of sustainability are “society, economy, environment” which are identified from the “Triple Bottom Line” concept (Kuhlman and Farrington, 2010). Environmental sustainability focuses on maintaining the quality of the environment, social sustainability aims to promote human rights, respect for diversity, race, and preservation of cultural identity, and economic sustainability strives to maintain natural, social, and human capital for income and living standards. The three pillars depend on each other, and true sustainability is achieved when they are in balance (Klarin, 2018).

The Conference of Parties (COP) is a formal event by the United Nations Climate Change Conferences which address the impacts of climate change and how to mitigate them. COP 1 was held in Berlin, Germany in 1995. In 1997 the Kyoto Protocol (COP 3) was introduced by the United Nations Framework Convention on Climate Change (UNFCCC) in Kyoto, Japan. The aim was to identify GHG emissions reduction obligations by partner countries. Developed countries had agreed to reduce the emissions of six GHGs (CO_2, water vapour, CH_4, ozone, chlorofluorocarbons, and nitrous oxide) by an average of 5% below the 1990 GHG emission levels from 2008 to 2012. Different countries had their own targets (Sharma, 2020). In 2015, during COP 21, the Paris Agreement was signed by 195 countries on topics of climate change mitigation, adaptation, and finance. The main focus was to keep the rise of mean global temperature below 2°C below 1990 industrial level emissions, preferably below 1.5°C (Capron et al., 2020; Quintana et al., 2021; Sharma et al., 2021). The most recent conference was COP 26 held in Glasgow, UK from October-November 2021. It aimed to implement the Paris Agreement further, and more than 140 countries pledged to reach net-zero emissions (Quintana et al., 2021). This would reduce the costs and impacts related to environmental degradation and help towards achieving national and global goals by the mid-21st century (Clémençon, 2016). For further developing the RE industry, integration of AM with renewable energy technologies can enhance process effectiveness and create efficient products. The implementation of AM to the RE industry can solve issues such as customized and complex manufacturing possibilities, localized and on-demand production, and more efficient supply chains for the growing RE industry (Hayes et al., 2018; Sivamani et al., 2020). The successful implementation of AM for the RE industry are impacted by a set of factors shown in Table 1.

Table 1: Factors affecting integration of AM to current markets adapted from (Flores Ituarte et al., 2016)

Strategy factors	Business alignment, technology available
Supply chain factors	Logistics, purchasing, suppliers
Operation factors	Production, planning, control, maintenance
Technological factors	Advantages and advancements, standardization

Organizational factors	Culture, ethics, size, structure

Several factors affect the integration of AM to markets today, as illustrated by Table 1. Some of these include strategical and operational factors such as the available technology, maintenance, control, and alignment with business values and goals. This thesis specifically deals with the deals with the supply chain, operational, and technological factors for an integrated AM and wind energy industry (Langnau, 2019; Sivamani et al., 2020). Since traditional manufacturing methods are characterized with higher negative emissions to the environment, wind energy industry companies such as GM and Vestas are adopting AM to manufacture wind turbine components. The manufacturing industry is the third largest contributor to GHG emissions worldwide and is followed by electricity production and transport (Burton, 2020). An environmental impact assessment can be carried out to learn about the different impacts between traditional and AM method of manufacturing. An environmental impact assessment (EIA) provides information about the effects arising from a specific project, construction, manufacturing process on the environment, to provide decision makers with the data and opportunity to make environmentally friendly decisions in their operations (Jay et al., 2007).

1.2 Research objective and problems

The objective of the thesis is to find out the opportunities that AM can provide in wind energy turbines, with a focus on raw material used, manufacturing, maintenance, and end of life. This is done *firstly* by performing a life cycle assessment (LCA) of a 2 MW wind turbine, *secondly* by reviewing a case study for manufacturing of spare parts of the wind turbine by powder bed fusion (PBF) which is the most widely used AM technology, *thirdly* by developing an illustration showcasing the environmental benefits of adopting AM to manufacture components for wind turbines, and *finally* by recommending various future research possibilities.

The above will be reviewed to find out the answers to the following research questions:

1. What are the materials used traditionally that contribute to global warming potential (GWP) in the life cycle of a wind turbine?

2. What other indicators traditionally contribute to the environmental impact in the life cycle of a wind turbine?
3. In which ways can AM benefit environmental sustainability of a wind turbine in comparison to traditional manufacturing?

1.3 Research methodology

This thesis uses two main methods to answer to the guiding research questions: 1) state-of-the art literature review and 2) life cycle impact assessment (LCIA) of traditionally manufactured wind turbine. A literature review of AM and RE with a focus on wind energy, and LCA was performed. The current state of the AM in wind energy was reviewed. An experimental study using LCIA for the life cycle stages for the wind turbine by traditional manufacturing was performed, analysed, and results were drawn. Following the LCIA, a case study performed at the Vattenfall site to use AM to develop spare parts for the wind turbine is brought out, following an image illustration providing the environmental benefits of integrating AM with the wind energy industry.

1.4 Outline of the thesis

The first chapter introduces the thesis, the research questions, and the outline that will follow. The second chapter deals with AM and its technologies, followed by the third chapter on RE which focuses on wind energy and the construction of a wind power energy system. The chapter also includes the current state of AM in the wind energy industry. The fourth chapter on LCA provides an understanding on concepts related to life cycle inventory (LCI) and LCIA. Finally, the experimental part deals with the results from the LCIA, and a case study of AM to manufacture spare parts for the wind turbine. Conclusions are drawn based on the results. The results provide a comparison of the traditional manufacturing and AM. The advantages and disadvantages are discussed. Recommendations for further research are presented based on main findings of this thesis.

2 ADDITIVE MANUFACTURING

AM is a technology that is rapidly growing in several sectors such as healthcare, manufacturing, and energy sectors, offering ways to overcome limitations in traditional manufacturing methods. Currently, AM is being explored intensively in the biomedical, aerospace, defence, construction, and food manufacturing industries (Ngo et al., 2018). AM is however still in the early development and understanding how it can be integrated into the market with value offerings is crucial to form new frameworks for business and industry (Ghobadian et al., 2020).

2.1 AM technologies

AM is defined by ISO/ASTM 52900:2021 as “a process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing” (ISO/ASTM 52900, 2021). There are seven (7) subcategories of AM by ISO/ASTM 52900:2021. AM builds the parts layer-by-layer and on demand which thereby reduces material consumption and lead times (Bhatia and Sehgal, 2021; Ghobadian et al., 2020). Table 2 describes the AM subcategories, types of materials used, advantages and disadvantages.

Table 2: Subcategories of AM processes (ISO/ASTM 52900, 2021; Kiran et al., 2019; Tofail et al., 2018)

AM process	Description	Materials
Vat photopolymerization (VAT)	An ultraviolet (UV) light hits a liquid photopolymer in a vat which hardens to form the product layer by layer downwards	Polymers, ceramics
Powder bed fusion (PBF)	A laser or electron beam melts and fuse powdered material on a powder bed in an enclosed chamber	Polymers, metals, ceramics, composites, hybrids
Material extrusion (ME)	Build material are extruded through heated nozzle in a layer wise manner	Polymers, composites

Material jetting (MJ)	Droplets of material are dropped onto a bed with a liquid being jetted continuously to form the layers	Polymers, ceramics, composites, hybrids, biologicals
Binder jetting (BJ)	A liquid bonding agent that are selectively deposited joins powder material, this forms so called green part which is then often cured in an oven after printing phase.	Polymers, metals, ceramics, composites, hybrids
Directed energy deposition (DED)	Focused thermal energy is used to fuse materials by melting as they are being deposited	Metals, hybrids
Sheet lamination (SHL)	Process in which sheets of material are bonded to form the final part	Polymers, metals, ceramics, hybrids

As seen from Table 2, the different subcategories of AM differ from each other by type of material used and the joining process, which for example may be a heat source to melt the material or a resin to bond the material. The main types of materials that can be used by AM are different metals, polymers, ceramics, composites, biologicals, and hybrid materials.

2.2 AM Workflow and DfAM

AM workflow can be classified into three main stages: the pre-processing, processing, and post-processing. Each stage of the workflow consists of sub steps as depicted in Figure 2.

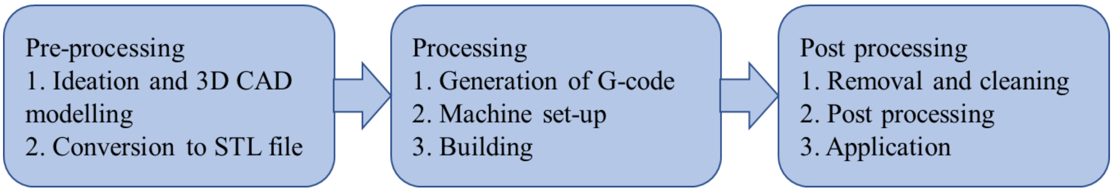


Figure 2: Process steps in AM

Figure 2 indicates that the pre-processing stage involves creation of the concept for the product, or ideation of the model. The next step is the development of the design as a three-dimensional computer aided design (3D CAD) model. The 3D CAD model depicts the expected final design of the product, the product requirements, and constraints. Next, the standard file format such as standard tessellation language (STL) or other is generated from the 3D CAD model. The model covers the surface of the solid with triangles from an in-built software. The file is then sent to the machine where the model is manipulated, where the orientation or position of the part can be changed. To avoid failures during the printing process, support structures may be required to ensure successful printing of parts. Support structure planning is done during the simulation stage, and the actual support and build layout is done during the build preparation on the AM machine (Prakash et al., 2018).

The processing stage starts with the slicing of STL file to 2-dimension (2D) layers which is used for the for G-code generation. The machine setup includes the selection of building parameters such as build chamber temperature, nozzle temperature, scan speed, etc., which affect the quality of the printing. The actual printing follows in a layer wise manner until the part is fully built. The final stage includes the removal and cleaning of the parts, support structures if utilized. The as build part is post-processed, if required. Testing for dimensional stability and quality assurance follow before application is done to ensure reliability of the built product and the quality (Orquéra et al., 2017; Wiberg et al., 2019).

To ensure the most optimal way for easy manufacturing and high-quality products with advanced complex designs, design for additive manufacturing (DfAM) is a term that is used in conjunction with AM technologies (Vayre et al., 2012). It means designing the product to allow easy manufacturing using AM for the product and has originated from the term design for manufacturing (DfM). It is important to identify specific constraints for the different AM processes to help manufacture optimized parts. DfAM helps to design parts with reduced residual stress, cracking, and loss of features of the product, while optimizing how much material is used. The product performance and life cycle objectives can be met by using DfAM (Culleton et al., 2017). DfAM consists of three steps which include component design, part design, and process design, which are shown in Figure 3.

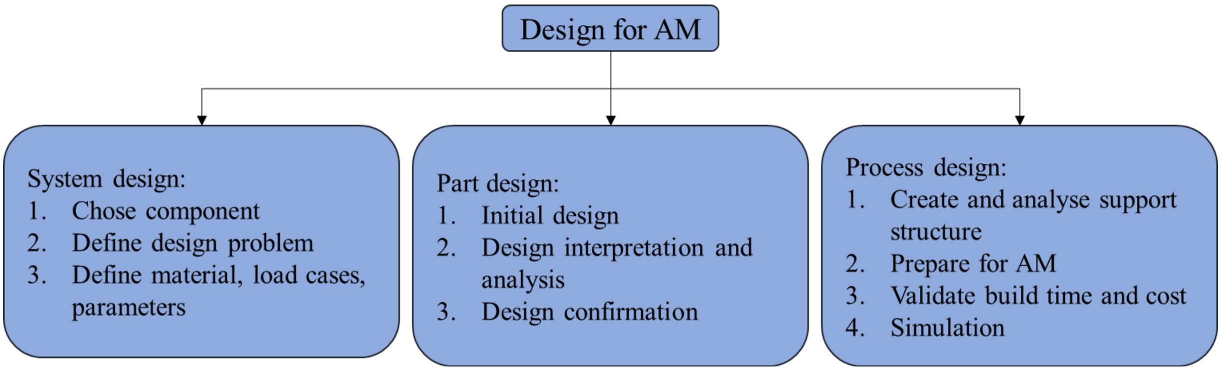


Figure 3: DfAM design process (Leutenecker-Twelsiek et al., 2016; Orquéra et al., 2017; Wiberg et al., 2019)

As Figure 3 depicts, the first step is to choose the component and define the design problem, material, and estimate the load cases along with other parameters. Secondly, the initial design is developed with design interpretation, analysis, and confirmation of the part. Finally, the support structures are created and analysed, the preparation of AM is performed, after which the build time is validated along with the cost and is then simulated.

2.3 Advantages and disadvantages of AM

Though AM has the capability to transform the practice of industries of today, there are several pros and cons for the technology that give it an edge or a slip up in comparison to traditional manufacturing practices. The advantages and disadvantages of AM in general are shown in Table 3.

Table 3: Advantages and disadvantages of AM (Duda and Raghavan, 2018; Ghobadian et al., 2020; Silva et al., 2020)

Advantages	**Disadvantages**
Design freedom	Slow build time
Highly complex parts	High cost of production
On-demand production	Post-processing
Reduced tooling	Limited product sizes
Lightweight and optimized design	Unfavourable finishing/ roughness
Consolidation of parts	Standardizations and compliance

Reduced production steps	Reworking
Reduced wastage	Limited materials and properties
Batching/ jobbing	Perception of AM
Improved supply chain	Unavailable skilled professionals
Localized manufacturing	High capital cost

Table 3 illustrates that AM has several advantages and disadvantages in the current state-of-arts. The high level of design freedom and ability to manufacture complex products gives it a major edge over traditional manufacturing method. Since the data to manufacture these products are in the digital format of STL, which can be purchased online, AM offers the benefit of localized and on-demand manufacturing. The AM machines have the ability to manufacture a part without tooling, which improves the production time, production steps and low reliance on fixtures (Javaid et al., 2021). It can be a highly economical process as the complex parts can be produced in single pieces, and these multiple parts can be consolidated, hence production bottlenecks can be avoided (Prakash et al., 2018). AM also provides the opportunity to explore lean and green manufacturing methods by reducing operational waste, or ‘muda’, and raw material wastage while also improving environmental standards by reducing emissions (Ghobadian et al., 2020). Because of strong ability of AM to solve several issues of current manufacturing methods, it has the potential to disrupt the current traditional practices and serve not only as a risk management tool for unstable markets, but also to change the way manufacturing is done.

There also are a few drawbacks to consider. Due to limitations in the material availability, usage and characteristics, the strength of the part may be reduced and hence there are size limitations for manufacturing (Prakash et al., 2018). The equipment for AM is expensive, which increases the capital expenditure, in addition to the high production cost due to expensive materials required in the metal, alloy, ceramic, polymers or other forms. AM processes do not give smooth and flat surfaces consistently, and hence post-processing or reworking and refurbishment may be needed, which in turn also in increase costs. The perception of AM is still yet to be fully understood, and exploited as a novel manufacturing method, and negative perceptions can slow down or even inhibit the growth of the technology into the industry. Additionally, the presence of clear and acceptable standards is low, as well as the number of skilled professionals in the industry (Ghobadian et al., 2020).

Spare parts that are manufactured by AM will also lead to a more resilient supply chain, which can further enable localized and on-demand manufacturing, while reducing costs related to transport and material even further. This is particularly beneficial for the offshore wind energy projects. PWC released a publication showing the advantages and challenges of the AM spare parts industry. They suggest that 85% of the spare part suppliers in the market would adopt AM into their businesses within the next five years. It is estimated that in 10 years, spare part suppliers in Germany would save up to € 3 billion. Companies that invest in printing spare parts through partnerships would gain a sustainable advantage in the years to come. However, lack of experience and know-how, awareness of the benefits gained, inability to supply for the demand, and traditional thinking are a few challenges in the spare part industry today (Strategy& - PWC, 2022).

2.4 Powder bed fusion

Metal AM can be categorized as either powder bed systems or nozzle (or feeder) type systems. The feedstock which is a metal material can be in the form of a powder or wire, and the bonding is done may be a heat source or by using a binding agent. PBF and DED are the most common for metal AM, as they can build complex geometries easily and fully dense products (Nyamekye et al., 2020). The thermal energy source is either a laser or an electron beam. Laser-based powder bed fusion (L-PBF) is the subcategory of PBF that uses a laser source to fuse metal powder material layer by layer on a powder bed in an enclosed chamber with inert gas (Gibson et al., 2010). L-PBF can build fully functional and dense metal components effectively, and the laser used can melt metal materials accurately (AMPOWER, 2019). As there are practically no design limitations, L-PBF can be used to manufacture components of any structure and can make lightweight, custom, and consolidated metal components. However, some obstacles that exist are the quality of the materials, and precise component design for the required mechanical properties, in addition to the cost of the machines which are expensive (Tofail et al., 2018). Further advancement in R&D on L-PBF will enable the challenges such as resolution, accuracy, and surface integrity to be overcome (Nyamekye et al., 2020).

The main components of the L-PBF are shown in Figure 4

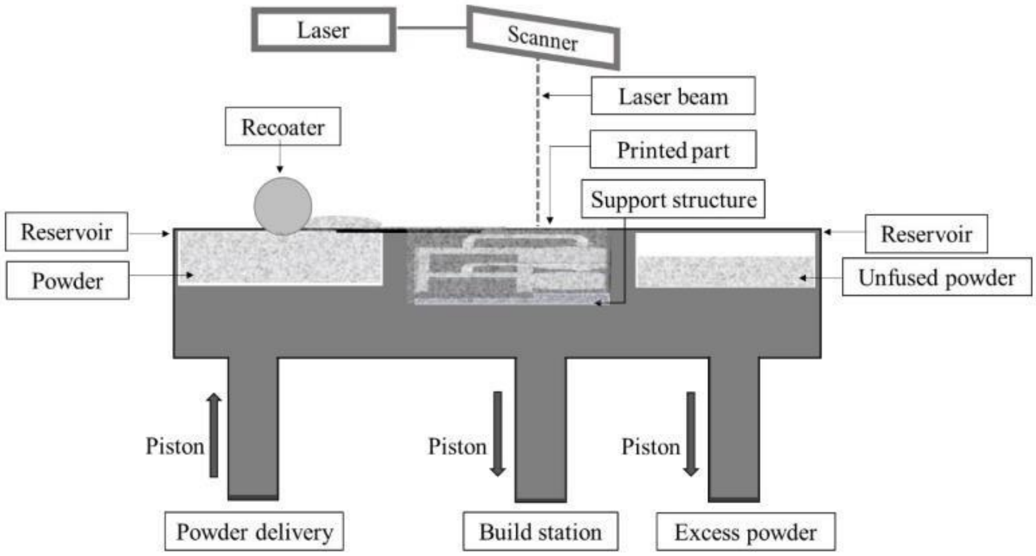


Figure 4: L-PBF layout (Foster et al., 2020.; Frazier, 2014; Nyamekye et al., 2020; Zhang etal., 2018)

Figure 4 illustrates the different components of the L-PBF arrangement and the movement direction. The workflow is as follows:

1. Metal powder is layered on the powder bed after the powder delivery piston raises the powder.
2. The laser melts this powder according to the sliced data, after which the build platform is lowered, and the powder reservoir is raised to start the next layer on the existing layer.
3. The build platform is lowered after each layer is printed to adjust tolerance levels (height between the layers).
4. This process continues until the whole part is built, after which excess powder is collected and can be recycled or reused after some treatment (Khairallah et al., 2016; Nyamekye et al., 2020).

Metal manufactured components by L-PBF usually require support structures for a successful build. These support structures are important to make sure that the component is kept in place, and to conduct heat away from the component and avoid defects (Tofail et al., 2018).

Some of the advantages and disadvantages of L-PBF for manufacturing metal components is shown in Table 4.

Table 4: Advantages and disadvantages of L-PBF adapted from (Nyamekye et al., 2020).

Advantages	Disadvantages
Design freedom	High cost of machine
On-demand and localized manufacturing	Low speed of build and energy efficiency
Cost friendly as moulds may not be required and products are optimized	Several parameters that affect the final part
Savings on raw material and efficient use	Need for support structures
Customizable	Insufficient testing and validation
Internal cooling channels	Low part quality
High grade materials and multi-functionality	Expensive powder materials

As Table 4 shows, the L-PBF has several advantages such as high design freedom and the ability to manufacture complex parts. The raw materials such as the metal powders are used efficiently as only the exact amount of powder feedstock would be required to build the parts. The parts are also highly customizable and L-PBF can use high quality materials which can offer multi-functionality. Additionally, the internal cooling channels can provide better mechanical properties for the product.

Some of the disadvantages are that the L-PBF machine and the powders are expensive. There are several build parameters that can affect the quality of the final part such as the surface finish. There is also insufficient qualification of the parts built, and more testing and validation of the processes should be done. Finally, the building speed for the components are slow, and the L-PBF process has a low energy efficiency.

3 RENEWABLE ENERGY INDUSTRY

The term energy is defined as the amount of force needed to move an object from one point to another, or the capacity of a system to do work (Bicen et al., 2018). Energy conversion technologies change one form of energy, for example kinetic, potential, gravitational, electromagnetic, etc, to another. This energy conversion is done to obtain either heat or electricity (Balcioglu et al., 2017). Since fossil fuels will deplete in the future, RE is a viable option to tackle future challenges of energy shown in Figure 5 below.

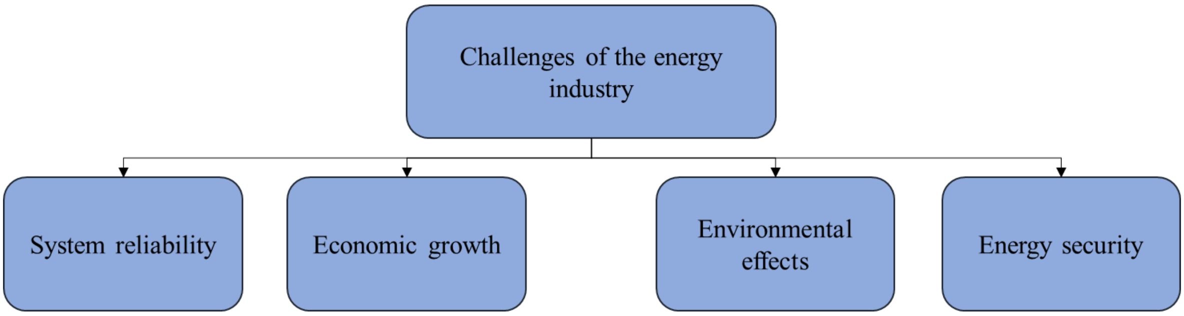


Fig 5: Challenges of the energy industry (Adapted from (Balcioglu et al., 2017))

Figure 5 shows that there are four key factors to managing the industry. Energy security is the availability of energy resources, economic growth refers to the integration of energy into the industries in different countries, which contributes to the net GDP of a country. The environmental effects describe the impacts that the energy industry has on the environment through its processes, and the electrical system reliability refers to the ability of the system to provide energy with constant quality and continuously (Balcioglu et al., 2017)

The planet is clearly moving towards an energy production industry with more RE (Statista, 2021) due to its multiple benefits. RE is clean and has lower negative environmental impact than traditional sources of energy. RE, by definition, means that it will never be depleted, and hence can be harnessed by future generations as well. It also increases the energy security and promotes economic growth, in addition to being more localized as well. It can be concluded that the major challenges of the energy industry can be addressed by integrating RE into the energy production mix (Alrikabi, 2014).

3.1 Wind power energy

The kinetic energy that winds generate from the velocity of air motion is originally caused due to solar radiation. Convective processes convert the heat to air motion to balance out the changes in air density and buoyancy. As a result, air moves from high to low pressure regions. Other factors such as precipitation, shade, variations in surface absorption, earth rotation, etc. also contribute to wind generation (Kalmikov, 2017). Equation 1 shows that the power generated from wind energy is dependent on wind speed, density of air and the swept area of the turbine (Kumar et al., 2018).

$$P = \frac{1}{2}\rho A V^3 \tag{1}$$

Where P is the power generated, ρ is the density of air, A is the swept area of the turbine and V^3 is the cubic dependence on wind speed. Hence, if the velocity of wind is increased by two (2), the power gets increased eightfold, and hence the velocity of wind is a key factor (Kalmikov, 2017; Kumar et al., 2018).

Wind power density (WPD) is used to compare regions without considering the size of the wind turbine and is represented by Equation 2.

$$WPD = \frac{P}{A} = \rho V^3 \tag{2}$$

The efficiency of extraction of the wind power can be given by the power coefficient (C_p). It represents the ratio of extraction of power to the total power of the wind and is shown in Equation 3.

$$C_p = \frac{P_t}{P_{wind}} \tag{3}$$

Where,

$$P_t = \frac{1}{2}\rho A V^3 C_p \tag{4}$$

Albert Betz confirmed that no wind turbine can convert more than 59.3% of the wind's kinetic energy into mechanical energy to rotate the blades, which is known as the "Betz limit". No commercially or practically designed turbine can match the Betz limit, and they have values between 35-45% conversion rates. However, considering other parts of the turbine including the tower, gearbox, nacelle housing etc., only approximately 10-30% power can be generated from the entire system (Ghenai, 2012).

Wind can be considered as a renewable fuel, which has a low environmental impact and reduces electricity prices, although the initial setup costs are high. The general construction of the wind turbine consists of the tower structure, the nacelle which houses the gearbox, generator, and drive train along with other electrical control equipment, and the rotor blades (Kumar et al., 2018), shown in Figure 6.

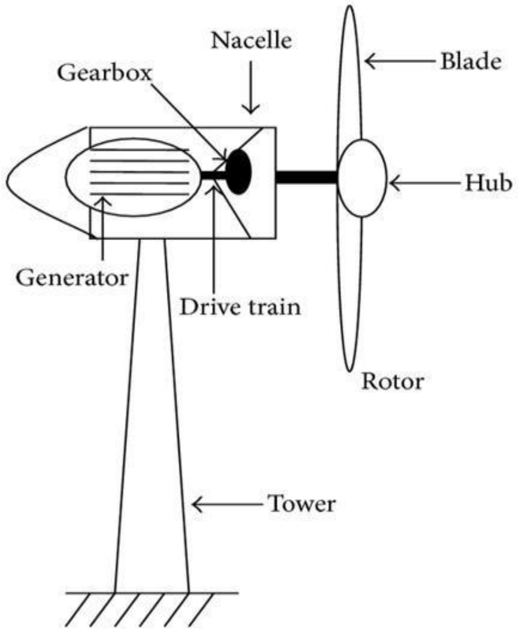


Figure 6: Wind turbine components (Arturo Soriano et al., 2013)

Figure 6 illustrates the simple diagram of a horizontal axis wind turbine (HAWT). The wind provides the force to rotate the blades and develops mechanical power to the drive shaft to produce electricity (Arshad and O’kelly, 2013). The tower holds the nacelle on the top of the turbine. The nacelle is supported by a yaw mechanism, which rotates the entire nacelle and blades to face the direction of the wind to capture maximum wind speeds for maximum energy. The torque captured by the blades is passed on through the hub to the drive train which is connected to the generator (Abdel-halim, 2015). The main rotor shaft may have two axes of rotation: horizontal or vertical, as shown in Figure 7.

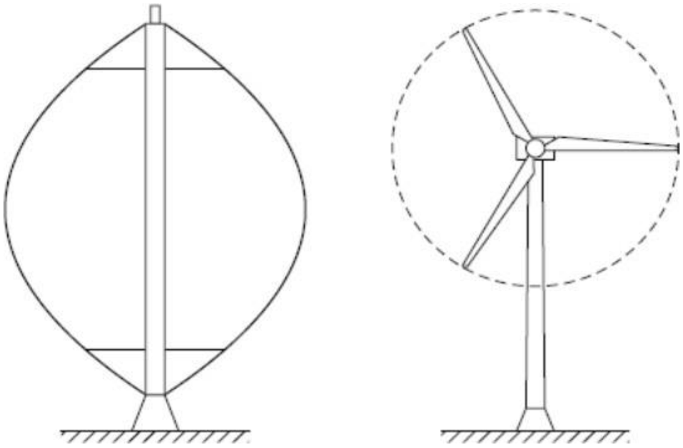


Figure 7: Vertical axis wind turbine (left) and horizontal axis wind turbine (right) (Abdel-halim, 2015)

Figure 7 depicts the two types of constructions of the wind turbine based on the axis of the rotor. Majority of the wind turbines have three blades. HAWT have blades that are horizontal to the direction of wind and the structure is placed parallel to the ground. The furling system in HAWT rotates the face of the rotor to constantly be perpendicular to the direction of the wind. Some advantages are that they can generate more energy as they have access to more strong wind due to the height of the tower. The disadvantages are that they have higher set-up costs, a strong tower must support the nacelle and its components, and orientation mechanism is required to face the wind direction. HAWT work well in regions which have low turbulent and consistent wind speeds which do not change direction often. Vertical axis wind turbines (VAWT) rotate perpendicular to the ground on a vertical axis. The research around VAWT is growing, and it can be used in regions with unpredictable wind turbulence and direction. Since the starting torque for VAWT is low, it can be used in regions with lower wind speeds. However, this means that they do not perform optimally in regions with higher wind speeds. They also have lower conversion efficiency when compared to HAWT. The cost of installation and maintenance is lower than HAWT as the gearbox and other electrical equipment is closer to the ground or on the ground (Abdel-halim, 2015; Arturo Soriano et al., 2013; Johari et al., 2018; Swati, 2013).

3.2 Design and performance of a wind turbine

For the design of the wind turbine, strength, dynamic behaviour, and fatigue properties of the material need to be addressed. Modern wind turbines have at most three blades as too many blades may cause the system to experience very high forces. Construction of narrow, lightweight, and few blades is essential to limit external negative influencing factors on the system performance (Ghenai, 2012). Apart from the orientation of the axis of the turbine blades (HAWT and VAWT) and the location of the wind energy system (onshore or offshore), wind turbines can be classified and designed on the following methods:

1. Reynolds number (Re): Depicts the wind speed at which the turbine operates. Reynolds number is defined as

   $$Re = \frac{Uc}{v} \qquad (5)$$

   where U is the relative velocity of the airfoil profile, c is the chord length, and v is the kinematic viscosity (Ge et al., 2015). The speed of turbines depends on the Reynolds number, and they can be listed as shown below:

    a. Low-speed turbines ($Re < 10^3$)

    b. Medium-speed turbines ($10^3<Re<10^5$)

    c. High-speed turbines ($Re>10^5$)

2. Upwind and downwind turbines: Upwind turbines have the rotor and hub facing the direction of the wind. This is done to ensure that more wind capture takes place, which could be lost as the tower may reduce the wind impact on the blades. Downwind turbines have the rotor and hub facing the opposite direction of the wind (Ghenai, 2012).

3. Type of aerodynamics: Drag type turbines exerts the force on the wind turbine in the same direction as that of the wind, whereas lift type turbines apply forces that are perpendicular to the flow of wind. Aerodynamic sounds are also generated when wind of a particular speed hits parts of the turbine. This effect makes different types of sounds depending on the wind speed and the part of the turbine (Ghenai, 2012; Sun et al., 2016).

4. Number of blades on the rotor: The turbines may be either single bladed or multi-bladed. As mentioned, the most common turbines use three blades, however there are also two bladed turbines. They have lower capital costs but require higher windspeeds to produce the same outputs as three blade turbines. The blade material selection is done to achieve lightweight and high strength blade parts (Ghenai, 2012; Rehman et al., 2018).

The performance of the wind turbine is mainly dependent on three factors. Firstly, if the length of the wind turbine blades is more, the area swept by the blade is greater, and higher power can be extracted from the wind. An increase in blade length increases both the mechanical and electrical power generated. Secondly, the wind speed plays an important part in the performance of the turbine. The cut-in speed is at 4 m/s, before which the wind speed is not usable by the turbine. As the speed increases from 4 m/s to 14 m/s, the power generated increases and stays stable until 25 m/s. Wind speeds higher than this forces a cut-off from the system and mechanical power falls. Thirdly, air density is directly proportional to the mechanical power generated. Higher the air density, higher is the power generation. Since density is a function of temperature and pressure, increased temperature causes the mechanical power generated to drop and increased pressure causes the mechanical power generated to rise (Arturo Soriano et al., 2013; Kalmikov, 2017; Zafar, 2018).

3.3 Applications of AM in the wind energy context

Integration of AM during the design stage can allow less geometrical constraints, which can help to develop more lightweight parts with enhanced functionality and shorter time to market (Ermakova et al., 2019). The use of AM in the wind energy industry can be illustrated by the Oak Ridge National Laboratory (ORNL) in USA (Post et al., 2017). Since rapid prototyping capabilities are possible by AM, blade moulds for the turbine blades can be manufactured by AM. They reported that Big Area Additive Manufacturing (BAAM), which is standardly a DED process can be used to manufacture the turbine blades. The first step involves manufacturing a plug from foam and tooling resin by subtractive manufacturing. Once the plug is manufactured using CAD drawings and computer numerical control (CNC) machining, which is the traditional manufacturing process. It is then shipped to the mould manufacturer, where fiberglass of the required thickness is injected as a wire of material into the mould and a steel structure is attached to the blade. They suggest that up to eight moulds can be manufactured from the plug without loss in performance, which reduces the cost of transportation, and materials used. This has a significant impact on the environmental emissions released as raw materials are used efficiently, transportation is reduced and hence emissions from transport are reduced, and there is reduced production wastage. The blade mould manufactured by AM is shown in Figure 8.

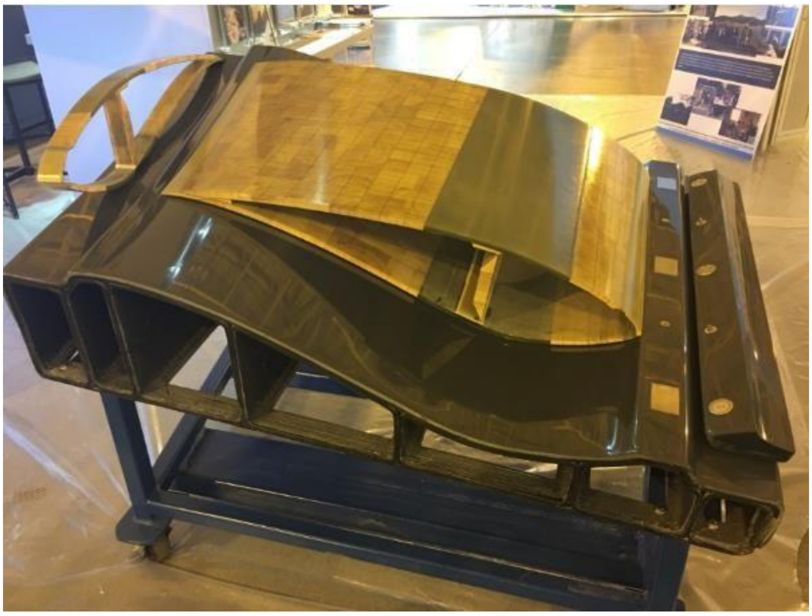


Figure 8: Blade mould and blade section by AM (Post et al., 2017)

Figure 8 illustrates the turbine blade manufactured from the Cincinnati BAAM process. They suggest that the cost savings can be obtained from using the moulds to manufacture the blades, which could otherwise cost millions of dollars. Additionally, the ORNL also manufactured nacelle covers which provide safety, which are made of fiberglass from moulds using AM which provides technical and economic advantages. Permanent magnets that are used in the wind turbines for the direct-drive generators and secure ladders and platforms in the turbine to reduce stress can also be manufactured by AM. Finally, heat exchangers which are used to cool the wind turbine can also be manufactured by AM, with complex geometries and designs that can have better performance than traditionally manufactured heat exchangers which would have less cooling capability as the flow channels are not optimized, while reducing the weight of the part as well (Post et al., 2017).

AM is being applied further in RE industries, including the solar and wind power energy industries (Prakash et al., 2018). As the cost of AM machines are reducing due to increased adoption of the technology, so are the associated materials that are used for the manufacture of the desired products. Other studies performed show that AM is now transforming from a rapid prototyping to a rapid manufacturing method for small scale wind turbines, which is the direct manufacture of the finished goods (Bak, 2003). Low cost of filaments or powders, reduced labour, cheaper printers can allow the manufacture of small scale wind turbines at a competitive cost (Bassett et al., 2015).

Bassett et al., 2015, worked on the RepRap project, a project to rapidly replicate the manufacture of a wind turbine. The main aim of the study was to provide electrification possibilities for rural areas, so they do not need to depend on the regional grid for electricity, provide disaster relief, and introduce more projects for rural areas. The study included using an existing design of a wind turbine, which was selected as the basis for the prototype to familiarize the designers with the construction and operation of the turbine.

The main materials used were Acrylonitrile Butadiene Styrene (ABS) and polylactic acid (PLA) which has promising properties such as low energy requirements and fewer emissions. They are also cheap and are commercially available. The AM technology used in this study was BJ. The reinforcement was done by acetone vapour baths, hypomethylating agents (HMA) injection, and biodegradation of PLA. The reinforcement allows the turbine to function under high wind speeds and stresses that the turbine may experience.

The acetone vapour bath is used to change the texture of the outer ridges of the part from rough to smooth. Here, the component is immersed into the vapour cloud where the outer surface melts and fuses a uniform outer shell. While the performance of the parts with this method provides good mechanical properties, the process requires time and acetone solution may be hard to acquire in rural locations.

HMA injection was used to reduce print time and component cost, which is desirable for this application. Additionally, PLA can also be obtained from plant-based starches which is a renewable resource. The study goes on to integrate the printed parts with the non-printed parts such as the tubing for the frame tubing which provides structural integrity, the blade tubing made of fiberglass material, the bearings, and the direct-drive generator. The blades for the turbine were designed by DfAM for the rural application using the AutoCAD software. The final printed part in application is shown in Figure 9.

Figure 9: VAWT manufactured by AM (Bassett et al., 2015)

Figure 9 illustrates the VAWT manufactured by the RepRap project which can be used for rural applications, where less than one kilogram of filament material is used for the printed parts for the whole turbine. Studies have also suggested that direct-drive generators can also be manufactured by AM which makes the full product more lightweight by the BJ AM process (Hayes et al., 2018).

4 LIFE CYCLE ASSESSMENT

The International Organization for Standardization (ISO) is an international body that sets technical, commercial, and industrial standards. It was founded on 23rd February 1947, and currently has 165 member countries with the headquarters in Geneva, Switzerland. They aim to develop standards that promote safe, good quality and reliable products and services. It enables organizations to offer better deliverables to consumers, increase productivity and reduce waste. Currently, ISO has over 24,000 standards that are active (Wikipedia, 2022). While developing a new product or service today, ensuring legislation compliance and sustainability driven offerings are important, which should be properly studied, monitored, and managed. In the case of environmental sustainability, the standardized tool used is LCA. LCA uses a cradle-to-grave (start to end) methodology in which there are many important factors to assess the environmental aspects of a product system. Using LCA can help decision makers to improve the product performance and plan effective business operations. Additionally, environmental product declarations and eco-labelling can be implemented by actors in regulatory authorities (Pickel and Eigner, 2012).

4.1 Concepts of LCA

The impact that a product or service may have depends on several factors such as energy and material use, emissions to the air, water and soil, toxic potential of waste, and compliance with legislation (Pickel and Eigner, 2012). LCA is a tool that addresses these factors and assesses the environmental impacts and resources that are being used through the life cycle of a product. Figure 10 shows the general idea of a product’s life cycle.

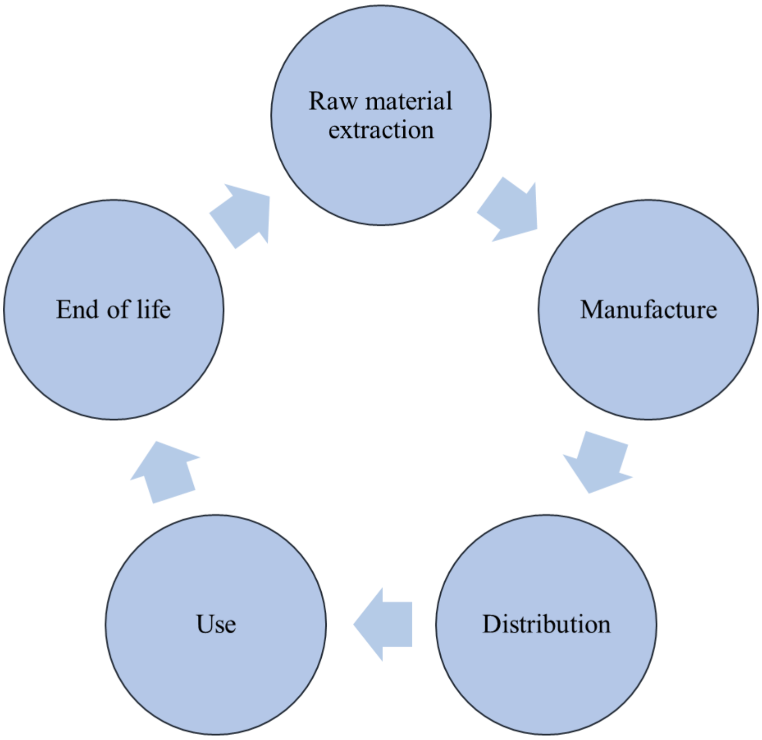


Figure 10: Circular concept of life cycle

As Figure 10 illustrates, raw material extraction is the first step for the life cycle of a product. At this stage, all the raw materials such as metals, water, and other materials that go into manufacturing the product are gathered. The manufacturing stage is when the product is built, after which it is distributed. Consumers purchase the product, during which the product goes through the use phase, after which it reaches its end of life. At the end-of-life stage, the product may either be reused, recycled, remanufactured, or disposed (Singh et al., 2013). LCA aims to assess the environmental aspects and potential impacts at theses stages by gathering an inventory of flows (inputs and outputs) that are environmentally related to the system. The potential of environmental impact is then related to the flows, after which it is interpreted according to the goals and objectives that are required (Cakmakli, 2008). Figure 11 shows the four (4) stages of an LCA study.

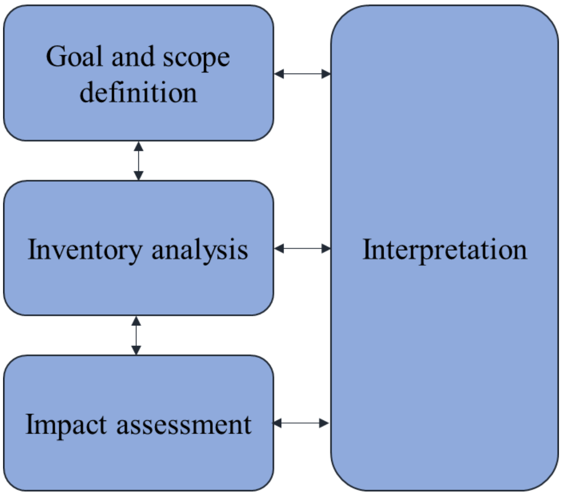


Figure 11: Four stages of an LCA study adapted from (ISO 14040 Standard, 2006).

As Figure 11 illustrates, the first stage is the ***goal and scope definition***. The goal states the intended application, audience, and reason for the study. It also states if the results used are to be applied in a comparative study that can be released for the public. The scope includes the product system to be studied, the functions of the product system, and the functional unit to be used. ISO states that “a functional unit defines the quantification of identified functions (performance characteristics) of the product” (ISO 14040 Standard, 2006). It serves as a reference point for the inputs and outputs, which can then be related after which the results can be compared based on a common factor. The scope also defines the system boundary, which defines the unit processes that are part of the system. While setting the system boundary, acquisition of raw materials, main inputs and outputs of the manufacturing process, distribution, use of fuels, heat and electricity, maintenance and use, disposal of waste and products, recovery, etc., should be considered. Additionally, the scope must also include the allocation procedure, impact categories, data requirements and assumptions, limitations of the study, and data quality requirements. Secondly comes the ***life cycle inventory (LCI)*** stage. In this stage, collection and calculation of data that needs to be quantified takes place. It is an iterative process where the rise of new data may cause the need for more limitations or alterations. The collected data may be energy and raw material inputs, ancillary inputs, or other inputs. It also consists of products, co-products, waste, emissions to the air, water, and soil. The calculation step consists of validating the collected data and relating the data to the unit processes and the reference flow of the functional unit. Thirdly is the ***life cycle impact assessment (LCIA)*** stage. The aim is to evaluate the potential environmental impacts from the results of the LCI stage. Environmental impact categories and indicators are related with the results from LCI stage which are then used in the interpretation stage. The LCIA stage has mandatory elements such as selection of impact categories and the indicators, assignment of LCI results (or classification), calculating the category results (or characterization), and developing the LCIA results (or LCIA profile). Some optional elements comprise of calculating the results with respect to the reference information (normalization), grouping, and weighting. Finally, the ***life cycle interpretation*** stage is where the findings from the LCI and LCIA are considered in relation to the goal and scope definition, with the aim to develop conclusions, recommendations, and provide limitations of the study. It should be complete, understandable, and consistent with the goal and scope definition (ISO 14040 Standard, 2006). Figure 12 shows the applications of LCA.

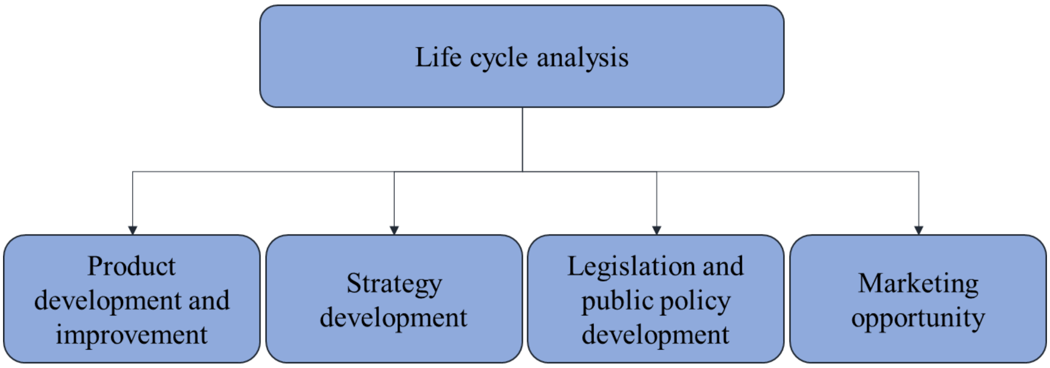


Figure 12: Applications of LCA for organizations adapted from (ISO 14040 Standard, 2006)

As Figure 12 illustrates, LCA can be used for decision making process to develop organization strategies. It can also be used to enhance the product development, performance, and cater improvement of the product. Finally, it allows government and other regulatory entities to develop regional public policies and enables marketers to provide a competitive advantage for their product offerings.

4.2 LCA impact indicators

Life cycle thinking (LCT) aims to identify how goods and services can be improved so that the negative environmental impacts and the use of resources are reduced (European

Commission, 2012). The inputs or outputs to a product system that have an impact on the environment, or the resources are quantified by performing an LCA, and reports for each impact category for the product can be assessed. The weighting can be done individually or grouped, shown in Figure 13.

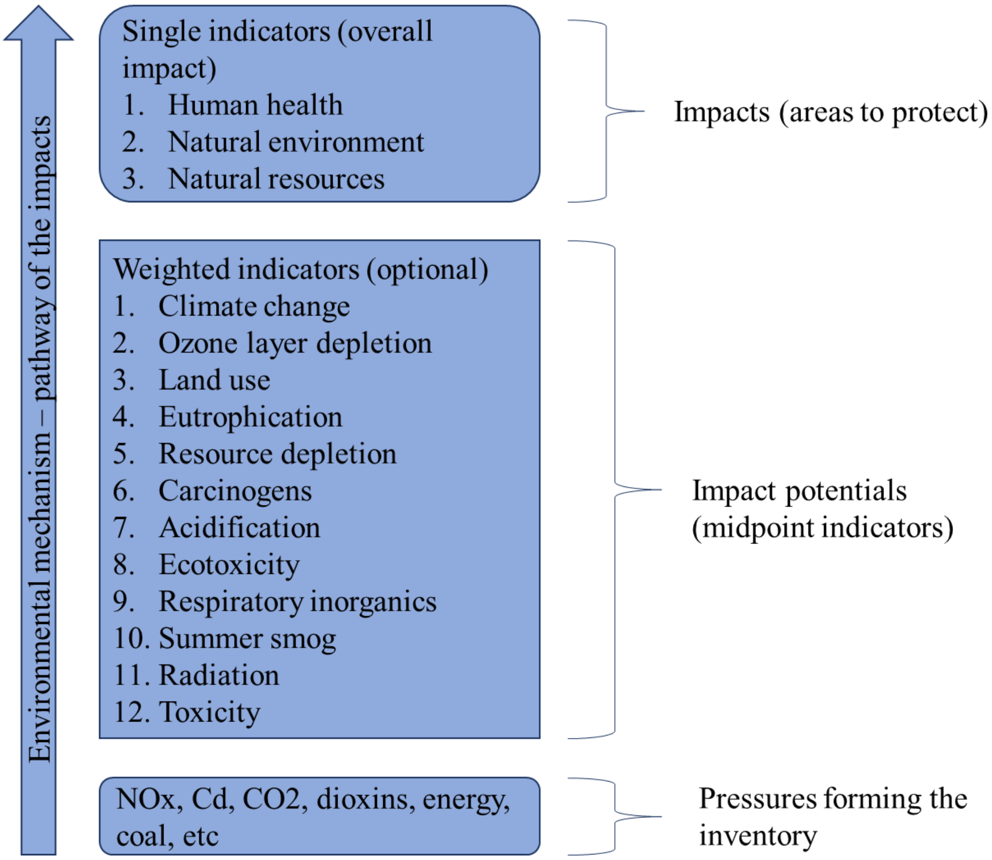


Figure 13: Impacts, indicators, and the impact pathway (Adapted from (European Commission, 2012))

Figure 13 showcases the bottom-top approach for analysing the pathway of the impacts. As seen, the impacts that need to be protected are human health, the natural environment, and resources. It is essential to set at least one of these indicators while performing an LCA. The weighted indicators are optional in the LCA, but their inclusion provides a specific understanding as to what impacts do the weighted indicators have on the life cycle of a product. Finally, the inventory is formed by further specific pressures such as nitrogen oxides (NO_x), carbon dioxide (CO_2), energy, coal, land use, silver ore, and other emissions and resource flows.

The experimental section deals with the indicators listed below along with their definitions. These are midpoint indicators, which are used to present results that reflect toward the endpoint indicators, that is the impacts/ areas to be protected.

1. Global warming potential (GWP): The measure of how much energy the emissions of 1 ton of gas will absorb over a specific time relative to the emissions of 1 ton of CO_2. CO_2 has a GWP of 1 and is used as the reference. Other gases have GWPs much higher than the reference, for example, (CH_4) has a GWP 30 times higher for a 100-year span, and nitrous oxide (N_2O) has a GWP 273 times higher for a 100-year span (US EPA, 2022a).

2. Ozone depletion potential (ODP): The indicator developed to measure the impact of a chemical on the stratospheric ozone layer. It is defined as the change in total ozone per unit emission of the gas relative to the change of ozone per unit mass emission of CFC-11 ($CFCl_3$) (Zhang et al., 2020). Depletion of the ozone layer can increase the ultraviolet (UV) levels at the surface of the Earth, which damages human health by causing skin cancer, cataracts, and other immune deficiencies (European Commission, 2022).

3. Abiotic resource depletion (ARD): ARD is the indicator that refers to the depletion of non-living, or abiotic resources, for example, fossil fuels, minerals, clay, and peat. Extraction of the elements and fossil fuels is multiplied with the characterization factor and the indicator is obtained as a result in kilograms of Antimony (Sb) equivalent (Biron, 2016; Ministerie van Verkeer en Waterstaat, 2002). This is an important indicator as resources are becoming scarcer, and further extraction of ores further cause harm to the environment.

4. Particulate matter (PM): PM is a mixture of solid particles and liquid in the air, for example, dust, soot, smoke etc. They may either be visible from the naked eye or much smaller that can only be detected by an electron microscope. PM 2.5 are small inhalable particles that have a particle diameter of 2.5 micrometres. There are many shapes and sizes, and the main source is from construction sites, roads, fields, fires, etc (US EPA, 2022b). Exposure to PM can affect the lungs and heart causing asthma, heart attacks, etc., and they can cause environmental damage such as

forming acidic lakes and streams, depletion of nutrients in soil, increased acid rains, damage to forests and crops, etc (US EPA, 2022c).

5. Water footprint (WF): The indicator that quantifies the environmental impacts related to water, and not primarily on the volume of water used (Pfister et al., 2017). Essentially, the WF assess impacts on freshwater resources, ecosystems, and human health. The total water use, water consumption, and degradation are studied. (Life Cycle Initiative, 2022).

The EU aims to use the LCA indicators to monitor progress towards sustainability, include indirect (imported) impacts which are related to consumption in the EU, and to cover relevant indicators by weighting them (European Commission, 2012).

4.3 LCA in AM

Majority of the energy transfer in AM occurs during the energy transfer from the laser onto the material, which is an electromagnetic radiation. Additionally, energy transfer also during heating or cooling of the components during the AM process. AM also uses less material and leave less scrap material during the manufacturing process than traditional manufacturing but may be more energy intensive. Environmental impacts that are associated with AM should not be limited to only energy use, but also to a larger context which would include raw material acquisition, product manufacturing, product use, service, end-of-life, and waste management (Výtisk et al., 2020). The application of LCA not only provides an added benefit from the environmental perspective, but also helps to quantify how much cost savings is possible through the adoption of AM. In this way, companies can offer superior products with efficient supply chains in the pursuit for new business models (McGrath and Shivdasani, 2015). The major impact categories to be addressed while performing LCA of AM are carbon footprint/ GWP, depletion of materials and fossil fuels, and PM formation (Výtisk et al., 2020).

By using eco-design principles, which focuses on the minimization of negative environmental impacts during the design stage can be advantageous, and provide good environmental results during the manufacturing, use, and disposal stages (Yi et al., 2020). The benefits of eco-design are:

1. Environmental sustainability is integrated during the design stage
2. Design advantages such as lightweighting, process optimizations, etc.

Applying eco-design principles for manufacturing of sustainable products can help in development of more sustainable materials, products, and processes (Muthu and Savalani, 2016). The main environmental benefits offered by AM are the efficient use of raw material, reduction of wastage, and reduction of emissions from the product life cycle. However, there are disparities between different researchers about the actual positive impact on the environment through the application of AM in comparison to traditional manufacturing processes. For example, one comparative study (Kreiger and Pearce, 2013) suggests that the environmental impact of polymer products that are additively manufactured are lower than that of traditional manufacturing. They further claim that using polylactic acid (PLA) in AM has significantly lower energy requirements and release lesser carbon. Another comparative study states that AM cannot be categorically more environmentally friendly than CNC machining, or vice versa. The relative sustainability of the two manufacturing methods depends on the usage of the products, and the machines used (Faludi et al., 2015). Other research suggests that AM can provide a positive societal transformation, by making conventional manufacturing methods obsolete and empower individuals to become independent inventors, developers, and manufacturers (Barros, 2017). Additionally, AM will change the way products are designed, manufactured, transported, and used (Lipson and Kurman, 2010). Finally, it can be concluded that due to limited understanding of how AM affects the overall consumption of resources, more studies will have to be done to truly understand the environmental impacts and sustainability offerings it can provide (Ford and Despeisse, 2015).

5 AIM AND PURPOSE OF THE EXPERIMENT

Wind energy has a low impact on the environment in comparison to fossil fuel-based electricity generation. The use phase of a wind turbine has almost no emissions during the operation, however, the production and post-use phase is where emissions are the most during the life cycle of the turbine. To compare the difference in emissions caused throughout the life cycle, LCA is carried out and analysed for traditional manufacturing. LCA helps to identify the environmental impacts that would occur from a product or process from cradle to grave (Guezuraga et al., 2012).

The initial aim of the thesis was to conduct an LCI for additively manufactured components of the wind turbine, including parts such as the turbine blade, components within the nacelle, the foundation, and the tower structure. This was to be compared against the LCI for the CNC machined products of the wind turbine, for which ample data was available. However, the layout for the thesis was changed due to a few reasons. Firstly, there was a lack of data available related to the materials required for the manufacture of the wind turbine, and other inventory data. Additionally, it was not possible to perform a full experimental setup in the laboratory due to time constraints. Hence, the new layout includes the LCA for traditional manufacturing, followed by a case study to show the material savings by using AM for manufacturing spare parts of wind turbine components. The AM method proposed for the manufacture of the component is PBF using a laser source. PBF was the selected AM technology as it has better design freedom than DED or other metal AM technologies. It is also the most developed metal AM technology. Finally, an illustration presenting the possible environmental benefits of integrating AM in the wind energy industry.

More research concerning the manufacturing of wind turbine components using AM, and its associated impacts on the environment, economy, and society must be performed. As the AM industry is growing rapidly, and with the energy industry becoming more important, the integration of the two is necessary to develop the two positively while providing several benefits.

6 EXPERIMENTAL SETUP AND PROCEDURE

This section deals with the experimental part of the thesis. The experimental setup is first presented, where the tools required, such as the software used is shown. Other information such as functional unit, time of work, formulae used are also presented. The experimental procedure shows how the experiment was conducted, which has the inventory list for the materials, life cycle stages considered, indicators that will be used in the results and discussion chapter, and the site attributes.

6.1 Experimental setup

The life cycle assessment is carried out by using the software eToolLCD, which is a software primarily used for the construction industry. The software is approved for use in Leadership in Energy and Environmental Design (LEED), Green Star, Living Building Challenge, and other schemes. It follows the standard "sustainability of construction works" (BS EN 15978:2011, 2011). Using eToolLCD helps to model the material, energy, and water impacts from a construction in line with BS EN 15978:2001.

The selected functional unit is "life cycle energy generated", using the "wind-powered electrical generation facility – electricity generation" as the functional focus.

16 hours of excavator and 15 hours of a compactor is assumed with two staff members operating the devices. 3 days of annual maintenance is also considered.

A 2 MW turbine is considered, with a lifetime of 45 years. Considering a 25% capacity factor, and assuming that the wind turbine is operating for 24 hours and 365 days of the year, the annual generated energy can be obtained from equation 6.

$$Annual\ energy\ generated\ by\ the\ wind\ turbine = Turbine\ power * number\ of\ days * number\ of\ hours * capacity\ factor = 4{,}380{,}000\ \text{kWh/year} \tag{6}$$

6.2 Experimental procedure

Using the eToolLCD software, a new project named “Wind turbine” was created with the annual energy generated by the wind turbine and number of years as mentioned in section 6.1. The land area was set to 6000 m^2 (Sciencing.com, 2018), Finland. The LCI source/ database used for the analysis was the Australasian LCI V10.2.

The different life cycle modules that were selected is shown in Figure 14.

Life Cycle Stage	Detail Description	Code	In Scope
Construction Phases	Product Stage	A1-A3	ON
	Transport of Equipment and Materials	A4	ON
	Construction	A5	ON
Use Phases	Use of Products	B1	ON
	Maintenance	B2	ON
	Repair	B3	ON
	Replacement	B4	ON
	Refurbishment	B5	ON
	Integrated Operational Energy	B6	ON
	Other Operational Energy	B6+	ON
	Operational Water Use	B7	ON
End of Life Phases	Deconstruction / Demolition	C1	ON
	Transport of Waste Offsite	C2	ON
	Waste Processing	C3	ON
	Disposal	C4	ON
Benefits and Loads Beyond the System Boundary	Operational Energy Exports	D1	ON
	Closed Loop Recycling	D2	ON
	Open Loop Recycling	D3	ON
	Materials Energy Recovery	D4	ON
	Direct Re-use	D5	ON

Figure 14: Scope of life cycle stages considered for the study

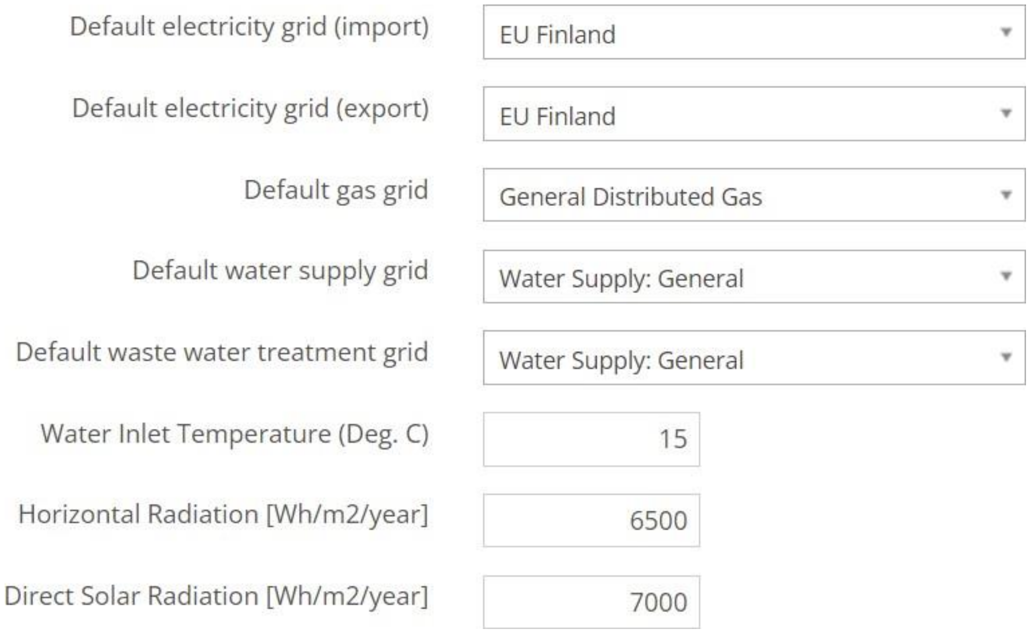
As Figure 14 illustrates, several factors within the construction, use, and end of life phases are considered for performing the analysis. Additionally, the benefits and loads beyond the system boundary also have few factors that are considered.

The list of selected indicators that have been used is shown in Table 5.

Table 5: Indicators, units, and their descriptions (Adapted from (Ecochain, 2022))

INDICATOR	Unit	Description
Global warming potential (GWP)	kg CO_2-eq	Potential of global warming due to GHG in air. Emissions may come from (i) fossil fuels, (ii) bio-based sources, or (iii) land use change
Ozone depletion potential (ODP)	kg CFC-11-eq	Emissions to air that destroy the stratospheric ozone layer
Abiotic resource depletion (materials and energy) (ARD)	kg Sb-eq	Depletion of non-fossil resources
Particulate matter (PM)	PM 2.5-eq	Potential of disease incidence due to PM emissions
Water footprint (WF)	m^3 world eq. deprived	Relative amount of water used based on the regional water scarcity indicators

The selected site attributes are shown in Figure 15.



Default electricity grid (import): EU Finland

Default electricity grid (export): EU Finland

Default gas grid: General Distributed Gas

Default water supply grid: Water Supply: General

Default waste water treatment grid: Water Supply: General

Water Inlet Temperature (Deg. C): 15

Horizontal Radiation [Wh/m2/year]: 6500

Direct Solar Radiation [Wh/m2/year]: 7000

Figure 15: Site attributes

As Figure 15 illustrates, the default electricity grid for imports and exports is EU Finland. The water and wastewater treatment grid use the general supply template, as well as the gas grid. The inlet temperature for water is 15°C, and the horizontal radiation and direct solar radiation at the site are set at 6500 Wh/m^2/year and 7000 Wh/m^2/year respectively.

The operational energy for monitoring, control, and automation is 3,600 kWh/ year or 12,960 MJ/ year. Table 6 shows the list of material used for the turbine.

Table 6: List of materials with their description, quantity, and product life

Category	**Description**	**Quantity (Kilograms)**	**Product life (Years)**
Concrete, unreinforced, Portland cement blends, 30 MPa			
Service equipment	Concrete foundation	805,000 kg	150
Ferrous metals, iron, unspecified			
Service equipment	Nacelle, generator/ transformer core, main shaft, other cast components, spinner, rotor	35,200 kg	22.5
Ferrous metals, steel, accessories, unspecified			
Service equipment	Foundation (steel)	27,000 kg	150
Service equipment	Tower structure (steel)	164, 000 kg	22.5
Ferrous metals, steel, stainless, unspecified			
Service equipment	Nacelle, gears, other forged components	22,000 kg	22.5
Fibre reinforced plastics and resins, fiberglass unspecified			
Service equipment	Nacelle, cover [Fiberglass - Ratio 1 (or glass fibres):2.5 (Epoxy resin)]	2,800 kg	22.5

Insulation, rigid foams and boards, polyethylene			
Sanitary installations	Transmission, insulation	1,380 kg	22.5
Metals (Non-ferrous), aluminium unspecified			
Service equipment	Nacelle, transformer, transmission, conductors	1,772 kg	22.5
Metals (Non-ferrous), copper sheet			
Service equipment	Nacelle, generator/ transformer, conductors	3,254 kg	22.5
Metals (Non-ferrous), zinc			
Service equipment	Tower, cathodic protection	203 kg	22.5
Resins and adhesives, epoxy resin			
Service equipment	Nacelle, cover [Epoxy - Ratio 1 (or glass fibres):2.5 (epoxy resin)]	18,900 kg	22.5

As Table 6 illustrates, the concrete used for the foundation contributes the maximum to the weight from the list of materials used for the construction of the wind turbine. It also has the longest product life of 150 years. The tower structure is constructed using steel which uses 164,000 kg with a product life of 22.5 years, and the foundation uses the same material with a product life of 150 years. Zinc is used for the tower and cathodic protection, copper and aluminium are used for the nacelle, transformer, and conductors. Iron, fiberglass, and polyethylene boards and foams are also on the list of materials used.

7 RESULTS AND DISCUSSION

7.1 LCA results for traditional manufacturing of the wind turbine

LCA is an effective technique to evaluate environmental impacts for not only material and energy usage, but also waste and emissions. The main phases that are included in in the study are acquisition of raw materials, production, operation and maintenance, transportation, and end-of-life of the product. LICA is performed for different indicators for the life cycle categories of the wind turbine.

The LCIA is performed for the 2 MW wind turbine, and the GWP summary for the life cycle categories of the turbine is shown in Figure 16.

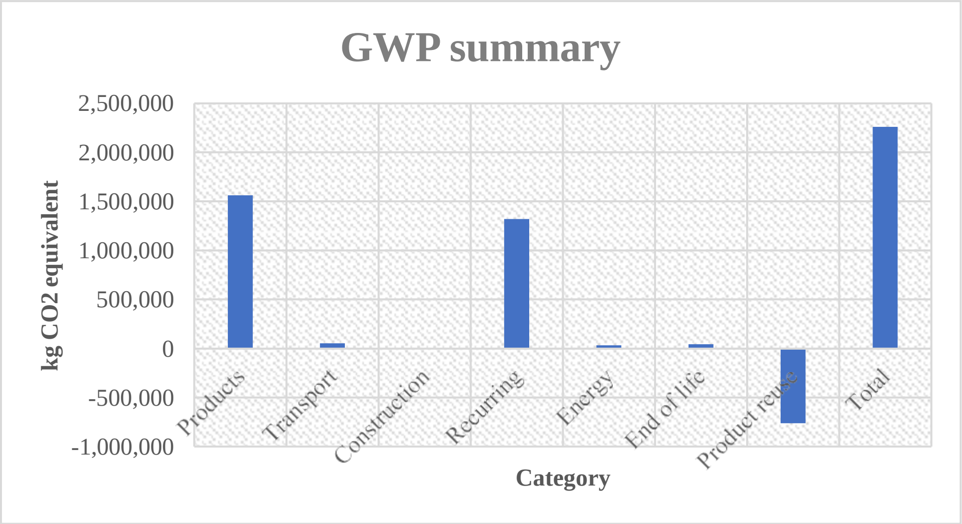


Figure 16: GWP summary of the life cycle of the turbine

Figure 16 shows the life cycle category of products (including the materials) contributes the maximum to GWP. The internally recurring unit processes contributes second highest to GWP, followed by transportation. Construction and the energy phase contribute least towards the GWP. As product reuse occurs after the end of life, it has a reversed impact on GWP, and the total GWP amounts to 2,262,346.72 kg CO_2 equivalent.

The material usage for the turbine from Table 6 can be illustrated by Figure 17 to show the GWP summary of the materials.

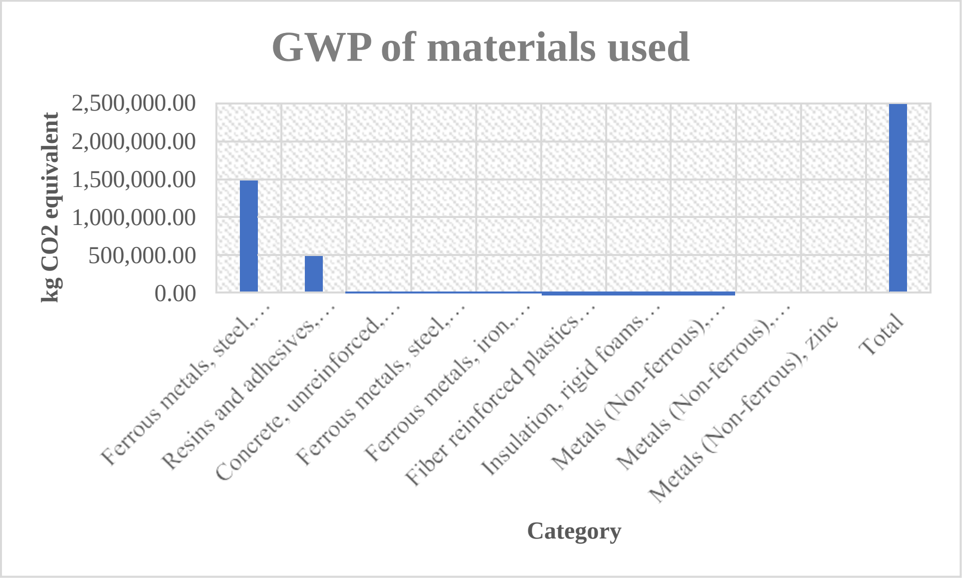


Figure 17: GWP summary by materials used

Figure 17 depicts ferrous metals, specifically for steel contributes the highest to GWP. Steel is used for the foundation and tower structure. Following this, resins and adhesives used for the nacelle cover and other parts of the turbine contributes the second highest to GWP. The total GWP of the materials is 2,221,548.08 kg CO_2 equivalent.

Waste disposal at wind farms have a minimal contribution to the environmental impact as most materials are recycled nowadays, or the materials will remain at the site (Arvesen and Hertwich, 2012). The end-of-life phase has three possible scenarios. Firstly, repairing and refurbishment of parts of the turbine such as the foundation, tower, etc. Secondly, replacing the older turbines with new parts designed with advanced and state-of-the-art technologies, which can improve the product life by approximately 20 years. This should be considered for the same wind calculations of the original site. Finally, decommissioning is where the parts are removed from the site, and recycled or disposed to landfill after treatment (Mello et al., 2022). The recyclability rate of the turbines is up to 90%, as the material used for the foundation, tower, and components of the gearbox can be treated or recycled. The materials such as steel, iron, copper, and aluminium have recycling rates up to 90%, and the non-recyclable material such as concrete is disposed to landfill (Windeurope, 2019). The material of the turbine blades is up to 95% recyclable, however reinforced plastics must be taken into consideration for the end-of-life process (Tazi et al., 2019). Close to 80% of the emissions occur at the raw material acquisition and the manufacturing phases. The end-of-life phase has very low emissions, but this must be made more important as the planning, logistics, and associated costs can have an impact on the overall environmental performance.

The operational energy required for monitoring, control, and automation is shown in Figure 18.

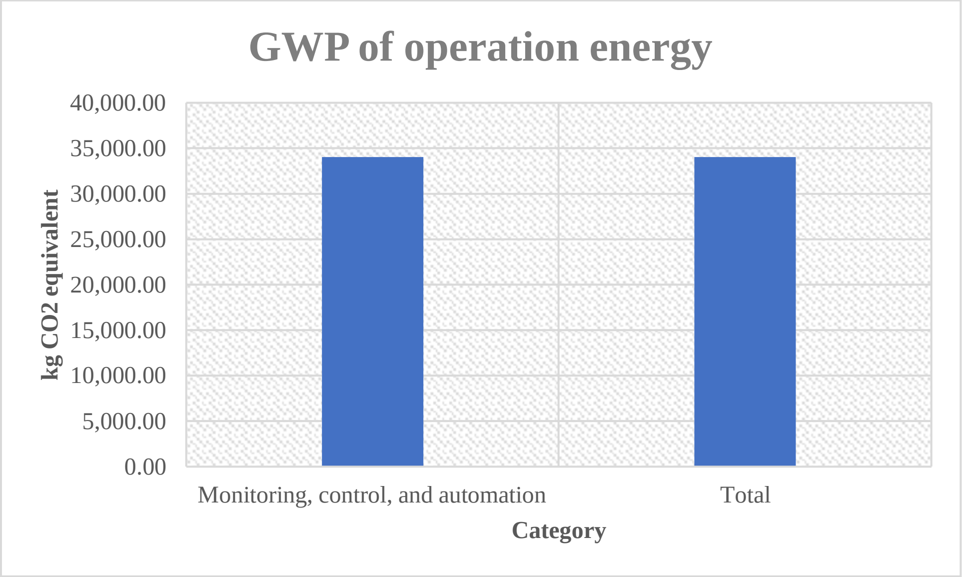


Figure 18: GWP summary of operational energy

As Figure 18 illustrates, the monitoring, control, and automation of the 2 MW turbine during its life cycle contributes to 34,024.11 kg CO_2 equivalent.

Finally, the GWP summary of the emissions by year are shown in Figure 19.

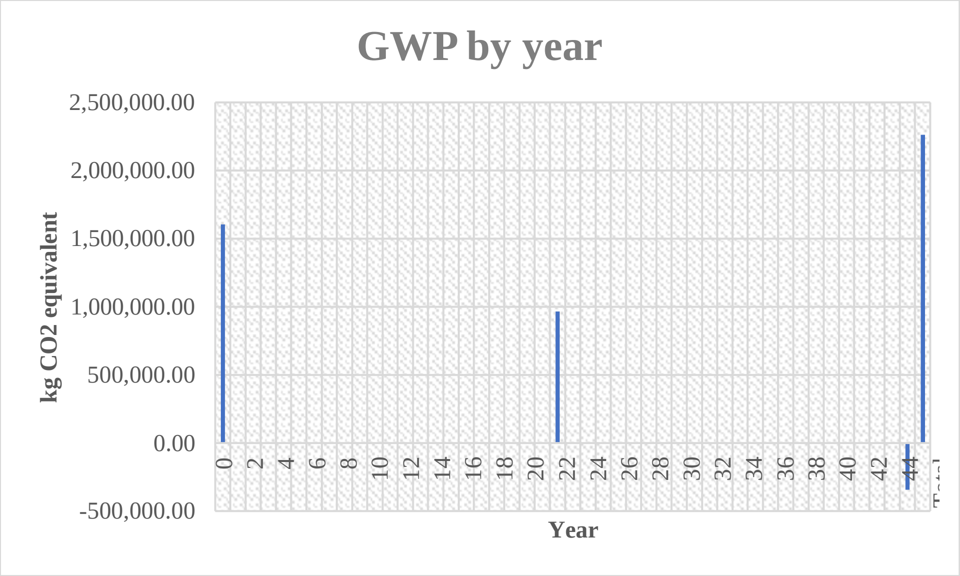


Figure 19: GWP summary by the year

It can be seen from Figure 19 that the manufacture of parts and construction of the turbine contributes to the highest GWP in the year 0, before the operation begins. Each regular year contributes 801.04 kg CO_2 equivalent, and during the half-life of the turbine, there is one heavy maintenance work considered, which contributes to 965,306.22 kg CO_2 equivalent. The 45th year is when the decommissioning takes place, which contributes to -343,125.42 kg CO_2 equivalent.

In addition to GWP, a few other impacts on the environment are presented, such as ODP shown in Figure 20.

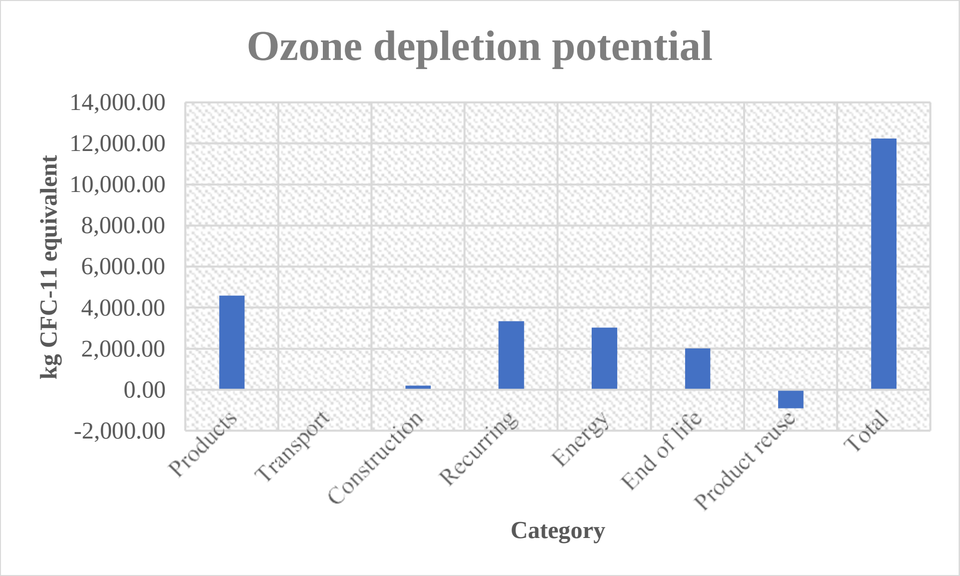


Figure 20: ODP for life cycle stages

Figure 20 shows that the product and recurring stages respectively contributes highest to ODP amounting to 7,912.11 kg CFC-11 equivalent. In addition, energy and end of life contributes 5,026.2 kg CFC-11 equivalent. The product reuse stage has a reversed effect on the ODP, and the total ODP is 12,234.93 kg CFC-11 equivalent.

The WF of the wind turbine is represented by Figure 21.

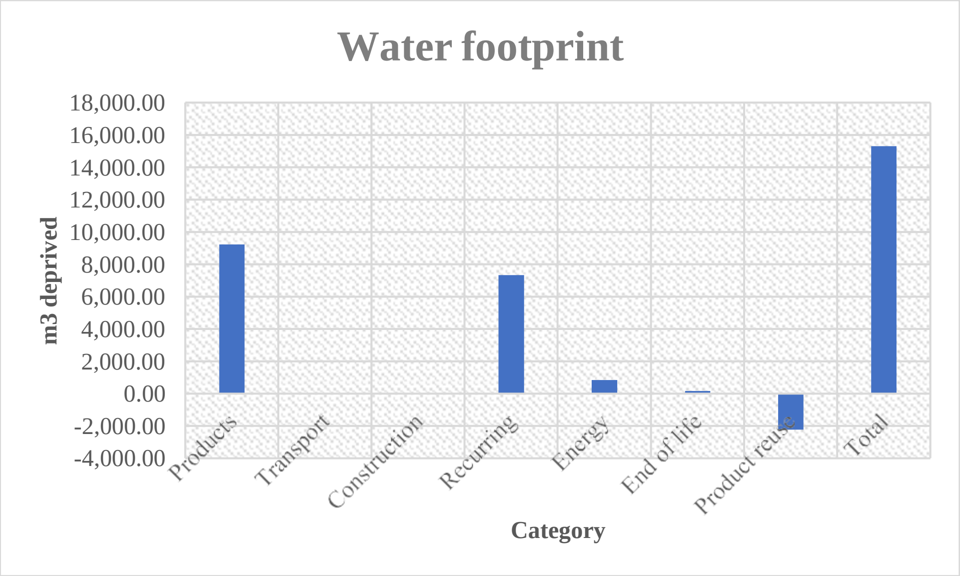


Figure 21: WF for life cycle stages

As Figure 21 shows, the product and recurring stages contributes to 16,544.03 m^3 of deprived water combined. Transport and construction contribute the least with a total of 18.41 m^3. The product reuse phase contributes to negative 2,246.28 m^3 of deprived water, with the total WF of 15,290 .79 m^3 during the life cycle of the turbine.

The ARD during the life cycle is depicted in Figure 22.

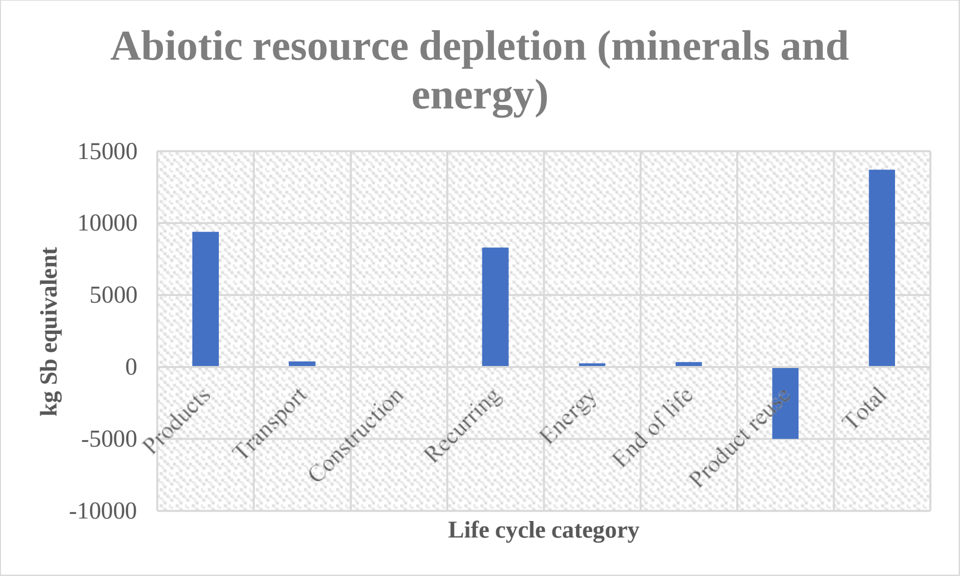


Figure 22: ARD for life cycle stages

As Figure 22 illustrates, the product and recurring stages contribute the maximum to the ARD respectively, collectively contributing to 17,993.5 kg Sb equivalent. Construction and energy contribute 308.4 kg Sb equivalent together, which are the lowest contributors to AP. The end-of-life stage contributes 334.5 kg Sb equivalent, and the product reuse stage contributes negative 5,000.9 kg Sb equivalent. The total ARD from all life cycle stages is 13,716.5 kg Sb equivalent.

The PM emissions for the wind turbine is shown in Figure 23.

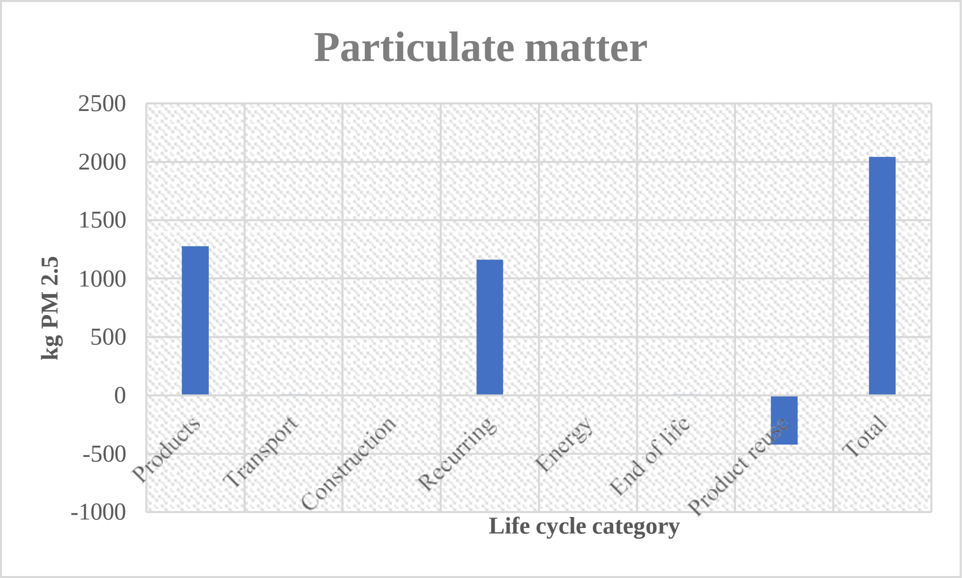


Figure 23: PM emissions for life cycle stages

From Figure 23, the product and recurring stages contributes 1,279 kg PM 2.5 equivalent and 1,161.7 kg PM 2.5 equivalent respectively to the emissions. The transportation phase contributes 7.8 kg PM 2.5, and the end-of-life phase contributes 7.76 kg PM 2.5. Once again, construction and energy stages contribute the least, with product reuse having a reverse impact on the PM emission. The total PM is 2,043.65 kg PM 2.5 equivalent during the life cycle of the turbine.

The LCIA results from the performed LCA provides results which can be used to enable stakeholders to make informed and practical decisions while developing the plans to execute wind farm projects. As can be seen from the results, most of the environmental impacts are caused during the material extraction stage. Steel used for the foundation and tower structure, resins and adhesives used for the nacelle and cover, and concrete for the foundation contribute highest to the environmental impacts. In comparison to other RE solutions, wind energy is one of the best ways to mitigate climate change and provide consistent energy for domestic use (Tremeac and Meunier, 2009). As the operational stage has little impact, turbines with high efficiency must be installed in sites with good wind resources, the materials used should be transported with minimal energy, and the recycling/ end-of-life decommissioning should be done effectively.

7.2 Utilization of AM for a wind turbine part: case of spare parts

Niklas Wahlström performed an intensive study to manufacture spare parts for the hydraulic pitch system of a wind turbine. One of the most major components of a wind turbine is the hydraulic pitch system, which keeps changing the angle of the blades to maximise the energy generated from the turbine. Additionally, they also provide a fail-safe function, and provide real time feedback on the positions of the blades (Hydratech Industries, 2022). The system essentially comprises of a power pack, rotating union, pitch actuators, and hydraulic manifolds shown in Figure 24.

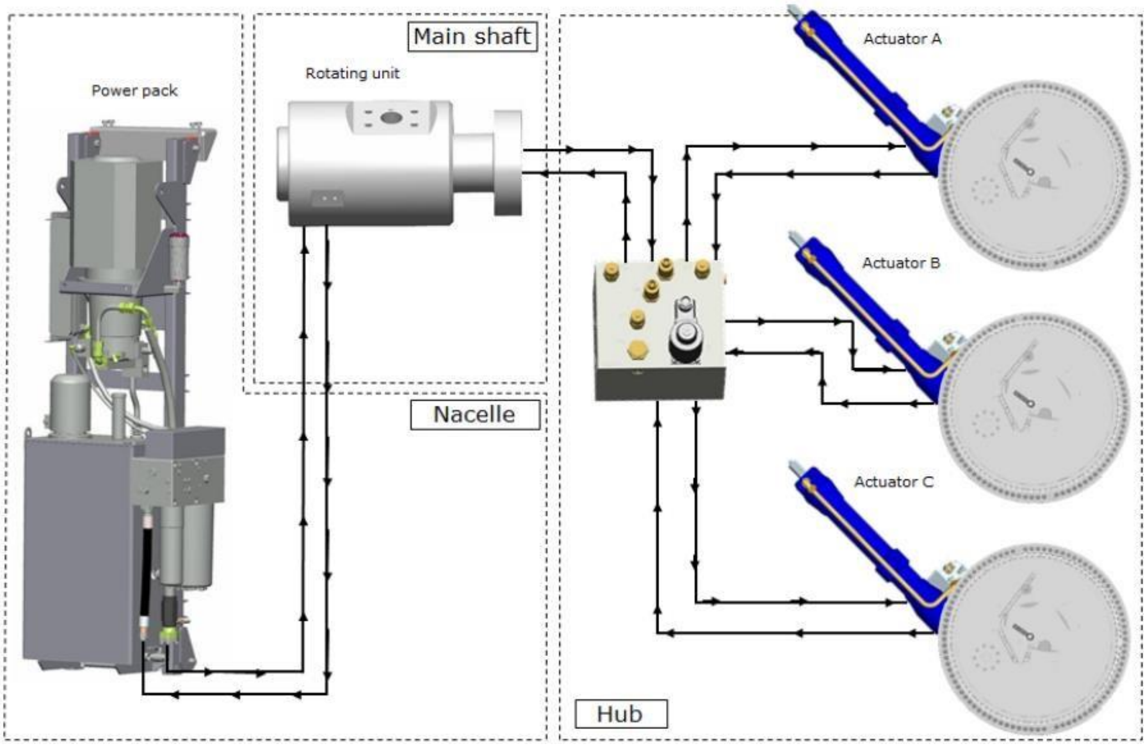


Figure 24: Hydraulic pitch system of a wind turbine (Wahlström and Gabrielsson, 2017).

As seen in Figure 24, the power pack is the part that comprises of a motor, a hydraulic pump, and a hydraulic tank containing oil. It is housed in the nacelle. The pump is driven by the motor and converts the electrical energy to hydraulic energy, which allows the oil to flow within the channels shown by the black arrows in the figure. The actuators are in the hub and are connected to the blades which allow them to move. The oil is transferred from the static shaft to the rotating member (hub) through the rotating unit (RU). This part is intended to be additively manufactured, and the related costs and contribution to environmental impact will be assessed.

The main components of the RU that allow for its smooth operation are the stator, rotor, seals, and bearings. The bearings allow smooth rotation of the part along a curved surface. The RU was manufactured traditionally by CNC machines, which comprised of milling, drilling, lathe usage, turning, and edge finishing. However, due to the use of subtractive manufacturing, there are material losses. The original design is shown in Figure 25.

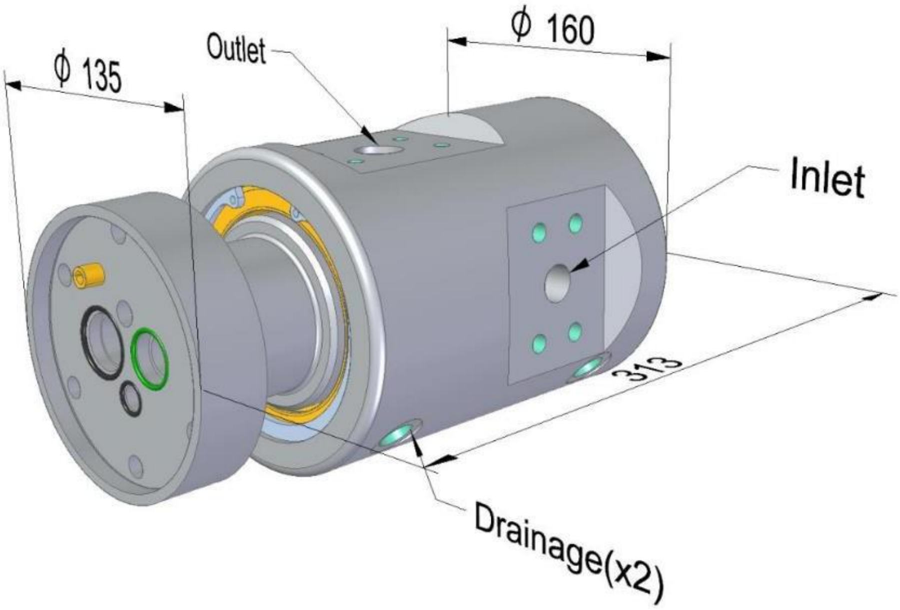


Figure 25: Assembly view of the RU (Wahlström and Gabrielsson, 2017)

Figure 25 illustrates that the part has an inlet, outlet, and drainage connections of the stator. The unit comprises of a stator and a rotor, and the dimensions of are shown. The material usage by CNC machining is shown in Table 7.

Table 7: Material losses by CNC machining

	Stator	**Rotor**
Raw material usage (m^3)	3230	4746
Volume of finished part (m^3)	2270	1347
Material losses (m^3)	960	3399

Table 7 indicates that there are major material losses when using CNC machining which is a subtractive manufacturing process. There are major material losses in the rotor section, which is almost 3400 m^3 of wastage, and 960 m^3 of losses in the stator section.

To reduce the losses, and provide other advantages that AM has to offer, laser-based powder bed fusion (L-PBF) has been selected as the AM technology to develop this part. DED is not considered as L-PBF has better design freedom, and final machining is required to obtain the required geometrical tolerances. PBF is also the most used technique for manufacturing metal parts with AM. Laser based melting is chosen in comparison to electron beam melting as better surface quality, readily available materials, and larger build sizes are possible. The material used is MS 1.2709, and the data is available from the EOS website (EOS, 2022). Additionally, some of the aspects while using DfAM are to avoid superfluous volumes, by only having material where needed. The build direction is important to avoid overhang and minimising support structure necessity. High design freedom is also needed to allow the internal channels to have smooth finishes and radius changes. Based on all the design factors, the CAD model has been created, shown in Figure 26.

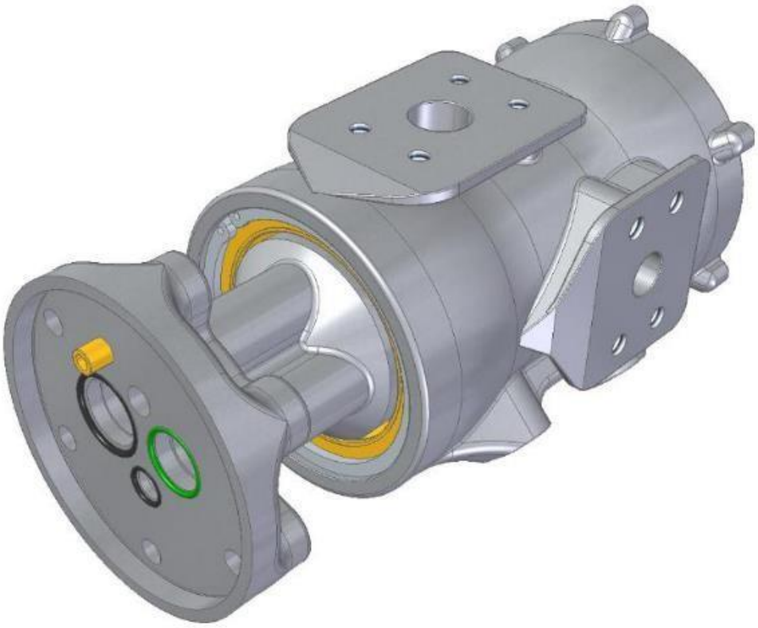


Figure 26: CAD drawing of proposed concept to be manufacture by AM (Wahlström and Gabrielsson, 2017)

As Figure 26 shows, based on the constraints and DfAM approach, the part has been developed. There are more circular channels integrated for smooth radius transitions. The build direction is selected to avoid any overhang angle above 35° so that minimal support structures are used. Finally, post-processing is required for some of the internal and outer surfaces of the part. For example, removal of support structures, threading, and adding connections. The weight reduction for the new part in comparison to the original design is shown in Table 8.

Table 8: Weight comparison and savings

Part	**Stator (kg)**	**Rotor (kg)**	**RU assembly (kg)**
Original	20.9	10.6	31.8
AM	8.4	8.4	17.9
Weight reduction	60%	21%	43.8%

Table 8 showcases the major change in weight for the stator and rotor, as well as the full unit by using L-PBF process. An overall of approximately 44% weight reduction is achievable. Reduced weight indicates that lesser emissions from transportation, raw material usage, manufacturing stage, etc, can further improve the environmental performance of the whole life cycle of the product. In addition, these parts can be locally manufactured, and on-demand to further improve the environmental performance of the system.

The material savings for the new part is shown in Table 9.

Table 9: Material comparison and savings

Part	**Stator (cm^3)**	**Rotor (cm^3)**	**RU assembly (cm^3)**
Original	3299	4746	7976
AM	1103	1102	2205
Material reduction	66%	77%	72%

Table 9 shows that there are significant material savings by using L-PBF process. By using DfAM, the savings of material from stator and rotor are 66% and 77% respectively. The final product uses 72% less material than when compared to subtractive manufacturing from CNC machining.

7.3 Environmental impact of AM on wind turbine

The LCIA performed presented results related to the environmental impacts from the various indicators selected. The case study performed shows that adopting AM for the manufacture of components of a wind turbine, specifically the RU of the hydraulic pitch system. PBF is chosen as the AM technology to manufacture the part due to design freedom. It provided benefits such as major reductions in the material used, which enables lightweighting of the component. In addition to lightweighting, it also means that significantly lesser material is also required during the stages prior to the manufacture, hence less amount of raw material is needed for the acquisition stage. This makes the processing stage for the materials more environmentally beneficial, and the end-of-life stage would deal with lesser material as well. Using AM also provided other benefits such as lower carbon emissions from transportation phase, as the lightweight material will save fuel costs for transportation of the components. In addition, since products can be manufactured locally and on-demand, transportation related to the components would further reduce.

The various benefits related to the environment by integrating AM for the manufacture of a wind turbine is illustrated in Figure 27.

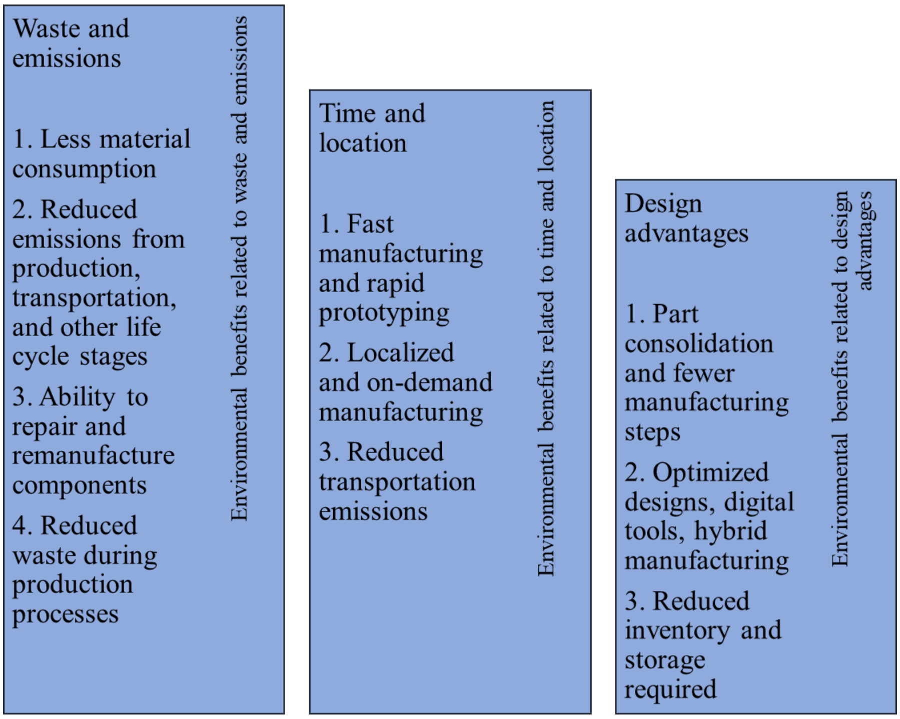


Figure 27: Environmental benefits of integrating AM to the manufacture of a wind turbine

As Figure 27 shows, the main benefits gained by integrating AM for the wind turbine are related to waste and emissions, time and location, and design advantages. As AM uses lesser material, there would be lesser consumption of resources at each stage of the life cycle. The ability to repair and remanufacture further reduces the need for additional resources, and production has minimal waste in comparison to traditional manufacturing. The GHG emissions, water footprint, depletion of fossil fuels and other raw material resources, and PM emissions are all significantly lowered by using AM. As AM is a subcategory of I 4.0, several digital tools are available, which can be stored on cloud and used on demand. AM allows for rapid prototyping and a fast manufacturing, especially for mass manufactured components. If standard components are required for the wind turbines, for example for a wind farm which would comprise of multiple turbines, AM would be highly advantageous to cater to the mass manufacturing. As the components can be manufactured on demand and locally (or closer to the site), transportation emissions also reduce, which has a positive impact on GHG, PM, and ARD. Finally, the design advantages that AM can offer to the components of a wind turbine are not fully explored yet. R&D in the fields of materials, energy efficiency, supply chain, and sustainability are rising, and emissions and harm to the environment may reduce in the years to come. Due to the ability to manufacture complex parts, AM can provide optimized components for the wind turbine which are lightweight, and have higher mechanical, and environmental performances. It is also to consolidate parts which can allow for fewer manufacturing steps. Finally, a reduced inventory means less space is needed for storage, and there is an overall reduction in the manufacturing area required as only the AM machines and required tools and resources would be needed which are significantly lesser.

8 CONCLUSIONS AND FUTURE WORK

This thesis has presented the environmental benefits that can be gained by using AM for the RE industry, specifically for the wind turbine construction. Firstly, a literature review on the topics of AM, wind turbine, and LCA were presented to give information about the different topics that would be in the experimental section. Sub-topics such as L-PBF, wind turbine components and construction, the use of AM in the wind energy industry, and concepts of LCA including the four (4) stages and the impact indicators were presented. Secondly, the experimental section included three (3) main parts: the LCIA for a 2 MW wind turbine with a 45-year life cycle, the case study to manufacture a RU for the hydraulic pitch system of the wind turbine using L-PBF which presented results on material usage, and finally an image to illustrate the multiple benefits of using AM for the manufacture of wind turbine components.

The research questions have been answered as below:

1. The materials that typically contribute to GWP in the life cycle of a wind turbine are steel, resins, and adhesives. Other materials that also contribute to the GWP are concrete, iron, foams, zinc, copper, and fibre reinforced plastics.
2. Other significant indicators that traditionally contribute to the environmental impact of a wind turbine are ODP, WF, ARD, and PM emissions. For all these indicators, the maximum emissions are during the product extraction, manufacturing, and recurring stages. However, for all the indicators, since there is product reuse included in the experimental by recycling the materials, the negative environmental impacts are lowered.
3. AM can benefit environmental sustainability of a wind turbine in comparison to traditional manufacturing by using less material, hence lower waste during the production process. There are also reduced emissions during the production and other life cycle stages. AM also allows rapid prototyping and manufacturing, which can be localized and on-demand which further reduces emissions from transportation, and throughout the supply chain. Finally, optimized designs, mechanical properties,

reduced inventory and storage, and part consolidation further provides several advantages.

The initial idea for the thesis was to perform a LCI comparison for traditional manufacturing process such as CNC machining and AM manufactured wind turbine. The inventory data related to the traditional manufacturing process was available, however, it was difficult to find data related to the inventory for the AM processes. Due to this, the outline of the thesis had been changed to perform the LCIA for traditionally manufactured wind turbine, present a case study for the manufacture of wind turbine components by L-PBF AM process, and drawing conclusions from both the results to present an illustration of the environmental benefits of using AM in the construction of wind turbine.

R&D around AM is increasing, and manufacturers of wind turbines are now longer highly sceptical of using AM in their manufacturing techniques. Several companies are already using AM to manufacture blades for the turbines, as well as internal components housed in the nacelle. There are future considerations that can be further researched so that the LCI and LCIA can be performed for both the manufacturing techniques, and comparisons can be made. In this way, the actual data related to environmental emissions from the AM process can be compared and further developed to integrate it further with the RE industry.

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