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MASTER'S THESIS

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Foreword

This master's thesis has been given to me by Equinor ASA, and I would like to thank the company and Laura Victoria Mejia for giving me this exiting thesis letting me learn more about the industry and production of our future energy source, wind turbines. Thank you to Kristian Holm for getting me in contact with Equinor's wind turbine vendor, SGRE. A thank you to Alf Holme, Anne Bergland, and Sindre Håvik for their participation in helping me understand the oil refinery and the different products refined from crude oil. I would like to thank Professor J.P. Liyanage for being my supervisor at the University, and for helping me and guiding me through the work of this master's thesis. And finally, I would like to thank all the companies and people that I have been writing e-mails to, for providing me more information related to the production of the different products used in the production of a wind turbine, for being so kind and helpful replying back to me; Jonas Pagh Jensen in SGRE for providing me information about wind turbine production, Christoph Schaedle and Karl Eichler in Westlake Epoxy helping me out with Epoxy, Ingvald Aase in Norsk Stål (Norwegian Steel) helping me out with the elements used in producing the steel, Luc Peters in 3B Fibreglass helping me out with Fibreglass, Magnus Lindenmo from Tata Steel helping me out with the elements used in electrical steel, Matthew Swallow in BUNTING-Berkhamsted helping me out with the NdFeB magnet, and Chris Yankee in Chevron Phillips Chemical Company LP for helping me out with the production of propylene.

All the help I have been receiving from the different people representing the different companies involved, directly or indirectly, in the production of wind turbines, have been highly appreciated.

Thank You!

Contents

Table of figures

List of Tables

List of Abbreviations

Al	aluminum
Al_2O_3	alumina / aluminum oxide
B	boron
°C	degree Celsius
C	carbon
Ca	calcium
$CaCO_3$	calcium carbonate
CaO	calcium oxide
C_2H_4	polyethylene (PE)
C_2H_6	ethane
C_3H_6	propylene / propene
$(C_3H_6)_n$	polypropylene (PP)
C_6H_6	benzene
C_3H_8	propane
$C_3H_8O_3$	glycerine / glycerol
CO_2	carbon dioxide
Co	cobalt
Cu	copper
Dy	dysprosium (lanthanide series and REE)
Fe	iron
$FeSO_4$	iron(II) sulphate
$FeTiO_3$	Ilmenite, an oxide mineral
Gd	gadolinium (REE)
GE	General Electric
H	hydrogen
H_2O	water
K_2O	potassium oxide
kg	kilogram
l	litre
Li_2O	lithium oxide
Mg	magnesium
MgO	magnesium oxide
Mn	manganese
Mt	megatonne = 1 million (10^6) tonnes
MW	megawatt
N	nitrogen
Na	sodium
Na_2CO_3	sodium carbonate / soda ash
Na_2O	sodium oxide
Nb	niobium
Nd	neodymium (lanthanide series and REE)
Ni	nickel
O	oxygen

OEM	original equipment manufacture
P	phosphorus
Pb	lead
PE	polyethylene
PGP	Polymer Grade Propylene
PMG	permanent-magnet generator
PMSG	permanent-magnet synchronous generator
PP	polypropylene
ppm	parts per million
Pr	praseodymium (REE)
PU	polyurethane
RE / REN	Renewable Energy
REE	Rare Earth Element
RGP	Refinery Grade Propylene
S	sulphur
SGRE	Siemens Gamesa Renewable Energy
Si	silicon
SiO_2	silica / silicon dioxide
TWh	Terawatt-hour
Ti	titan
$TiCl_4$	titanium(IV) chloride
$TiOSO_4$	titanium oxygen sulphate
TiO_2	titanium dioxide or titanium(IV) oxide
t	metric ton or tonne (1 t = 1000 kg)
UK	United Kingdom
USA	United States of America
wt%	weight percent / percentage by weight

List of Symbols and Values

M	molar mass [g/mol] -> found in the periodic table for atoms
m	mass (measured in [tonne, kilogram, or gram])
m_t	total mass
n	mole [mol]

$M = m/n$	[g/mol]

Johan Sverdrup oil at 15°C	0,883 kg/l = 1/0,883 l/kg = 1,132502831 l/kg
1 barrel of oil	158,987 litre
1 billion	10^9
1 kilo	10^3
1 million	10^6
1 mole	$6,022*10^{23}$ atoms, molecules, protons, etc.
1 ppm	1/1 000 000 = 0,001‰ = 1 mg/kg
1 pound	0,453592 kg
1 W	1 J/s [Joule per second]
1 kWh	3600 kWs = 3600 kJ
1 MW	10^6 W
1 TW	10^{12} W
1 tonne	1.000 kg = 1,1023 short tons

Summary

As the world is working towards a greener energy environment, we see that more and more companies are changing their course to meet the green shift. Our future jobs will try to move more away from oil and fossil fuels, and rather focus on greener energy.
The author of this master's thesis finds the new renewable energy focus very interesting and has therefore chosen to look at renewable energy within wind turbines during her master's studies. In the search of a master's thesis related to wind energy, Equinor was contacted, as it is well known that Equinor is a company focusing on wind energy. Equinor provided a thesis where they wanted to have a look at the production of wind turbines in their projects. They mainly wanted to have a look at the resources and raw materials used in the production of the wind turbines to map the wind turbines' sustainability, but also the environmental and human consequences of the production.

In this master's thesis it has been looked at the production of the Hywind Tampen wind turbines delivered to Equinor in accordance with the company's energy shift and commitment to renewable energy (REN). The thesis is going into details of the materials used to produce one wind turbine, where information has been given by Siemens Gamesa Renewable Energy (SGRE) who is the vendor of the wind turbines for Equinor's Hywind Tampen project. The materials have been broken down, as much as possible, to the natural raw materials. This has been done to be able to analyse how much of the Earth's resources are used to produce the renewable energy, which again has been compared to the yearly production of the raw material. This master's thesis is trying to give an answer to how sustainable the wind energy production is and how the wind turbine production affecting the environment in terms of the resources that are being used. Saying that something is sustainable means that the resource is being replenished at roughly the same rate as it is being used (Coley, 2008, p. 27).

The thesis's building structure starts with an introduction to the energy supply today, and the scope and objectives. The master's thesis got 3 objectives:

- Looking at how much of natural raw materials that are used in the production.
- Looking at the environmental impact of producing and using the raw materials.
- Then provide improvements and recommendations.

The thesis proceeds with some literature overview related to wind energy in general, wind turbine construction and how the technology works, and the materials used when building a wind turbine.

In chapter 3 the author introduces Equinor as a company including a short introduction to its wind energy history and a brief overview of company's wind farm projects, both in operation and under construction/in planning face.

The theses then analysis the Hywind Tampen project in chapter 4 with details about the materials used, the world's annual production of the raw materials, how much reserves are estimated left in the world, and the environmental impact of the usage, before the master's

thesis rounds off with potential improvements and other recommendations in chapter 5, and discussion and conclusion in chapter 6.

When writing this master's thesis, the author started out with gathering general information about energy, wind energy, wind turbines, and some background information about Equinor. The vendor for the Hywind Tampen wind turbines, SGRE, were contacted to get information about the materials used in the production of their wind turbines. After that, hours were spent to get into details of the materials used, so that the author was left with raw materials. In this process a lot of time was spent to find companies producing some of the materials used, and then to send out e-mails to ask for the material's raw components. Then calculations were done to get into the details of the raw materials and creating tables with a good overview. Literature was searched for and read to get an insight in the environmental consequences of the usage and production of the raw materials, before recommendation, improvements, discussion, and conclusion was given based on the findings from the master's thesis. The main result of this thesis project is to establish the amount of Earthly resources used to produce wind turbines, and then conclude on its sustainability based on that.

In this master's thesis the author is using (,) as the separator character for decimals, and (.) for separating thousands. However, in the screenshots taken from the Johan Sverdrup crude oil summery report the (.) character is used to separate decimals.

1. Introduction

Equinor ASA is a Norwegian state-owned company based primarily on petroleum technology, but now also investing in renewable energy like wind farms. Related to Equinor's wind farm projects they have asked to investigate the materials used in the offshore wind turbines, and its sustainability and impact on the environment.

1.1. Background

We are living in a world with global environmental challenges, where there is an increase in population and the demand for energy is rapidly growing. In 2015 an international agreement, the Paris Agreement, was signed where countries around the world agreed to make plans on how they can reduce the greenhouse gas (GHG) emissions. Equinor will participate in this green shift by changing the company to become more sustainable by focusing on, among other things, renewal energy like wind farms. Even though the operation of a wind turbine, when up and running, is green, non-pollutive, and sustainable it is important to understand what the resources used to produce these huge creations do to our environment, and how much resources are there for us to be used. Is the production of the wind turbines sustainable?

From a figure found in the report/book "Renewable Energy Sources and Climate Change Mitigations" (Endenhofer, Pichs-Madruga, Sokona, Seyboth, & m.m, 2011, p. 10) it shows the following shares of energy sources in total global energy supply in 2008:

- Oil 34,6%
- Coal 28,4%
- Gas 22,1%
- Renewable Energy (RE) 12,9%
    - Bioenergy 10,2%
    - Hydropower 2,3%
    - Geothermal Energy 0,1%
    - Direct Solar Energy 0,1%
    - Wind Energy 0,2%
    - Ocean Energy 0,002%
- Nuclear Energy 2,0%

While a web page from Statista (Sönnichsen, 2021a) shows the following for distribution of primary energy supply worldwide in 2019:

- Oil 30,9%
- Coal 26,8%
- Natural gas 23,2%
- Biofuels & waste 9,4%
- Nuclear Energy 5%

- Hydro 2,5%
- Other 2,2% (geothermal energy, solar, wind power, thermal energy, tide, wave and ocean energy)

Except for the increase of Nuclear Energy from 2008 to 2019, the author finds it natural to believe that the decrease of oil and coal usage from 2008 to 2019 has been substituted with renewable energy like wind energy, in our struggle to bring down CO_2 emissions. Wind power could be supplying up to 19% of the world's electricity and avoiding over three billion tonnes of CO_2 per year, by 2030. By 2050, 25-30% of global power could come from wind energy (Spear & EcoWatch, 2014).

1.2. Scope and objectives

The scope of this master's thesis is to look at the production, and then in terms of the material used, of the wind turbines delivered to Equinor in their Hywind Tampen project. Even though Equinor got many more projects under construction or in planning phase, it is not enough time to look at them all, so one project has been chosen.

Objective 1: How much of natural raw materials are used

As the demand for wind turbines grows, so does the demand for rare Earth elements (REEs). REE are metals that are classified as critical for the European industry. They are important in the manufacturing of HiTeck and green technology production like wind turbines. While REE's are not actually rare in nature, exploitable concentrations are uncommon (Coint & Dahlgren, 2019, p. 1 and 6). However, REEs are not the only elements used in wind turbines, also common elements such as iron, aluminium, copper, cobalt, etc. are used, and none of these have infinite resources on Earth.

The objective of this master's thesis is to have a look at these natural raw materials used, that we find in the crust of the Earth or under the seabed, to get an understanding of what resources are used and how much are being used.

Objective 2: The environmental impact

Unfortunately, "mother" Earth is not providing unlimited with resources, and even though some resources might be renewed, like oil, it will take millions of years for it to be renewed, and with the speed the oil is used today, it will go empty. As a second objective in this master's thesis, it will be looked at the environmental impact when mining and using the resources for wind turbine production. After getting an idea of the resources used and how much, it will be compared to the yearly productions and what has been estimated that can be extracted from the Earth. In addition to looking at what the mining industry do to the environment and the people around it.

Objective 3: Improvements and recommendations

The last objective will be to suggest some improvements and recommendations to reduce the environmental impact that the wind turbine production might have. And point out some areas that the industry could be focusing on improving, as a result of this thesis findings. For sure the production of wind turbines will have an environmental footprint, and as the need for energy is growing fast, it is necessary to improve our energy solutions so that they can become as sustainable as possible.

1.3. Methodology of the master's thesis

In this master's thesis it has been tried go into the details of the raw materials in each product used in the wind turbine production. To be able to get down to such detailed level, getting in contact with companies producing the different products, was necessary. E-mails to many different companies was sent, and a few positive replies were received. Based on feedback given related to the different products, it was possible to get down to most of the raw materials used in the products, and then calculate the quantity of it. Only two products, the plastic material polyurethanes and plywood, were not possible to get information about, so no data has been provided for these.
A lot of time has been spent on searching the internet for the different products, reading through documentations that has been relevant for the different products, and to find companies that might be able to help out with more details around the product.

The author has performed her own calculations to get down to more detailed information regarding the quantities of the raw materials used, based on information given from people in the relevant areas, formulas from school studies, and information provided on the internet.

1.4. Limitation

Equinor currently got many wind turbine projects, either under construction or in the planning phase, in addition to their completed projects already in operation. However, this master's thesis is limited to Equinor's Hywind Tampen project. In addition, the foundation of the wind turbine is not included.

The calculations done in this thesis is limited to information provided to the author by professionals within different areas, and information provided in different articles and web sites found on the internet. When calculating crude oil quantities in different oil products, the study is limited to the data given from an oil sample from Johan Sverdrup in 2021. As the oil quality differ from oil field to oil field, this oil sample might not have been the best sample to extract the different products used in the production of wind turbines, and this could result in more crude oil from the specific sample is needed to get the quantity of the products needed, compared to another oil sample.

The author of this master's thesis is also not a chemist, but a mechanical engineer, so her background for doing these calculations related to chemistry and her knowledge in the field, is limited.

2. Literature review

Within the spectrum of renewable energy sources, wind power plays an outstanding role. Compared to other sources of renewable energy, wind energy comes second after solar energy, and given all the challenges, scientist in the field believe that wind power can provide a quarter of the total energy demand worldwide (ref. lecture notes (Nikpey, 2021, p. 4)). It has been estimated that by 2050, 25-30% of global power could come from the wind (Spear & EcoWatch, 2014).

2.1. Wind energy

The wind got its origin from the sun caused by the uneven heating of the Earth by the sun and the Earth's own rotation, and it usually flow from a high pressure-area to a low-pressure area. As the hot air rises and the cool air sinks, it causes spatial differences in atmospheric pressure, resulted by uneven heating (Coley, 2008, p. 36).

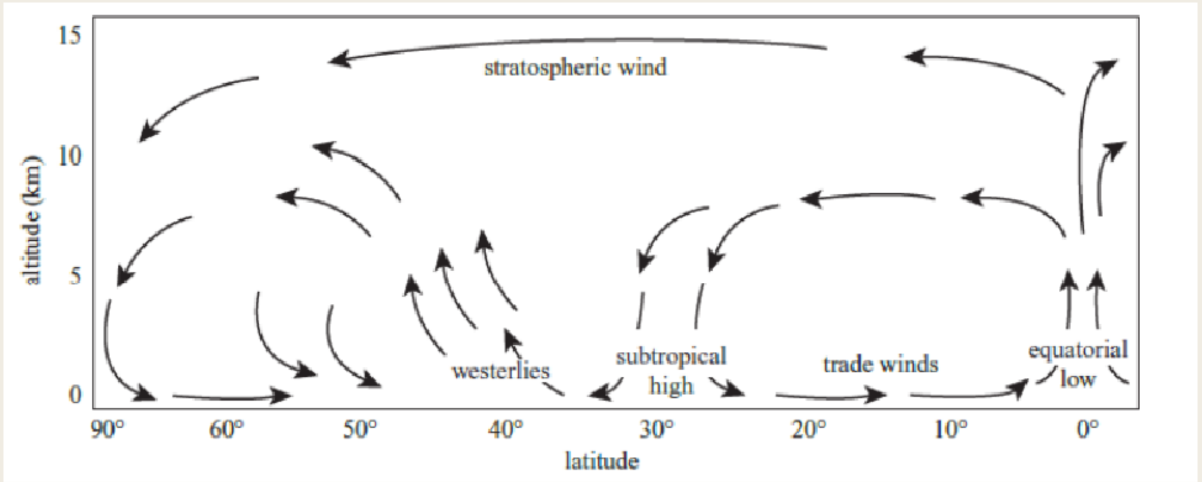


Figure 1 A section through the atmosphere showing large-scale winds (Coley, 2008, p. 36)

2.2. Wind turbine

Instead of using electricity to make wind – like a fan – wind turbines use wind to make electricity. A wind turbine turns wind energy into electricity using the aerodynamic force from the rotor blades, which work like an airplane wing or helicopter rotor blade. When wind flows across the blade, the air pressure on one side of the blade decreases. The difference in air pressure across the two sides of the blade creates both lift and drag. The force of the lift is stronger than the drag and this causes the rotor to spin. The rotor connects to the generator, either directly (if it is a direct drive turbine) or through a shaft and a series of gears (using a gearbox) that speed up the rotation and allow for a physically smaller generator. This translation of aerodynamic force to rotation of a generator creates electricity (Wind Energy Technologies Office, n.d). The kinetic energy created when the wind turns the blade of the wind turbine (also called mechanical energy) is then converted into electric energy by a generator within the wind turbine nacelle.

There are both on-shore and off-shore wind turbines in the world today. Whereas on-shore wind powers refer to turbines situated on land, off-shore is defined as wind power at the sea. Horizontally axled wind turbines are divided into two main groups: geared turbines using a gear box and direct-drive turbines using Permanent-Magnet Generators (PMG), or they can use a combination of the two. In this thesis the analysed wind turbines are using PMG.

Below is a drawing showing a horizontal axis wind turbine with references to its components on a high level:

Drawing of the rotor and blades of a wind turbine, courtesy of ESN

Figure 2 The rotor and blade of a wind turbine (European Wind Association, n.d.)

The main components of the machine are the tower, the nacelle, and the rotor. While the blades are generally made of materials such as carbon fibre or glass fibre, and wood, steel is holding the turning blades in place, utilizing a cast iron or forged steel rotor hub. At the top of the tower are the rotor and the nacelle. Because a nacelle can weigh as much as 300 tonnes, the steel's strength makes it the perfect material for the nacelle's frame, housing, and machinery. Behind the blades, a low-speed shaft transfers the rotational force of the rotor to the gearbox, in wind turbines using a gearbox. Here, the gears are operated using precision tools and hardened steel components. It increases the low rotational speed of the rotor shaft to the high speed required to power the generator. The mechanical energy captured by the blades is converted into electric energy, which is then directed to the transformer and converted to the higher voltage needed by the electricity grid (Posco Newsroom, 2016). In a direct-driven turbine, the rotor blades are connected directly to the generator via a horizontal shaft, which means that the generator must rotate at the same speed as the rotor blades. Unliked a geared turbine where the generator can have faster rotation than the rotor blades.

In offshore wind turbines (OWT) the following are the major foundation types used:

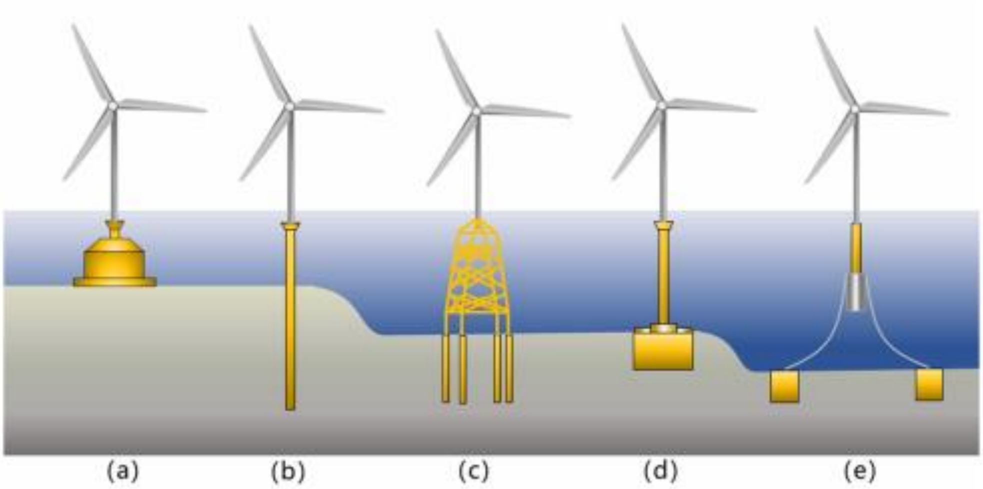


Figure 5. Major foundation types used in OWT design: (**a**) gravity foundation; (**b**) mono-pile; (**c**) jacket foundation piles; (**d**) suction bucket (mono-pod); (**e**) floating wind turbine with anchors (modified from [67]).

Figure 3 Major foundation types used in OWT design (Huang & Han, 2020, p. 7)

The figure below (fig. 4) shows the constructive composition of a wind turbine running with a gear box:

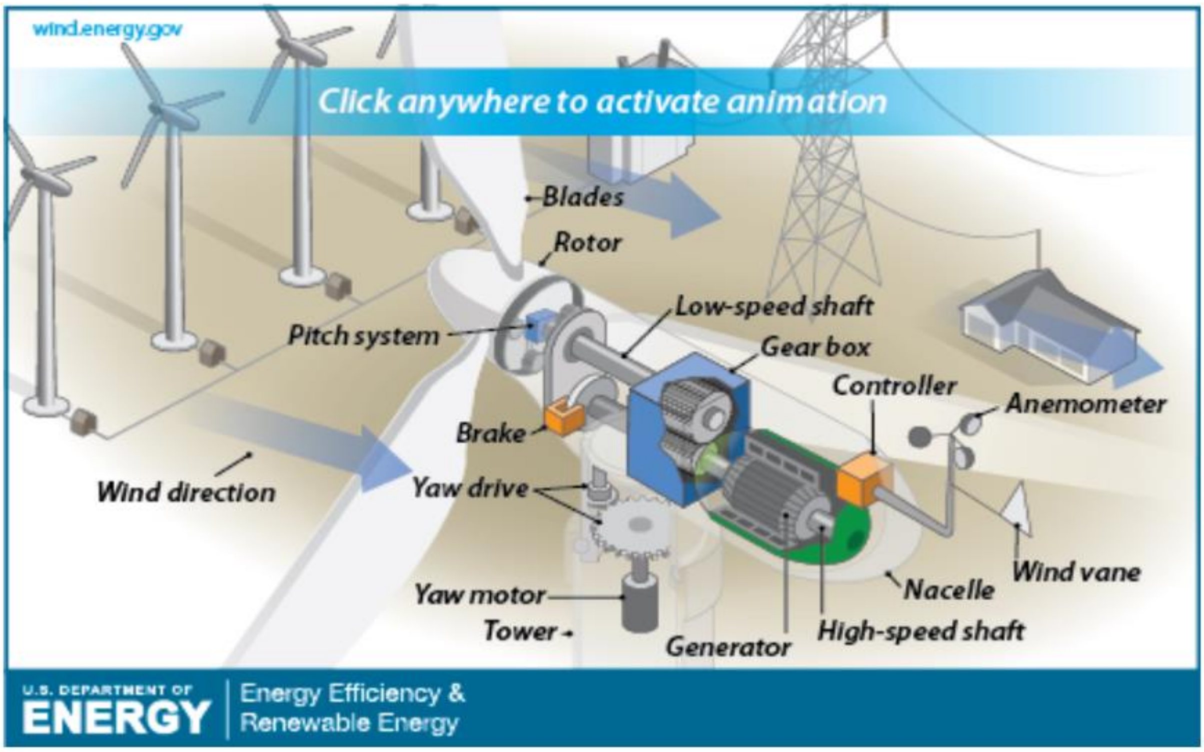


Figure 4 Inside of a wind turbine (Wind Energy Technologies Office, n.d)

2.3. Material types

The increase in production of renewable energy like wind turbines requires increased access to a number of metals and other raw materials. Modern wind turbines require among other aluminium, cobalt, copper, iron, and several special metals. Several types of rare earth elements (REE) are also needed to make light and small magnets that are part of wind turbines (Smelror, 2016). In addition to this, wind turbines using concrete is also produced, and concrete is used in some of the wind turbine foundations, especially for onshore wind turbines.

Rare Earth Elements (REE)

REE are a group of 17 metallic elements with similar physical and chemical properties that occur together in the periodic table. Sixteen of these occur in nature and are typically found in varying proportions in the same ore deposits. REEs are vital to industrialized societies worldwide as they are used in a range of products, including nuclear reactor components, cell phones, magnets, camera lenses, and batteries (Wyoming State Geological Survey, 2021).

The term ”rare earth elements” is a misleading name. They are not really rare if you’re willing to dig for them. In fact, most (though not all) of the rare earth elements are fairly common; several of them are more abundant in the Earth’s crust than lead or nitrogen (Homans, 2010). The challenge is that they typically do not occur in concentrated deposits, but often found mixed together and are difficult, and therefore expensive, to separate (Dodd, 2018). The stuff has been mined everywhere from Sweden to Southeast Asia to the American West. Today, however, rare earth mining is almost nonexciting outside China, which came to dominate the market in the 1980s and ’90s by cutting world prices and now controls as much as 97% of the supply of some of the elements. The limited supply of the minerals in the marketplace is the result of economics and environmental concerns, not scarcity (Homans, 2010).

The REEs most used in the wind industry are neodymium (Nd) and dysprosium (Dy), plus small amounts of praseodymium (Pr). Alloys of these three are key constituents of the powerful permanent magnets used in everything from smartphones, medical equipment, electric vehicles, and robotics to the permanent-magnet synchronous generators (PMSGs) employed in some wind turbines. PMSGs can be used in both geared and direct-driven drivetrains, although the amount of REEs is significantly higher in the latter. MHI Vestas’ V164 platform features a medium-speed geared PMSG with a lower REE content than used in the direct-drive PMSGs produced by Siemens Gamesa Renewable Energy (SGRE) and General Electric (GE). (Dodd, 2018).

Steel

Steel is an alloy of iron with a carbon content that can range from 0,03% to 1,075% of its composition, depending on its grade. Steel retains the metal characteristics of iron in its purest form, but the addition of carbon and other elements either metallic or non-metallic improves its physical-chemical properties, especially its resistance. There are many types of steel according to content of alloying elements. Each type of steel will allow different uses and applications, making it a versatile and widely used material in modern life (alacero, n.d.).

From its all-important foundation down to its screws and studs, every part of a wind turbine-machinery used to produce wind energy-depends on iron and steel. In fact, steel, on average, represents 80 percent of all the materials used to construct a wind turbine.

Most of the steel in a wind turbine is utilized in the tower. There are a variety of towers, including steel-concrete hybrid towers, steel truss towers and steel lattice towers, but 90 percent of all wind turbine towers are tubular steel towers (Posco Newsroom, 2016).

Electrical steel

Electric steel, also called silicon steel, is a soft magnetic material that is used in electrical power transformers, motors, and generators. It has a high silicon content of about 3,2 mass %, which increases the electrical resistivity of iron and, therefore, reduces eddy current losses. Grain-oriented silicon steel that is used for non-rotating applications, i.e. transformers, is characterised by a strong preferred crystallographic orientation (Raabe, n.d).

The nacelle contains some of the highest-value steel, including electrical steel, a specialty metal tailored to fabricate the specific magnetic properties that make wind energy feasible (Posco Newsroom, 2016).

Iron (Fe)

Iron is a brittle, hard substance, classified as a metal in group 8 of the periodic table of the elements. It is the most abundant of all metals, its pure form rapidly corrodes from exposure to moist air and high temperatures. Iron is the fourth most common element in the Earth's crust by weight and much of Earth's core is thought to be composed of iron (Blaszczak-Boxe, 2017).

Ferrous metals are a common term for iron, cobalt, and nickel. Pure iron is silvery white, relatively soft, magnetic, and easy to process. Iron occurs purely in nature and reacts easily with oxygen but does not normally occur freely (solidly) in nature. An exception is the iron meteorites, which are pure iron and were probably the first iron to be known and used (Haraldsen, Kofstad, & Pedersen, 2021).

Iron is the most important of all metals, and 90% of all metal that is refined today is iron. Mostly it is used to manufacture steel, used in civil engineering (reinforced concrete, girders etc.) and in manufacturing (Royal Society of Chemistry, n.d.).

Copper (Cu)

Copper is a reddish, extremely ductile metal of group 11 of the periodic table that is an unusually good conductor of electricity and heat. Copper is found in the free metallic state in nature. Native copper is found at many locations as a primary mineral in basaltic lavas and as reduced from copper compounds, such as sulphides, arsenides, chlorides, and carbonates. Copper occurs combined in many minerals, such as chalcocite, chalcopyrite, bornite, cuprite, malachite, and azurite (The Editors of Encyclopaedia Britannica, n.d.-a)

Aluminium (Al)

Aluminium is the third most abundant element in the Earth's crust, after oxygen and silicon (Norsk Hydro ASA, 2021). It is an element that is a silvery-white metal, which is light, and alloys of aluminium are becoming stronger. In addition to being a typical light metal, aluminium can be easily shaped and processed by rolling, pressing, extrusion, drawing and printing. It is also excellent for the production of castings. For many applications, however, aluminium does not have sufficient strength, but the strength can be significantly improved by alloying with other metals.

The electrical conductivity of aluminium is almost two thirds of that of copper. This, together with the density of only 2.7 g / cm^3 and the low price, means that aluminium (often with a steel core) is used in electric power lines where weight plays a significant role in addition to the conductivity.

Aluminium does not corrode in air, because the metal on the surface is covered by a thin, cohesive, sticky, and transparent oxide film (thickness at normal temperature 0.01 mm) which protects the metal from oxidation. By anodizing, the oxide film can be reinforced (Pedersen, n.d).

NdFeB permanent magnet

Neodymium (Nd) magnets – largely comprised of neodymium (Nd), iron (Fe), and Boron (B) – are the strongest type of permanent magnet commercially available and offer highly efficient electricity generation. The magnet is used in the generator of some wind turbines and are called permanent-magnet synchronous generator (PMSG). PMSGs allow a lighter and more compact turbine design, which is particularly beneficial at low wind-speed sites and offshore, where size is key. They generally also require less maintenance and enhance grid compatibility. While a wind turbine using gears can have a gear box weighing 35 tonnes and would require more maintenance and reparations due to broken gear boxes.

Of the major original equipment manufacturers (OEMs), offshore leader Siemens Gamesa Renewable Energy (SGRE) uses direct-drive PMSGs in all its offshore turbines, as does General Electric (GE) in the Haliade 6MW turbine, and most likely, its forthcoming 12MW machine. MHI Vestas’ V164 platform features a medium-speed geared PMSG, with a lower REE content (Dodd, 2018).

Polyethylene (PE)

Polyethylene (PE), $(C_2H_4)_n$, is a thermoplastic polymer with a variable crystalline structure, and it is the most widely produced plastic in the world. Plastics are synthetic materials that originally derive from organic products such as hydrocarbon fuels (coal, natural gas, and crude oil), salt, sand, and a number of other possible constituents (Rogers, 2015).

Polypropylene (PP)

Polypropylene (PP), $(C_3H_6)_n$, is a thermoplastic “addition polymer” made from the combination of propylene monomers (Creative Mechanisms, 2016).

Polyurethane (PU)

Polyurethanes (PU) is a plastic material, which exists in various forms. It can be tailored to be either rigid or flexible (Polyurethanes, n.d.). It is formed by reacting a polyol with a diisocyanate, both derived from crude oil (Europur, 2021).

Fiberglass

Fiberglass is thin fibres made from melted glass. Glass is a rigid, but at the same time very elastic material until it reaches its breaking point. Thin fibres drawn from glass are very flexible, but also resilient, so that they straighten out again without permanent deformation as soon as the bending force is removed (Årtun, 2017).

The most important glass-forming raw material is silica (SiO_2), mainly quartz sand or ground quartz, but also phosphoric acid and boron oxide are glass-forming substances of practical importance. In addition to glass-forming substances, glass in most cases contains other oxides. The most important are usually sodium oxide (Na_2O), calcium oxide (CaO), and alumina (Al_2O_3) (Store Norske Leksikon, 2019).

The fiberglass used in the wind turbine production is mainly for the wind turbine blades.

Epoxy

Epoxy is created by mixing two different compounds known as a resin and a hardener. When the resin is mixed using a specific formula, the two ingredients begin to cure.

Curing is when molecular chains react chemically, forming a strong bond. When the resin and the hardener, or catalyst, are combined, it creates a strong, rigid material. Thermoplastic polymers may also be added to increase the harness factor of epoxy (Matt, 2019).

Epoxy is a type of polymer, a group of chemical compounds that consist of large molecules with repeating subunits. The molecular structure of polymers gives them their toughness and elasticity, making polymers (both natural and manmade ones) ubiquitous in daily life.

This particular polymer plays an essential role in construction – as adhesives and in coatings. Epoxy resins include epoxides – highly reactive groups of molecules – that harden (or cure) through chemical reactions, which are caused wither by combining it with other substances or heating it to a higher temperature. This is the process through which an epoxy becomes “cross linked”, as polymer strands form into a hardened structure (Copeland, 2020). Epoxy resins are produced industrially from raw materials that are for most part derived from petroleum (Reepol, n.d).

Balsa wood (Ochroma pyramidale)

Balsa trees grow naturally in the humid rainforest of Central and South America as well as in tropical seasonal thorn forests there. Its natural range extends from southern Mexico down through Central America, to the north and west coast of South America as far as Bolivia. Balsa wood is very light, soft, and buoyant, with a coarse, open grain. It is one of the lightest varieties of wood available and it is remarkably sturdy and is often considered the strongest wood for its weight in the world. Like all timbers, it comes in various grades. Balsa trees grow very rapidly. Six months after germination, the stem is already about 3 cm in diameter and 3-4 meter tall. After 6 to 10 years, it is ready for cutting, having reached a height of 20-28 meters and a diameter breast height (DBH) of 55 cm (Dr Jackson, 2021).

Today’s wind turbine blades are made from balsa wood which is sandwiched between two bits of fibre glass. The bigger the blades, the more balsa wood they contain (2EA, 2021).

Plywood

Plywood is not a wood or tree type, but a building material consisting of thin wood layers or piles (veneers) bonded with an adhesive. There are two types of plywood: softwood plywood and hardwood plywood. Softwoods generally correspond to coniferous species, and the most used softwoods for manufacturing plywood are firs and pines. Hardwood generally corresponds to deciduous species like oak, poplar, maple, cherry, and larch (United States Environmental Protection Agency (EPA), 2001, p. 1).

Softwood plywood is manufactured by gluing several layers or piles of dry thin softwood together with an adhesive, and it is used for wall siding, sheathing, roof decking, concreate formboards, floors, and containers (United States Environmental Protection Agency (EPA), 2001, p. 1).

Hardwood plywood is made of hardwood layers or piles bonded with an adhesive, where the outer layers (face and back) surround a core which is usually lumber, veneer, particleboard, or medium density fibreboard. Hardwood plywood may be pressed into panels or plywood components, and it is used for interior applications such furniture, cabinets, architectural millwork, panelling, flooring, store fixtures, and doors (United States Environmental Protection Agency (EPA), 2001, p. 1).

3. Industrial cases

3.1. Introduction to Equinor

Equinor ASA is a broad Norwegian energy company with more than 21,000 employees. The company was formed in 1972 as the Norwegian State Oil Company, Statoil, but changed the name to Equinor in 2018. The company started out as an oil and gas company on the Norwegian continent shelf but has grown to become an international company with businesses in countries such as Argentina, Angola, Brazil, USA, Canada, UK, and Mexico. In 2020 36% of the oil and gas equity production took place outside Norway, and 2,07 million barrels of oil equivalent was produced each day.
Equinor's purpose is to turn natural resources into energy for people and progress for society, and their vision is to shape the future of energy. As the company embrace the need for change and the new opportunities that lie within the transition of the global energy markets and the technological shift, they also started to look into renewable energy (Equinor, 2021).

Equinor's first wind farm started its production already in 2012 in Sheringham Shoal, UK, but it was not before Eldar Sætre in 2014 took over as the Executive Vice President of the company that Equinor strengthened its focus on renewable energy. Between 2012 and 2016, just over 3.6 percent of the company's total investments went to renewable projects. In 2015, Sætre established a separate business area for renewable energy (called REN) in the company, and in 2016, the company launched the renewable fund Statoil Energy Ventures.

In 2018, Equinor stated that the company would invest NOK 100 billion in renewable energy by 2030. This is between 15 and 20 percent of the company's total investments in this period. In 2021, this investment was doubled to NOK 200 billion. In 2020 the company supplied 1 million European homes with energy coming from wind turbines (Tollaksen, Ryggvik, & Solbakken-Smith, 2022).

3.2. Wind energy projects in Equinor

Equinor already got a few wind parks in operation, and then some under construction and in a planning face. The below table shows projects in production, under construction, and in a planning phase.

Already in operation/production:

	Sheringham Shoal	**Dudgeon Windfarm**	**Hywind Scotland**	**Arkona**
Technology	Bottom fixed	Bottom fixed	Floating	Bottom fixed
Installed capacity	317 MW (1 wind turbine = 3,6 MW)	402 MW (1 wind turbine = 6 MW)	30 MW (1 wind turbine = 6 MW)	385 MW
# Wind turbines	88	67	5	60
Type			Siemens Gamesa SWT-6.0-154? (Use PMG)	
Production start	2012	2017	2017	2019
Country	UK	UK	UK	Germany

Table 1 Projects in operation/production (ref. internal Equinor documentation)

Under construction or in planning:

	Dogger Bank: A, B, C	**Hywind Tampen**	**Empire Wind**	**Poland**
Technology	Bottom fixed	Floating	Bottom fixed	Bottom fixed
Installed capacity	3600 MW (1 wind turbine = 13 MW)	88 MW (1 wind turbine = 8 MW)	816 MW	~2500 MW
# Wind turbines	270-277	11	60-80	
Type	GE Haliade X (no gear box, use PMG)	Siemens Gamesa (use PMG)		
Production start	2023	2022	2024	
Country	UK	Norway	USA	Poland

	US East coast	**UK Extensions**	**South Korea**	
Technology	Bottom fixed	Bottom fixed	Floating	
Installed capacity	~3500 MW	~720 MW	~200 MW	
# Wind turbines				
Production start				
Country	USA	UK	South Korea	

Table 2 Projects under construction or planning (ref. internal Equinor documentation)

Sheringham Shoal, UK

The Sheringham Shoal offshore wind farm is Equinor's first wind farm starting its production back in 2012. The wind farm is located in the Greater Wash, between 17 and 23 kilometres off the Norfolk coast, north of the seaside town of Sheringham. The farm covers an area of approximately 35 km^2 and got 88 wind turbines installed with a total capacity of 317 MW. The turbines are placed on foundations fixed to the seabed, with a turbine tower height of 80 meters and turbine blade length of 52 meters (Sheringham Shoal, n.d.).

Dudgeon Wind farm, UK

The Dudgeon wind farm is another wind farm located off the coast of North Norfolk in England. This wind farm started its production in 2017 and with its 67 turbines it gives a total capacity of 402 MW which is an annual production of 1.7 TWh, enough to power around 410,000 UK homes. These are bottom fixed wind turbines reaching 170 meters from the surface to the blade tip (ref. internal Equinor documentation).

Hywind Scotland, UK

In 2017 Equinor opened the first full-scale floating offshore wind farm in the world, Hywind Scotland, 25 km off Peterhead on the east coast of Scotland, UK. By freeing the wind power from bottom-fixed designs opens a world of new markets and opportunities. Hywind Scotland wind farm contains 5 wind turbines delivering 6 MW each, giving a total capacity of 30 MW. In March 2021 Hywind Scotland had reached its third consecutive year reaching the highest average capacity factor for any wind farm in the UK (Equinor, 2022).

Arkona, Germany

The Arkona wind farm, with production start in 2019, is located 35 km northeast of the island of Rügen, in the German part of the Baltic Sea, and was the first wind farm to supply electricity into the German electricity grid. The wind farm has a capacity of 385 MW which it supplies around 400,000 German households with renewable energy. Arkona saves up to 1.2 million tonnes of CO_2 annually compared to conventionally generated electricity (Equinor, 2018).

Dogger Bank, UK

Dogger Bank is a wind farm project under construction, with production start in 2023. The farm will be developed in three phases – Dogger Bank A, B, and C – located outside the Northeast cost of England. Dogger Bank A and B will contain approximately 95 wind turbines each, while Dogger Bank C will contain around 80 wind turbines. All together there will be a total of 270-277 wind turbines generating capacity of up to 3.6 GW and will be capable of powering up to 6 million homes (Dogger Bank Wind Farm, 2021). The wind turbines will be bottom fixed and delivered by General Electric (GE) Offshore Wind. The wind turbines delivered to Equinor by GE Offshore Wind are the type of GE Haliade X, which is not using a gear box but Permanent-Magnet Generators (PMG), and therefore got a bigger generator which requires more elements like REE.

It is considered that the wind turbines used in the Dogger Bank project will consist of close to 2 tonnes of the REE Neodymium (Nd) and Dysprosium (Dy). Cerium (Ce) is also used as a hydrophobic coating for turbine blades. In energy storage, batteries and hydrogen storage uses Lanthanum (La). (personal communication an internal Equinor Yammer article by Kristian Holm, 2021).

Hywind Tampen, Norway

Hywind Tampen is another of Equinor's wind farm projects under construction, with a planned production start in 2022. This project is the second floating wind farm from Equinor and is a part of electrifying the Norwegian continent shelf to reduce the CO_2 emission for the Norwegian oil production. Hywind Tampen will consist of 11 floating wind turbines located between the oilfields Snorre and Gullfaks on the Norwegian Continent Shelf. The wind turbines are delivered by Siemens Gamesa Renewable Energy (SGRE) and will produce electricity to the fields Snorre and Gullfaks, with an estimated CO_2 reduction of 200,000 tonnes/year (ref. personal communication internal Equinor ppt. (Hansen, 2019)). Each wind turbine will be anchored with 1km of steel chain. The wind turbines delivered will not use a gear box but Permanent-Magnet Generators (PMG), and therefor they will have a big generator using more of the REE metals Nd and Dy than a gear box driven wind turbine.

Fig. 5 below is a drawing of the Hywind Tampen windfarm located between the two oil rigs Snorre and Gullfaks.

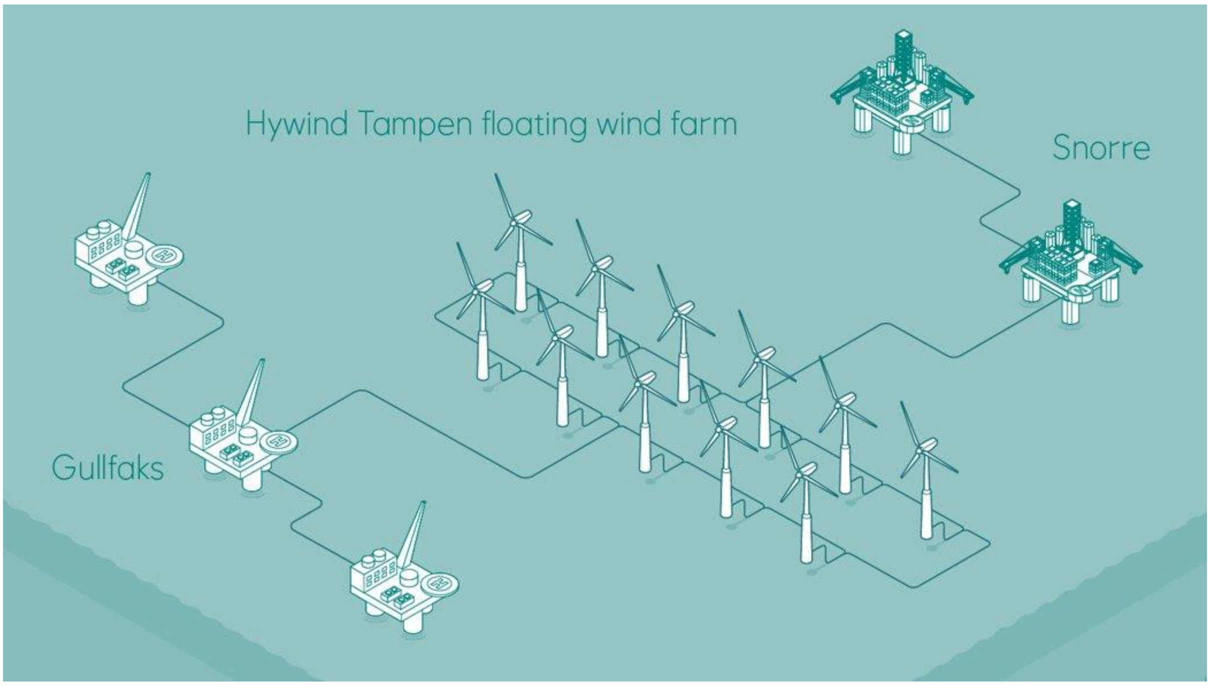


Figure 5 Picture taken from a ppt. presentation created by Equinor (Hansen, 2019, p. 9)

In this master's thesis it will be focused only on the wind turbines delivered by SGRE for this Hywind Tampen project.

4. Hywind Tampen analysis

As mentioned before Hywind Tampen is an ongoing project with planned production start in 2022. Equinor's wind turbine manufacture for this project is Siemens Gamesa Renewable Energy S.A (SGRE) which is a Spanish-German wind energy company, and the world's second largest wind turbine manufacture.

4.1. The Hywind Tampen wind turbine

The turbine type used for the Hywind Tampen project is the SG 8.0-167 DD, which is a wind turbine with a rotor diameter of 167m and nominal power of 8.0MW. SGRE has shared the following data related to the material used in one wind turbine of type SG 8.0-167 DD. The data is not including the foundation of the wind turbine (personal communication, 26.05.21.

Material/metal	**Mass [tonnes]**
Steel	522,730
Iron cast (Fe)	93,623
Fiberglass	54,614
Epoxy	23,406
Electric steel	15,604
Copper (Cu)	15,604
Aluminium (Al)	7,802
Polyethylene (PE) $(C_2H_4)_n$	3,901
Polypropylene (PP) $(C_3H_6)_n$	3,901
Polyurethane (PU)	1,560
NdFeB magnet	1,560
Balsa Wood	1,560
Plywood	1,560
Miscellaneous	9,362
Total	**756,787**

Table 3 Material and metal used in one wind turbine (personal communication, 26.05.21)

Note that the comma character (,) in the table above is separating the decimal numbers.

Steel

Information given by SGRE is that the standard steel used in their wind turbines is S355 alloy, but they could not go into more details around which type of the S355 alloy that is used. According to the mechanical engineering and design information website MEADinfo (MEADinfo, 2015) there are 4 types of S355: S355JR, S355J0, S355J2, and S355K2. After contacting the Norwegian company Norsk Stål it was confirmed that the steel used in wind turbines are mostly S355J2 or S355K2, depending on its location.

According to MEADinfo the chemical composition for S355J2 and S355K2 are the same:

S355 Chemical Composition

Designation	C%	Si%	Mn%	P%	S%	N%	Cu%
S355JR	0,24	0,55	1,6	0,035	0,035	0,012	0,55
S355J0	0,2	0,55	1,6	0,030	0,030	0,012	0,55
S355J2	0,2	0,55	1,6	0,025	0,025	-	0,55
S355K2	0,2	0,55	1,6	0,025	0,025	-	0,55

Table 4 S355 Chemical Composite (MEADinfo, 2015)

Norsk Stål has confirmed that the rest is Iron (Fe), which means that 97,05% is Fe. In this master's thesis it is assumed that S355J2 or S355K2 is used based on the above content.

Table 5 below, shows the calculations done to find mass in tonnes of the different elements used in S355J2/S355K2 per wind turbine ((Total mass steel in tonnes * x% of element) / 100%)

Steel	Mass [tonnes]	Element	Mass [tonnes]
S355J2 / S355K2	522,730 (tbl. 3)		
		Fe (97,05%)	507,309465
		C (0,2%)	1,04546
		Si (0,55%)	2,875015
		Mn (1,6%)	8,36368
		P (0,025%)	0,1306825
		S (0,025%)	0,1306825
		Cu (0,55)	2,875015
Sum (100%)	522,730	**Sum (100%)**	522,730

Table 5 The mass of each element in the S355J2/S355K2 steel alloy per wind turbine

Fiberglass

For fiberglass the only information given is that it is typically of the type E-glass. 3B Fiberglass, a company producing fiberglass, provided an European patent specification for "High strength glass composition and fibers" (EP 2 655 276 B1), where the following was written "*FR 2930543 discloses glass fibres, which according to its example in Table 1 have a glass composition in wight percent:* SiO_2 *60,50;* Al_2O_3 *19,9; CaO 7,7; MgO 9,5;* Na_2O *0,2;* K_2O *0,5;* Li_2O *1,4;* TiO_2 *0,13*" (Hausrath & Longobardo, 2019).

In an e-mail received from a technical service manager of the fiberglass company, referring to the above FR 2930543 glass fibre, it was written the following (personal communication e-mail, 19.07.21):

> "*The glass fiber compositions you have identified are typical for the High Modulus glass fiber composition used in the Wind Turbine blades, especially for spar caps and some root Joints… Please note that there is also some E*

> *glass (no MgO and more CaO) which is used in the parts of the blade where stiffness is not critical (shells, shear webs, …). See table* (table 6) *hereafter for the composition rages.*"

Glass type	**SiO_2**	**Al_2O_3**	**MgO**	**CaO**	**Alkali (Na, K, Li)**	**E mod Gpa**	**Log 3 °C**	**Delta T °C**
E Glass	52-62	12-15	0-5	16-25	0-2	72-82	<1210	>65
Advantex®	59-62	12-15	1-4	20-24	0-1	81	~1260	~69
S Glass	64-65	24-25	10-11	0	0-0,3	90	>1300	<10°C
HiPer-tex^{TM}	59	18	10	12	0-0,5	87-88	~1300	~70
Comp. 1	60	16	8	13,5	1,3	87-88	~1270	~80
Comp. 2	61	15	7	16		87-88	~1275	~65

Table 6 Different glass fibre compositions (personal communication, 19.07.21)

The composition of the fiberglass used in wind turbines is different depending on where in the wind turbine the fiberglass is to be used and what properties/functionality it needs, and since it has not been revealed more details about the fiberglass used in these wind turbines, this master's thesis is assuming the FR 2930543 is used, and it is used in all the fiberglass parts of the wind turbine.

In the "High strength glass composition and fibers" patent it shows the following composition for FR 2930543: 60,50% SiO_2; 19,9% Al_2O_3; 7,7% CaO; 9,5% MgO; 0,2% Na_2O; 0,5% K_2O; 1,4% Li_2O; 0,13% TiO_2.

By using the chemistry formulars to calculate the molar mass M [g/mol] of each molecule or chemical compound ($M_x + M_y = M_{xy}$) (Lumencandela, n.d), n = m/M, and m = M*n where m is the mass in grams of the molecule and n is the moles per molecule, it is possible to calculate the mass of each element present in the molecule. Approximately 54,614 tonnes (table 3) of fiberglass (assumed to be FR 2930543) are used in the production of one wind turbine of type SG 8.0-167 DD. This gives the following mass m [tonnes] of the different elements in the fiberglass used per wind turbine (please see appendix 7.1 and 7.2 for the full calculation of the values in this table):

Fiberglass	**Mass [tonnes]**	**Molecules**	**Mass [tonnes]**	**Molecules/atoms**	**Mass [tonnes]**
FR 2930543	54,614				
		SiO_2 (60,5%)	33,04147		
				Si	*15,44281754*
				O_2 (oxygen molecule)	*17,59865246*
		Al_2O_3 (19,9%)	10,868186		
				Al_2	*5,75173908*
				O_3 (ozone)	*5,116446922*
		CaO (7,7%) (Extracted from $CaCO_3$)	4,205278		
				Ca	*3,005483991*
				O (oxygen atom)	*1,199794008*
		MgO (9,5%)	5,18833		

				Mg	*3,128958133*
				O (oxygen atom)	*2,059371869*
		Na_2O (0,2%)	0,109228		
				Na_2	*0,08103103325*
				O (oxygen atom)	*0,02819696677*
		K_2O (0,5%)	0,27307		
				K_2	*0,2266886837*
				O (oxygen atom)	*0,04638131635*
		Li_2O (1,4%)	*0,764596*		
				Li_2	0,3551737778
				O (oxygen atom)	0,4094222222
		TiO_2 (0,13%)	0,0709982		
				Ti	*0,04255269605*
				O_2 (oxygen molecule)	*0,02844550394*
Sum (100%)	54,614	**Sum (99,83%)**	54,5211562	**Sum (99,83%)**	54,5211562

Table 7 The mass m [tonnes] of elements used in the fiberglass FR 29305443 per wind turbine

The molecules add up to 99,83% which means 0,17% of element(s) are missing and cannot be account for. The molecules written in black in the table above are the ones found in nature, or extract from other elements in nature, or produced through chemical reactions. The numbers written in black in the table above are the ones of interest in this master’s thesis.

Epoxy

To get the content of the Epoxy used to produce one wind turbine, the company Westlake Epoxy was contacted by e-mail, and the following drawing was provided to produce 23,406 tonnes (or 23.406 kg) Epoxy:

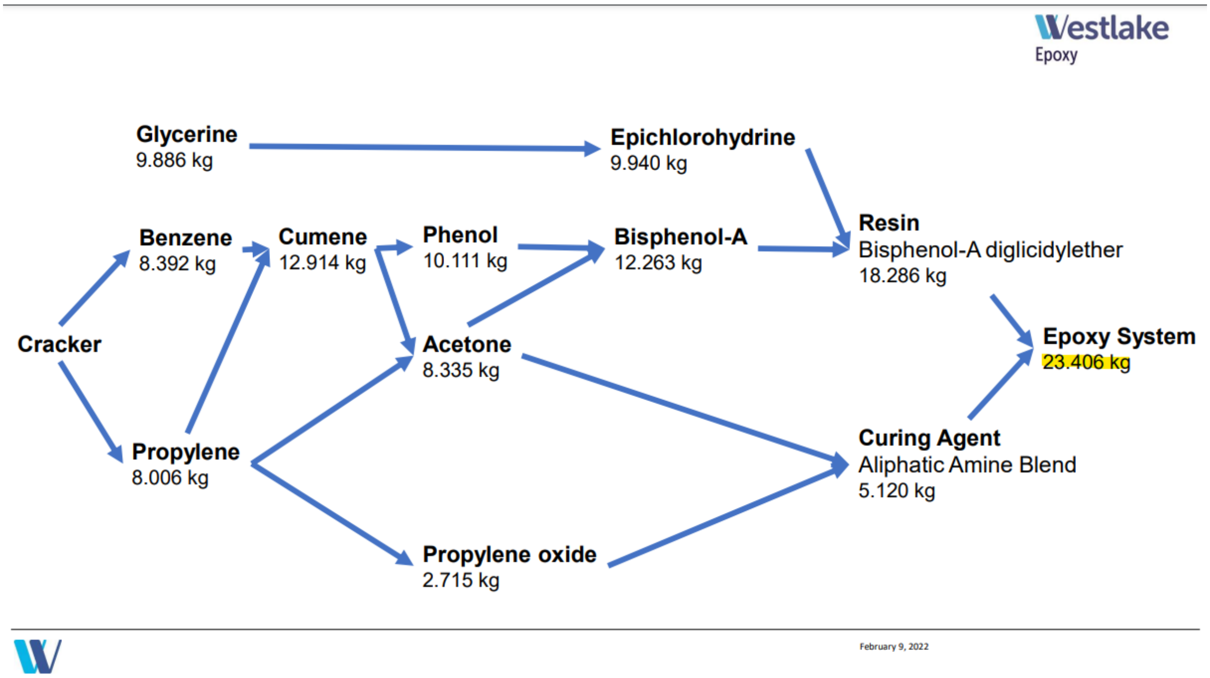


Figure 6 A drawing provided by Westlake Epoxy (personal communication, 09.02.22)

Figure 6 shows that the starting ingredients for making Epoxy are Glycerine (also called Glycerol ($C_3H_8O_3$ or $C_3H_5(OH)_3$)), Benzene (C_6H_6), and Propylene (C_3H_6 or $CH_3CH{=}CH_2$). And the ingredients to make 23.406 kg of Epoxy are 9.886 kg Glycerine, 9.392 kg Benzene, and 8.006 kg Propylene.

Cracker/cracking:
Cracking, in petroleum refining, is the process where heavy hydrocarbon molecules are broken up into lighter molecules by means of heat and usually pressure and sometimes catalysts. Cracking is the most important process for the commercial production of gasoline and diesel fuel (The Editors of Encyclopaedia Britannica, n.d).

Glycerine:
There are two kinds of glycerine, the natural one made from plant and/or animal fat, and the synthetic glycerine which is petroleum-based. In the Epoxy used in wind turbine production it is the synthetic glycerine that is used. A principal laboratory engineer at Equinor's refinery at Mongstad could tell that synthetic glycerine mainly is produced from propylene (also called propene) (personal communication, 15.02.22:

Crude Oil -> Ethane or Propane (steam cracker) -> Propylene -> Glycerine
Crude Oil -> C_2H_6 or C_3H_8 (steam cracker) -> C_3H_6 -> $C_3H_8O_3$

At Mongstad (a cracking plant) they use catalytic cracking to producing Refinery Grade Propylene (RGP) which got a purity of 70% propylene then the rest is basically propane. However, steam cracking is a more efficient way of producing Propylene, this is produced at petrochemical plants and the Propylene produced is called Polymer

Grade Propylene (PGP) which is 99,5% propylene and 0,5% propane (personal communication, 22.02.22 and 31.03.22)

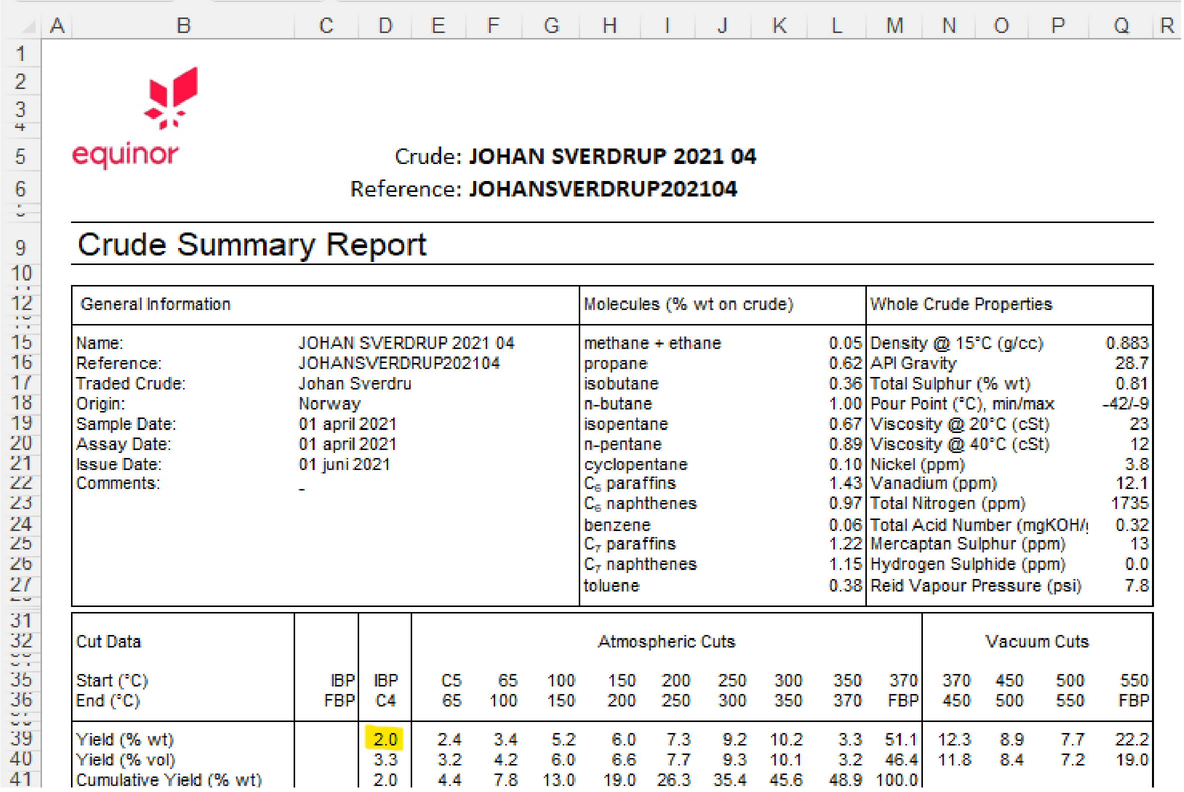
To get more information about the production of propylene an e-mail was sent to Chevron Philips Chemical Company LP where a speciality in chemicals, replied informing that propene can be produced from ethane and propane. He wrote (personal communication, 14.02.22):

> "*Roughly, for every 1 ton of ethane feed into a cracker will produce 0.1 tons of propylene. For every one ton of propane, you produce 0.4 tons of propylene. The range to produce glycerine is between 0.7 to 0.9 with the typical being 0.78. So, it takes 0.78 pounds of polymer grade propylene to produce one pound of glycerine.*"

The propylene calculations done in this master's thesis is based on the information provided above.

According to the chemical specialist about 1000 kg of ethane feed into a steam cracker will give around 100 kg of propylene, and about 1000 kg propane will give 400 kg propylene. Then the rang to produce glycerine is between 0,7 to 0,9 with the typical being 0,78. Meaning it takes 0,78 kg of Polymer Grade Propylene (PGP) to produce one kg of glycerine.

The different oil qualities contain different amount of benzene, propane, and butane, depending on how the conditions have been in the reservoir when the oil was formed and how it have been stored. This thesis will consider an oil sample taken from Johan Sverdrup 1st of April 2021 (see appendix 7.3 "Crude Summery Report" for the full content of the oil sample). According to the crude oil analyst specialist at Mongstad, who has provided the data for the Johan Sverdrup oil, the column called 'IBP C4' in the report (cell D39) shows the combination of propane and butane being 2,0 wt%, and the distribution, according to the specialist, is 0,6 wt% propane and 1,4 wt% butane (personal communication, 19.02.22:



equinor

Crude: **JOHAN SVERDRUP 2021 04**
Reference: **JOHANSVERDRUP202104**

Crude Summary Report

General Information		Molecules (% wt on crude)		Whole Crude Properties	
Name:	JOHAN SVERDRUP 2021 04	methane + ethane	0.05	Density @ 15°C (g/cc)	0.883
Reference:	JOHANSVERDRUP202104	propane	0.62	API Gravity	28.7
Traded Crude:	Johan Sverdru	isobutane	0.36	Total Sulphur (% wt)	0.81
Origin:	Norway	n-butane	1.00	Pour Point (°C), min/max	-42/-9
Sample Date:	01 april 2021	isopentane	0.67	Viscosity @ 20°C (cSt)	23
Assay Date:	01 april 2021	n-pentane	0.89	Viscosity @ 40°C (cSt)	12
Issue Date:	01 juni 2021	cyclopentane	0.10	Nickel (ppm)	3.8
Comments:	-	C_6 paraffins	1.43	Vanadium (ppm)	12.1
		C_6 naphthenes	0.97	Total Nitrogen (ppm)	1735
		benzene	0.06	Total Acid Number (mgKOH/	0.32
		C_7 paraffins	1.22	Mercaptan Sulphur (ppm)	13
		C_7 naphthenes	1.15	Hydrogen Sulphide (ppm)	0.0
		toluene	0.38	Reid Vapour Pressure (psi)	7.8

Cut Data			Atmospheric Cuts									Vacuum Cuts			
Start (°C)	IBP	IBP	C5	65	100	150	200	250	300	350	370	370	450	500	550
End (°C)	FBP	C4	65	100	150	200	250	300	350	370	FBP	450	500	550	FBP
Yield (% wt)		2.0	2.4	3.4	5.2	6.0	7.3	9.2	10.2	3.3	51.1	12.3	8.9	7.7	22.2
Yield (% vol)		3.3	3.2	4.2	6.0	6.6	7.7	9.3	10.1	3.2	46.4	11.8	8.4	7.2	19.0
Cumulative Yield (% wt)		2.0	4.4	7.8	13.0	19.0	26.3	35.4	45.6	48.9	100.0				

Table 8 Showing the wt% of propane and butane combined, in a Johan Sverdrup crude oil sample (personal communication, 16.02.22)

9.886 kg glycerine is needed to produce 23.406 kg Epoxy. It is given that 0,78 kg of PGP (99,5%) is needed to produce 1 kg glycerine:

0,78 PGP/glycerin * 9.886 kg glycerin = 7711,08 kg PGP

1000 kg propane -> 400 kg propylene (PGP): 1000 kg propane/400 kg PGP = 2,5 propane/PGP

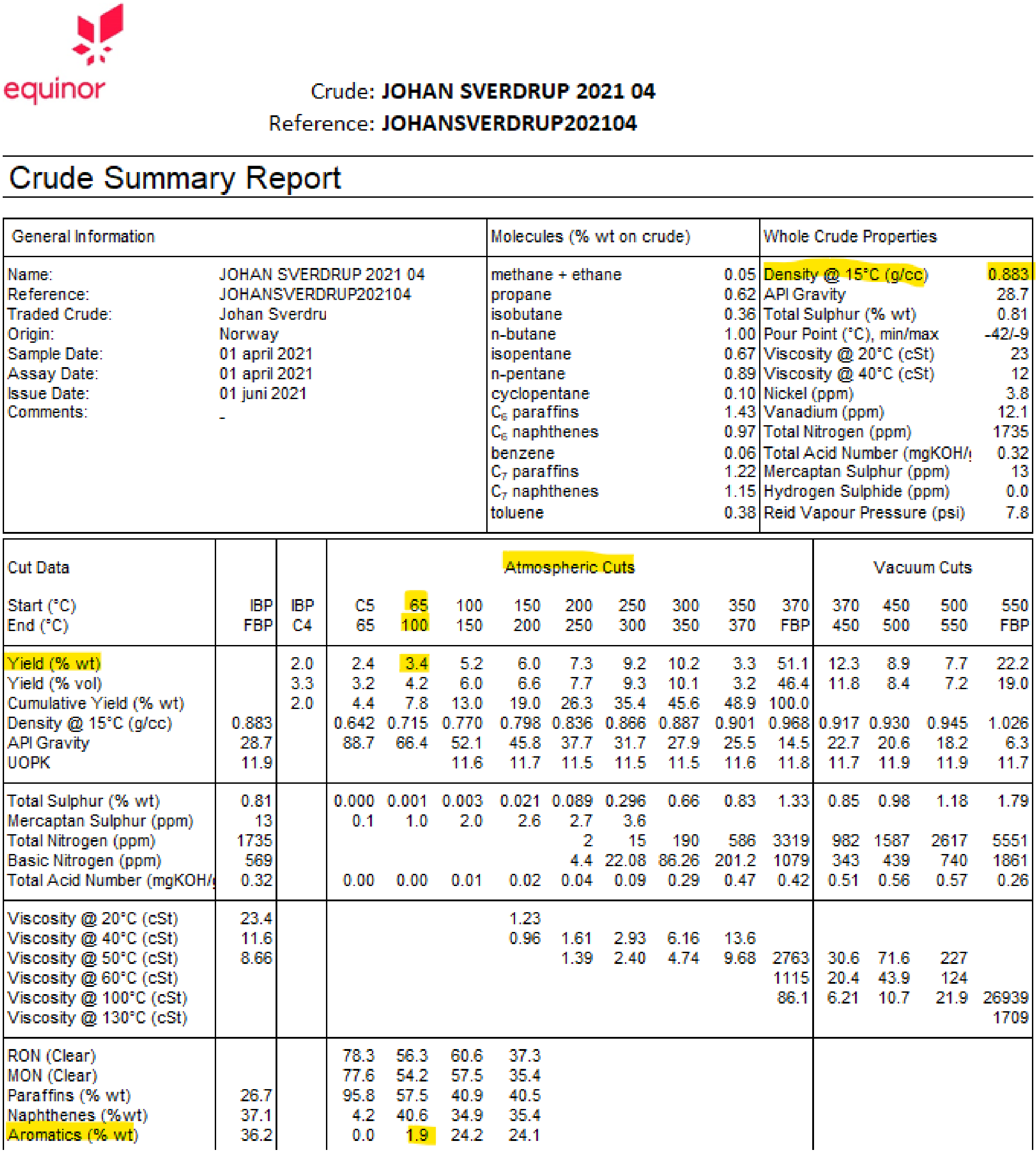
2,5 propane/PGP*7711,08 kg PGP = 19.277,7 kg propane

The sample of the Sverdrup crude oil got 0,6 wt% propane, how much crude oil is needed to get 19.277,7 kg propane: ($X_{\text{crude oil}}$*0,6)/100 = 19.277,7 kg -> $X_{\text{crude oil}}$ = (19.277,7*100)/0,6 = 3.212.950 kg crude oil

The amount of crude oil that is needed to produce 9.886 kg glycerine is 3.212.950 kg. The density of the Johan Sverdrup crude oil is 0,883 kg/l at 15°C (see Crude Summary Report cell Q15 above) = 1,132502831 l/kg, this gives 3.638.674,972 litre of crude oil which is equal to 22.886,62 barrels of oil (1 barrel = 158,987 litre).

Benzene:

Benzene is an aromatic found in crude oils and produced by oil refining. As mentioned above this master's thesis is considering a sample from Johan Sverdrup taken 1st of April 2021 (see appendix 7.3 “Crude Summery Report” for the full content of the oil sample):



equinor

Crude: **JOHAN SVERDRUP 2021 04**
Reference: **JOHANSVERDRUP202104**

Crude Summary Report

General Information		Molecules (% wt on crude)		Whole Crude Properties	
Name:	JOHAN SVERDRUP 2021 04	methane + ethane	0.05	Density @ 15°C (g/cc)	0.883
Reference:	JOHANSVERDRUP202104	propane	0.62	API Gravity	28.7
Traded Crude:	Johan Sverdru	isobutane	0.36	Total Sulphur (% wt)	0.81
Origin:	Norway	n-butane	1.00	Pour Point (°C), min/max	-42/-9
Sample Date:	01 april 2021	isopentane	0.67	Viscosity @ 20°C (cSt)	23
Assay Date:	01 april 2021	n-pentane	0.89	Viscosity @ 40°C (cSt)	12
Issue Date:	01 juni 2021	cyclopentane	0.10	Nickel (ppm)	3.8
Comments:	-	C_6 paraffins	1.43	Vanadium (ppm)	12.1
		C_6 naphthenes	0.97	Total Nitrogen (ppm)	1735
		benzene	0.06	Total Acid Number (mgKOH/	0.32
		C_7 paraffins	1.22	Mercaptan Sulphur (ppm)	13
		C_7 naphthenes	1.15	Hydrogen Sulphide (ppm)	0.0
		toluene	0.38	Reid Vapour Pressure (psi)	7.8

Cut Data			Atmospheric Cuts									Vacuum Cuts			
Start (°C)	IBP	IBP	C5	65	100	150	200	250	300	350	370	370	450	500	550
End (°C)	FBP	C4	65	100	150	200	250	300	350	370	FBP	450	500	550	FBP
Yield (% wt)		2.0	2.4	3.4	5.2	6.0	7.3	9.2	10.2	3.3	51.1	12.3	8.9	7.7	22.2
Yield (% vol)		3.3	3.2	4.2	6.0	6.6	7.7	9.3	10.1	3.2	46.4	11.8	8.4	7.2	19.0
Cumulative Yield (% wt)		2.0	4.4	7.8	13.0	19.0	26.3	35.4	45.6	48.9	100.0				
Density @ 15°C (g/cc)	0.883		0.642	0.715	0.770	0.798	0.836	0.866	0.887	0.901	0.968	0.917	0.930	0.945	1.026
API Gravity	28.7		88.7	66.4	52.1	45.8	37.7	31.7	27.9	25.5	14.5	22.7	20.6	18.2	6.3
UOPK	11.9				11.6	11.7	11.5	11.5	11.5	11.6	11.8	11.7	11.9	11.9	11.7
Total Sulphur (% wt)	0.81		0.000	0.001	0.003	0.021	0.089	0.296	0.66	0.83	1.33	0.85	0.98	1.18	1.79
Mercaptan Sulphur (ppm)	13		0.1	1.0	2.0	2.6	2.7	3.6							
Total Nitrogen (ppm)	1735						2	15	190	586	3319	982	1587	2617	5551
Basic Nitrogen (ppm)	569						4.4	22.08	86.26	201.2	1079	343	439	740	1861
Total Acid Number (mgKOH/	0.32		0.00	0.00	0.01	0.02	0.04	0.09	0.29	0.47	0.42	0.51	0.56	0.57	0.26
Viscosity @ 20°C (cSt)	23.4					1.23									
Viscosity @ 40°C (cSt)	11.6					0.96	1.61	2.93	6.16	13.6					
Viscosity @ 50°C (cSt)	8.66						1.39	2.40	4.74	9.68	2763	30.6	71.6	227	
Viscosity @ 60°C (cSt)											1115	20.4	43.9	124	
Viscosity @ 100°C (cSt)											86.1	6.21	10.7	21.9	26939
Viscosity @ 130°C (cSt)															1709
RON (Clear)			78.3	56.3	60.6	37.3									
MON (Clear)			77.6	54.2	57.5	35.4									
Paraffins (% wt)	26.7		95.8	57.5	40.9	40.5									
Naphthenes (%wt)	37.1		4.2	40.6	34.9	35.4									
Aromatics (% wt)	36.2		0.0	1.9	24.2	24.1									

Table 9 Shows the attributes used to calculate the benzene content in the Johan Sverdrup sample (personal communication, 16.02.22)

To calculate the wight percentage (wt%) of benzene in this crude oil sample found on Johan Sverdrup, the crude oil analyst specialist at Mongstad said to take the aromatics (wt%) content of the atmospheric cut 65°C -100°C (which is benzene) and multiply it with the weight fraction of the cut shown as yield (% wt) in the table, then you will get the benzene content of the crude oil sample (personal communication, 16.02.22).

(Aromatics (wt%) content of the atmospheric cut 65°C -100°C) * (Yield (% wt)) = 0,019 * 0,034 = 0,000646 * 100% = 0,0646 wt%

This means that the Johan Sverdrup crude oil sample contains 0,0646 wt% benzene.

In fig. 6 it shows that it's needed 9.392 kg benzene to produce 23.406 kg Epoxy, by adding this into the wt% formula ($m_{\text{crude oil}}$*wt%)/100 = m_{benzene} it gives: ($m_{\text{crude oil}}$*0,0646%)/100 = 9.392 kg which gives $m_{\text{crude oil}}$ = (9.392 kg/0,0646%) * 100%. The amount of crude oil that is needed to produce 9.392 kg benzene is 14.538.699,69 kg. The density of the Johan Sverdrup crude oil is 0,883 kg/l at 15°C, which gives 16.465.118,56 litre of oil which is equal to 103.562,67 barrels of oil (1 barrel = 158,987 litre).

Propylene:
The crude oil analyst specialist at Equinor's refinery at Mongstad says that propylene is not found in crude oil, but it is formed in so-called cracking. There are two types of cracking she says, catalytic cracking and steam cracking. At the refinery at Mongstad we have a catalytic cracker that makes petrol as the main product, and where propylene is a by-product. However, the most common way to make propylene is by steam cracking in a petrochemical plant. Raw materials used to make propylene can be ethane or propane, which are gasses, or it can be naphtha which is in liquid form (personal communication, 16.02.22).

8.006 kg propylene is used to produce 23.406 kg of Epoxy. It is not known if it is PGP or RGP that is used as the propylene in the Epoxy, so in this thesis it will be assumed PGP.

1000 kg propane -> 400 kg propylene: 1000 kg propane/400 kg PGP = 2,5 propane/PGP

2,5 propane/PGP*8.006 kg PGP = 20.015 kg propane

The sample of the Sverdrup oil got 0,6 wt% propane, how much crude oil is needed to get 20.015 kg propane: ($X_{\text{crude oil}}$*0,6)/100 = 20.015 kg -> $X_{\text{crude oil}}$ = (20.015*100)/0,6 = 3.335.833,333 kg crude oil

The amount of crude oil that is needed to produce 8.006 kg propylene is 3.335.833,333 kg. The density of the Johan Sverdrup crude oil is 0,883 kg/l at 15°C = 1,132502831 l/kg, which then gives 3.777.840,694 litre of oil which is equal to 23.761,947 barrels of oil (1 barrel = 158,987 litre).

Table 10 below shows the total amount of Johan Sverdrup crude oil needed to produce glycerine, benzene, and propylene:

Products	**Crude oil [tonnes]**	**Crude oil [litre]**	**Crude oil [barrels]**
Glycerine (9.886 kg)	3.212,95	3.638.674,972	22.886,62
Benzene (9.392 kg)	**14.538,69969**	**16.465.118,56**	**103.562,67**
Propylene (8.006 kg)	3.335,833333	3.777.840,694	23.761,947
Sum	21.087,48302	23.881.634,226	150.211,237

Table 10 Crude oil from Johan Sverdrup needed to produce glycerine, benzene, and propylene.

However, the table above do not give the correct picture of how much crude oil from Johan Sverdrup is needed to produce 23.406 kg of Epoxy. There is no need for 150.211 barrels of crude oil from Johan Sverdrup to produce 23.406 kg of Epoxy because different parts/organic chemical compounds of the oil are used. To produce glycerine and propylene, propane is extracted from the oil, while producing benzene it is benzene that is extracted from the oil, meaning that the same oil can be used to extract both these organic chemical compounds (propane and benzene). From table 10 it shows that a total of 6.549 tonnes (3.212,95 + 3.335,83) of crude oil is needed to get enough propane to produce glycerine and propylene, while 14.539 tonnes is needed for benzene. This means that the crude oil needed to produce benzene will also be enough to produce the propane needed, and therefore 14.539 tonnes of crude oil from Johan Sverdrup is needed to produce 23.406 kg of Epoxy.

Another important thing to notice is that it is only 0,6wt% of this oil that is propane and 0,0646 wt% that is benzene, the rest of the oil is of a different organic compound used for other productions.

There are more products included when producing Epoxy, but this thesis has not gone into more details regarding the Epoxy production, as it seems that crude oil is the main raw material in Epoxy.

Electric Steel

In the search for electric steel used in the wind turbine production the company Tata Steel was contacted by e-mail, a technical manager from the company replied with the following (personal communication, 03.02.22):

> *"Exactly which electrical steel grade which is used in the generator for a wind turbine varies. My guess is that the average is something like the following: Si 2,4 %, Al 0.4 %, Mn 0,2 % (everything in weight-%). Other elements are at very low levels, say total together for all other elements <0.3%. In most cases these elements are unwanted impurities. Some like C, S, N, O, Ti, Nb needs to be at very low levels (typically < 0.005% per element) which makes the requirement on the steel making rather demanding."*

In a research article from the University library called “Effect of primary grain size and nitrogen content on the magnetic properties of a grain-oriented electrical steel obtained by Steckel Mill” (Silveira, Landgraf, & Paolinelli, 2020) the following table showing chemical composition of electrical steel was found:

Si%	**Al%**	**Mn%**	**S%**	**Cu%**	**N(ppm)**	**Cu(ppm)**
3,0-3,3	0,027-0,035	0,12-0,22	0,003-0,009	0,2-0,3	50-100	450-650

Table 11 Electrical Steel chemical composition (Silveira et al., 2020)

In the above table ppm is an abbreviation for “parts per million”: 1 ppm = 1/1 000 000 = 0,001‰ = 1 mg/kg.
In this thesis an average value of the numbers given in table 11 will be used as the content of the electrical steel: a = $(x_1+x_2)/2$, example a_{Si} = (3,0%+3,3%)/2 = <u>3,15%</u>, where the remaining element is Iron (Fe). This gives the following assumed composition of the electrical steel used: 3,15% Si; 0,031% Al; 0,17% Mn; 0,006% S; 0,25% Cu; 0,000075% N; 0,0011% C, which means that the remaining 96,391825% is Fe.

The below table shows how much of each element it is in 15,604 tonnes (tbl.3) of electric steel used in one wind turbine:

Electrical Steel	**Mass [tonnes]**	**Element**	**Mass [tonnes]**
Electric Steel	15,604 (tbl. 3)		
		Fe (96,391825%)	15,04098037
		Si (3,15%)	0,491526
		Cu (0,25%)	0,03901
		Mn (0,17%)	0,0265268
		Al (0,031%)	0,00483724
		S (0,006)	0,00093624
		C (0,0011%)	0,000171644
		N (0,000075%)	0,000011703
Sum (100%)	15,604	**Sum (100%)**	15,604

Table 12 The mass m [tonnes] of elements used in electrical steel per wind turbine

Polyethylene (PE) and Polypropylene (PP)

<u>Polyethylene (PE)</u>

Polyethylene (PE) is a thermoplastic polymer which is a synthetic material that originally derive from organic products such as crude oil. The crude oil analyst specialist at Equinor’s refinery at Mongstad has provided me with the following information (personal communication, 30.03.22):

> *“Add the weight fractions from the cuts C5-65, 65-100, and 100-150 in the Crude Summary Report for Johan Sverdrup* (tbl. 14)*, this makes up the Full Range Naphtha (FR Naphtha), the raw material for plastic production. Then use the below table* (tbl. 13) *which shows that out of 1 kg FR Naphtha you get 0,304 kg ethylene and 0,129 kg propylene. You get approximately 99% PE*

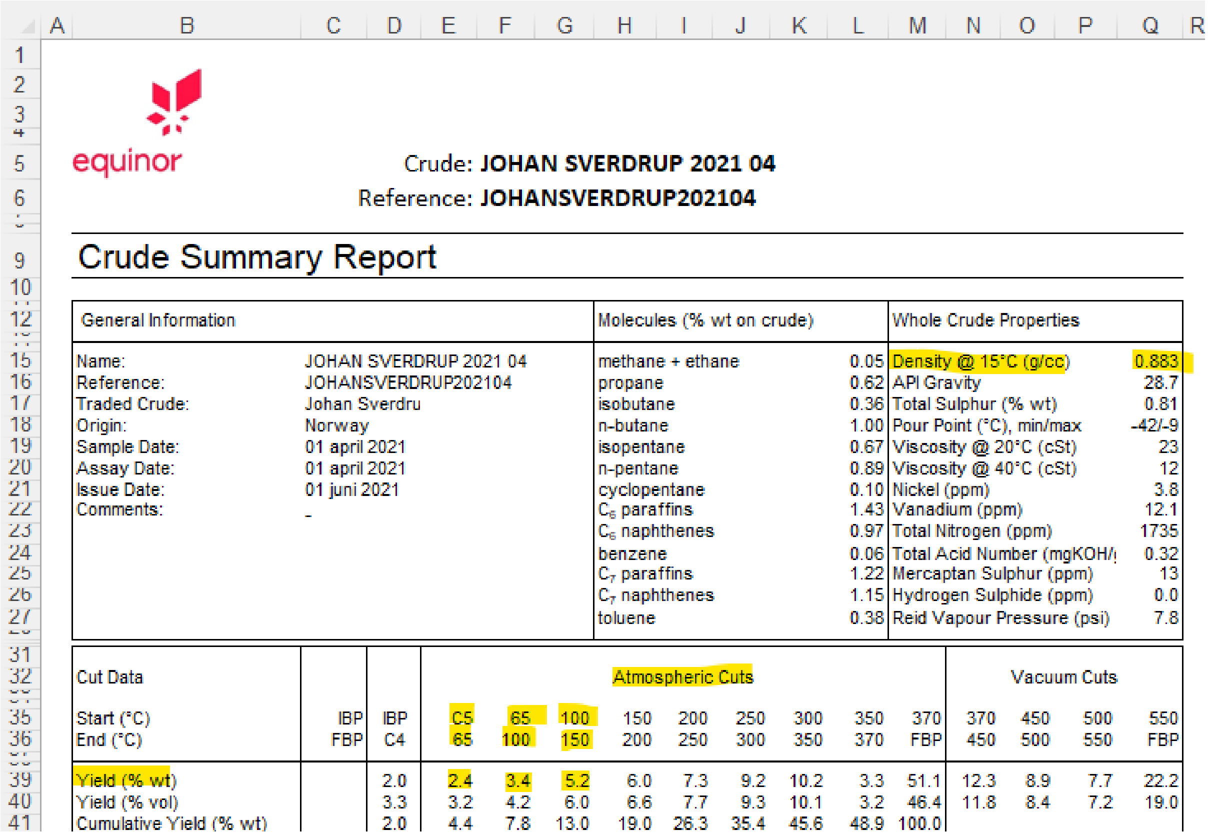
from ethylene and the same for PP from propylene. Based on this you should be able to calculate the number of kg of oil needed to make PE and PP. You can count on this being the same oil you need for propane and benzene production. You possibly subtract the amount of benzene in the 65-100 cut.

To calculate from kg oil to litres, use Density in cell Q15, which is in kg/l."

Table 13 below shows a typical yield data for four different raw materials, which is not specific to the Johan Sverdrup sample, but data in general/typical.

Feedstock	**Ethane wt% dry**	**Propane wt% dry**	**Butane wt% dry**	**FR Naphtha wt% dry**
Hydrogen	1,6	1,1	0,8	1,0
Methane	27,9	22,8	14,5	16,9
Ethylene	44,8	43,5	30,2	**30,4**
Propylene	15,8	15,2	14,2	**12,9**
Propane	0,4	0,7	0,8	0,7
Butadiene	2,9	3,7	4,9	4,6
Raffinate-1	1,1	5,7	4,1	3,5
Pygas	4,8	6,4	21,5	22,8
Fuel oil	0,7	0,9	9,0	7,2
Total	**100**	**100**	**100**	**100**

Table 13 wt% raw material from different feedstocks (personal communication, 30.03.22)



equinor

Crude: **JOHAN SVERDRUP 2021 04**
Reference: **JOHANSVERDRUP202104**

Crude Summary Report

General Information		Molecules (% wt on crude)		Whole Crude Properties	
Name:	JOHAN SVERDRUP 2021 04	methane + ethane	0.05	Density @ 15°C (g/cc)	0.883
Reference:	JOHANSVERDRUP202104	propane	0.62	API Gravity	28.7
Traded Crude:	Johan Sverdru	isobutane	0.36	Total Sulphur (% wt)	0.81
Origin:	Norway	n-butane	1.00	Pour Point (°C), min/max	-42/-9
Sample Date:	01 april 2021	isopentane	0.67	Viscosity @ 20°C (cSt)	23
Assay Date:	01 april 2021	n-pentane	0.89	Viscosity @ 40°C (cSt)	12
Issue Date:	01 juni 2021	cyclopentane	0.10	Nickel (ppm)	3.8
Comments:	-	C_6 paraffins	1.43	Vanadium (ppm)	12.1
		C_6 naphthenes	0.97	Total Nitrogen (ppm)	1735
		benzene	0.06	Total Acid Number (mgKOH/	0.32
		C_7 paraffins	1.22	Mercaptan Sulphur (ppm)	13
		C_7 naphthenes	1.15	Hydrogen Sulphide (ppm)	0.0
		toluene	0.38	Reid Vapour Pressure (psi)	7.8

Cut Data			Atmospheric Cuts									Vacuum Cuts			
Start (°C)	IBP	IBP	C5	65	100	150	200	250	300	350	370	370	450	500	550
End (°C)	FBP	C4	65	100	150	200	250	300	350	370	FBP	450	500	550	FBP
Yield (% wt)		2.0	2.4	3.4	5.2	6.0	7.3	9.2	10.2	3.3	51.1	12.3	8.9	7.7	22.2
Yield (% vol)		3.3	3.2	4.2	6.0	6.6	7.7	9.3	10.1	3.2	46.4	11.8	8.4	7.2	19.0
Cumulative Yield (% wt)		2.0	4.4	7.8	13.0	19.0	26.3	35.4	45.6	48.9	100.0				

Table 14 The attributes used to make up the full range (FR) Naphtha in the Johan Sverdrup sample (personal communication, (personal communication, 16.02.22)

When adding the weight fractions from the atmospheric cuts C5-65, 65-100, and 100-150 it gives 2,4 wt% + 3,4 wt% + 5,2 wt% = 11 wt%. With this information the following calculations can be done:

Crude oil (11%) -> FR Naphtha (30,4%) -> Ethylene (99%) -> PE

According to information given 3.900 kg PE is needed to produce one wind turbine, and since you can count on getting 99% PE out of the ethylene it is needed:

(X_{ethylene}*99%)/100% = 3900 kg PE -> X_{ethylene} = (3.900 kg*100)/99 = 3.939,393 kg

FR Naphtha gives 30,4% ethylene. It is needed 3.939,393 kg ethylene:

($X_{\text{FR Naphtha}}$*30,4%)/100% = 3.939,393 kg -> $X_{\text{FR Naphtha}}$ = (3.939,393 kg*100)/30,4 = 12.958,53 kg

Out of the Johan Sverdrup crude oil sample it gets 11% FR Naphtha:

($X_{\text{Crude oil}}$*11%)/100% = 12.958,53 kg -> $X_{\text{Crude oil}}$ = (12.958,53 kg*100)/11 = 117.804,82 kg Crude oil = 117,80 tonnes crude oil

The density of the crude oil is 0,883 kg/l, which makes 117.804,82 kg crude oil equal to 133.414,29 litre of crude oil, which is 839,15 barrels of crude oil.

Polypropylene (PP)

For the plastic polypropylene the same information as given above can be used. The following calculation is done:

Crude oil (11%) -> FR Naphtha (12,9%) -> Propylene (99%) -> PP

According to information given 3900 kg PP is needed to produce one wind turbine, and since you can count on getting 99% PP out of the propylene it is needed:

($X_{\text{propylene}}$*99%)/100% = 3900 kg PE -> $X_{\text{propylene}}$ = (3.900 kg*100)/99 = 3.939,393 kg

FR Naphtha gives 12,9% propylene. It is needed 3.939,393 kg propylene:

($X_{\text{FR Naphtha}}$*12,9%)/100% = 3.939,393 kg -> XFR Naphtha = (3.939,393 kg*100)/12,9 = 30.537,93 kg

Out of the Johan Sverdrup crude oil sample it gets 11% FR Naphtha:

($X_{\text{Crude oil}}$*11%)/100% = 30.537,93 kg -> $X_{\text{Crude oil}}$ = (30.537,93 kg*100)/11 = 277.617,55 kg Crude oil = 277,62 tonnes crude oil

The density of the crude oil is 0,883 kg/l, which makes 277.617,55 kg crude oil equal to 314.402,66 litre of crude oil, which is 1.977,54 barrels of crude oil.

Since PE is using ethylene and PP is using propylene, which are two different materials extracted from the FR Naphtha, it can be assumed that the same FR Naphtha is used to produce PE and PP, which also means the same crude oil. In other words, 277.617,55 kg Crude oil is needed to get 3900 kg PE and 3900 kg PP.

Note that samples from other oil fields will contain more FR Naphtha than Johan Sverdrup, examples like the Åsgard field has shown 40% FR Naphtha and Gullfaks 22% (personal communication, 31.03.22), which means that calculating the crude oil used for PE and PP using any of these samples, would result in less use of crude oil.

Polyurethane (PU)

It has not been possible to obtain information related to the production of Polyurethane. Information received is that PU contains benzene, nitrogen (N), and some alcohols (OH), but no information about how much of each have been found. The only thing that is known is that crude oil is used to produce polyurethane.

NdFeB magnet

In table 3 it shows that 1,560 tonnes of Neodymium Iron Boron (NdFeB) magnet are used in SGRE’s wind turbines. On e-Magnets UK / Bunting’s Web page (e-magnets uk, n.d.) the following table can be found regarding the NdFeB magnet:

Typical composition of NdFeB alloy

Main elements within NdFeB	Percentage by weight (wt%)
Neodymium (Nd)	29-32
Iron (Fe)	64,2-68,5
Boron (B)	1,0-1,2
Aluminium (Al)	0,2-0,4
Niobium (Nb)	0,5-1
Dysprosium (Dy)	0,8-1.2

Table 15 Typical composition of NdFeB (e-magnets uk, n.d.)

They also write the following about the NdFeB magnet:

> “*The exact chemical composition within NdFeB depends on the grade of NdFeB. Dysprosium and Praseodymium are added as a replacement for some of the Neodymium to improve the corrosion resistance and to improve the Hci (Intrinsic coercivity) of the “Neo”*”

The company BUNTING-Berkhamsted, experts in the design and manufacture of permanent magnets, was contacted to get some more details around their production of NdFeB magnet. The company provided a link with information (Venkatesan, n.d.).

The link provided the following table related to the content of the NdFeB magnet in wt%:

Elemental composition of NdFeB magnets in wt%

Element	Content (wt%)	Element	Content (wt%)
Fe	63,54	Gd	0,15
Nd	22,21	Al	0,09
Dy	8,19	Cu	0,07
Co	2,99	Nb	0,06
B	1	Ni	0,04
Pr	0,76	**Total**	**99,1**

Table 16 Elemental composition of NdFeB magnets in wt% (Venkatesan, n.d.)

The mass in tonnes of each element from table 16 for the total of 1,560 tonnes of NdFeB used in one wind turbine, has been calculated in the below table:

Magnet	Mass [tonnes]	Element	Mass [tonnes]
NdFeB	1,560		
		Fe (63,54%)	0,991224
		Nd (22,21%)	0,346476
		Dy (8,19%)	0,127764
		Co (2,99%)	0,046644
		B (1%)	0,0156
		Pr (0,76%)	0,0118556
		Gd (0,15%)	0,00234
		Al (0,09%)	0,001404
		Cu (0,07%)	0,001092
		Nb (0,06%)	0,000936
		Ni (0,04%)	0,000624
Sum (100%)	1,560	**Sum (99,1%)**	1,5459596

Table 17 The mass of each element used in 1,560 tonnes of NdFeB

The sum of elements used in NdFeB add up to 99,1%, the remaining 0,9% cannot be accounted for. From the above elements in the table the following elements are REEs: neodymium (Nd), dysprosium (Dy), praseodymium (Pr), and gadolinium (Gd).

Miscellaneous (9,362 tonnes)

It has not been possible to go into more details regarding the products and raw materials that lies under miscellaneous, nor the quantity of it, as SGRE could not provide more details about it. The only information received is that products and raw materials like polycarbonate, brass ABS, REE, oils, silicone, paint, and cooling liquids are among the products that lies under this category.

4.2. Material overview

Table 18 below is a summary of all the raw materials, calculated in section 4.1, that are used in the producing of one wind turbine. The calculations have been converted from tonnes to kilograms, and the results have been rounded to two decimal places, with comma (,) separating the decimal numbers. The elements written with a brown colour are REEs.

Material/ Element/ Metal	**Mass [kg]**	**Steel (S355J2 /S355K2) [kg]**	**Fiberglass [kg]**	**Epoxy [kg]**	**Electric Steel [kg]**	**NdFeB magnet [kg]**	**Polyethylene Polypropylene Polyurethane [kg]**	**Total of each material [kg]**
Iron cast (Fe)	93.623	507.309,47			15.040,98	991,22		**616.964,67**
Copper (Cu)	15.604	2.875,02			39,01	1,09		**18.519,12**
Aluminium oxide / alumina (Al_2O_3)			10.868,19					**10.868,19**
Aluminium (Al) (From Al_2O_3)	7.802				4,84	1,40		**7.808,24**
Balsa Wood	1.560							**1.560**
Plywood	1.560							**1.560**
Carbon (C)		1.045,46			0,17			**1.045,63**
Silicon dioxide / Silica (SiO_2)			33.041,47					**33.041,47**
Silicon (Si) (From SiO_2)		2.875,02			491,53			**3.366,55**
Manganese (Mn)		8.363,68			26,53			**8.390,21**
Phosphorus (P)		130,68						**130,68**
Sulphur (S)		130,68			0,94			**131,62**
Neodymium (Nd)						346,48		**346,48**
Boron (B)						15,60		**15,60**
Niobium (Nb)						0,94		**0,94**
Dysprosium (Dy)						127,76		**127,76**
Calcium oxide (CaO) (From $CaCO_3$)			4.205,28					**4.205,28**
Magnesium oxide (MgO)			5.188,33					**5.188,33**
Cobalt (Co)						46,64		**46,64**
Sodium oxide (Na_2O)			109,23					**109,23**
Potassium oxide (K_2O)			273,07					**273,07**
Lithium (Li)			355,17					**355,17**
Oxygen (O)			409,42					**409,42**
Titanium dioxide (TiO_2)			71					**71**
Praseodymium (Pr)						11,86		**11,86**

Gadolinium (Gd)						2,34		**2,34**
Nickel (Ni)						0,62		**0,62**
Nitrogen (N)					0,01			**0,01**
Crude oil				14.538.699,69			277.617,55	**14.816.317,24**
Miscellaneous	9.362							**9.362**
Total [kg]		522.730,01	54.521,16	14.538.699,69	15.604,01	1.545,95	277.617,55	

Table 18 An overview of the raw materials used in the production of one wind turbine

4.3. The annual production of Elements

All the elements and organic chemical compound listed in table 18 above are materials that are found naturally on Earth on in the Earth's crust, either by mining for it or drilling for it. For most of these elements it only exists a certain amount, which can be used in our productions, after that it will be empty. In this section it will be looked at how much of the yearly production of these natural material provided by the Earth is used to produce the Hywind Tampen wind turbines, and how much has been estimated that is there to be used.

Iron (Fe)

Iron is classified as a metal in the periodic table of elements, and it is believed to be the most abundant element on Earth. It is one of the most useful metal elements and do not exist independently, but in the form of oxides below the earth's surface. These oxides are called iron ore and are found in many volcanic rocks. Iron ore makes up almost 5% of the earth's crust, and when looking at both the crust and the inner core, iron and its ore makes up about 35% of the earth's mass. Iron is extracted from the ore by removal of oxygen, which is a process called reduction. Another process is through a blast furnace where the ore is heated with carbon (coke) (Strephonsays, n.d.).

According to data from the U.S. Geological Survey (Tuck, 2021, p. 2) the total worldwide production of iron ore in 2020 was around 2,4 billion tonnes, which contented 1,5 billion tonnes iron. The world resources are estimated to be greater than 800 billion tonnes of crude ore containing more than 230 billion tonnes of iron. If assuming that today's iron reserves are 230 billion tonnes and it continues to be produced 1,5 billion tonnes of iron each year, then we have about 153 years left with iron before it is empty. The top five mining countries are Australia, Brazil, China, India, and Russia.

From table 18 it shows that it takes around 616.965 kg iron to produce one wind turbine for the Hywind Tampen wind farm, and if we multiply this with 11, which is the number of wind turbines in the farm, the total quantity of iron needed for the wind farm is 6.786.615 kg (6.786,615 tonnes). This turns out to be around 0,00045% of the worlds annual production.

Copper (Cu)

Copper is a reddish, stabile, and not very reactive metal that is easy to process. It has very good electrical conductivity and is widely used in cables and wires. There is not much copper in the earth's crust (only around 68 ppm), but many copper-containing ores are known. The most common is copper(I)iron(III)sulfide $CuFeS_2$. The trivial name is copper pyrite or chalcopyrite (Pedersen, n.d.).

The world mine production of copper in 2021 was 21 million tonnes, with Chile as the world leading copper provider. Then Peru, China, Democratic Republic of the Congo, and USA are the next countries on the list. When it comes to the worlds copper reserves Chile also had the largest global copper reserves with 200 million tonnes. Worldwide it has been estimated to be around 880 million tonnes of copper reserves globally in 2021 (U.S. Geological Survey, 2022c, p. 55). If assumed the world's annual mine production of 21 million tonnes of copper continues, the Earth's copper resources will be empty after approximately 42 years, around year 2064.

In table 18 it has been given that 18.519 kg copper is used in one wind turbine, if this is multiplied with the number of wind turbines in the farm, 11, then 203.709 kg of copper is used for the farm (this is only copper used in the wind turbine and not including the cables on the seabed transporting the electricity to the rigs). This means that $9,7 \cdot 10^{-4}$ % of the annual production is used to produce the Hywind Tampen wind park.

Aluminium (Al) and alumina (Al_2O_3)

Aluminium (Al) is the third most abundant element in the Earth's crust, after oxygen and silicon, where it makes up 8,2% of the earth's crust, and it is classified as a metal in the periodic table of elements. In nature, aluminium occurs only as Al_{3+} in silicates and as alumina (Al_2O_3) or hydroxide in some minerals (Pedersen, n.d). Aluminium (Al) is a chemical element, while alumina is a chemical compound having the chemical formula Al_2O_3. The production of primary aluminium metal begins with bauxite ore ($Al_2H_2O_4$), which is composed of hydrated aluminium oxide mixed with silica and iron oxide (Government of Canada, 2022). The production of aluminium (Al) starts with the raw material bauxite, a clay like soil type found in a belt around the equator. The bauxite is mined from a few meters below the ground. The clay is washed of the bauxite before it passes through a grinder. Then the alumina is extracted from the bauxite through refining by using a hot solution of caustic soda and lime. The mixture is heated and filtered, and the remining alumina is dried to a white powder. The next stop is the metal plant, where the refined alumina is transformed into aluminium using electricity (Hydro, 2022). It takes approximately 4 to 5 tonnes of bauxite ore to produce 2 tonnes of alumina (Al_2O_3). Then it takes approximately 2 tonnes of alumina to produce 1 tonne of aluminium (Al) (Government of Canada, 2022).

In 2020 the world's primary aluminium (Al) production was estimated to have been 65,26 million tonnes, where China was the largest producer with 37 million tonnes, followed by India, Russia, and Canada. Norway was number 8th on the list with 1,4 million tonnes. The world's production of alumina (Al_2O_3), this year, was 136,76 million tonnes (Government of Canada, 2022).

The world's reserves of bauxite ore were 29,7 billion tonnes in 2020, with Guinea, Australia, and Vietnam as the leading reserves countries (Government of Canada, 2022). If considering it takes 5 tonnes of bauxite ore to produce 2 tonnes of alumina, 29,7 billion tonnes of bauxite will result in 11,88 billion tonnes of alumina (Al_2O_3). And if it takes 2 tonnes of alumina (Al_2O_3) to produce 1 tonne of aluminium (Al), then 11,88 billion tonnes of alumina will give 5,94 billion tonnes of aluminium (Al), which will be the world's reserves. In other words, if continuing producing 65,26 million tonnes of aluminium annually the reserves will be empty in about 90 years (91 years in 2020).

According to table 18 10.868 kg (10,868 tonnes) of alumina (Al_2O_3) and 7.808 kg (7,808 tonnes) aluminium (Al) was used in the production of one wind turbine. To be able to sum these two numbers into one, the quantity of aluminium (Al) will be converted into alumina (Al_2O_3) by using the information provided above saying 2 tonnes of alumina (Al_2O_3) give 1 tonnes of aluminium (Al). 7,808 tonnes of aluminium (Al) are then equal to 15,616 tonnes of alumina (Al_2O_3), which means that 10,868 tonnes of alumina + 15,616 tonnes of alumina gives a total of 26,484 tonnes of alumina (Al_2O_3) has been used in the production of one wind turbine. Considering the 11 wind turbines in the farm, it is needed 291,324 tonnes of alumina to set up the wind farm. This means that if considering an annual alumina (Al_2O_3) production of 136,76 million tonnes, 0,000213% went to the Hywind Tampen wind farm.

Balsa Wood (Ochroma pyramidale)

As already mentioned in chapter 2 balsa trees grow naturally in the humid rainforest of Central and South America as well as in tropical seasonal thorn forests there. Balsa trees grow very rapidly. Six months after germination, the stem is already about 3 cm in diameter and 3-4 meter tall. In 6 to 10 years, it is ready for cutting, having reached a height of 20-28 meters and a diameter breast height. The author has not succeeded in finding any data on how much balsa wood is harvested every year, so an analyse on balsa wood used in the wind turbine production compared with the annual harvest has not been possible. However, information related to sustainability and harvesting problems have been found and will be discussed later in this master's thesis.

Plywood

Plywood is not a wood or tree type, but a building material consisting of thin wood layers or piles (veneers) bonded with an adhesive. There are two types of plywood:

softwood plywood and hardwood plywood. Softwoods generally correspond to coniferous species, and the most used softwoods for manufacturing plywood are firs and pines. Hardwood generally corresponds to deciduous species like oak, poplar, maple, cherry, and larch. For this master's thesis it is not known if softwood-, or hardwood plywood is used, nor what kind of wood, so making an analysis of the plywood used compared to the annual harvest of the wood will not be possible.

Carbon (C)

Carbon is a non-metal element, found in the Earth's crust or as hydrocarbons found in crude oil and natural gas. Carbone is dissolved in many metals in the solid state, such as iron like in this thesis where it is a part of the alloys steel and electrical steel. Carbone is used in the form of coal and coke to produce metals such as iron, copper lead, zinc, etc, by reducing the respective oxides. It occurs in nature as diamonds, graphite, and coal of various kinds (anthracite, coal, lignite). In petroleum (crude oil and natural gas), carbon is chemically bound, mainly with hydrogen. Petroleum and coal are formed by plants and marine animals by slow decay and heating without air supply. In total, carbon makes up 0,032% by wight of the Earth's crust (Pedersen, 2019). There are 1,85 billion, billion tonnes ($1{,}85 \cdot 10^{18}$ tonnes) of carbon on Earth, with more than 99% of it resident beneath our feet. On Earth, most carbon is stored in rocks and sediments, while the rest is in the ocean, atmosphere, and in living organisms. The Earth's crust along with its outer layers contain about 10^{20} kg of carbon (FAQ-ANS, 2021).

The carbon used in steel is there due to the manufacturing of iron (Fe). Most of the iron produced in the world is produced by reducing iron oxides with carbon and carbon monoxide (CO). The ore Fe_2O_3 and/or Fe_3O_4, coke and slag-forming oxides such as CaO or SiO_2 are used. The iron produced has a carbon content of 3-4%, and this iron is very hard and brittle. To obtain a steel that can be rolled, the carbon content must be reduced to less than 2% (Kjemisk institutt UiO, n.d.-b).

Coke is produced from coal by heating coal at high temperatures for a long period of time. The total world proved recoverable reserves of coal by December 31, 2020, were about 1.156 billion (or 1,16 trillion) short tons (1 tonne = 1,1023 short tons), which equals to about 1.049 billion tonnes (U.S. Energy Information Administration, 2021). In 2021 the global coal production was 853 Mt which is equal to 853 million tonnes (iea, 2022).

From table 18 it shows that 1.046 kg of carbon, in terms of coke produced by coal, is used in the production of steel and electric steel for the manufacturing of one wind turbine. Considering the 11 wind turbines in the farm it gives a total of 11.506 kg of carbon. Out of the global coal production in 2021 these 11.506 kg of coal would be $1{,}35 \cdot 10^{-6}$ % of that annual production, in other words very small. In this calculation it is assumed that 1 kg coal makes 1 kg coke, but the truth is probably that you will get less coke from the coal, and therefore it will properly be used a bit more coal than estimated in this calculation. Considering the numbers found related to the annual production and estimated world reserves it will take around 1230 years before it is empty assuming the production is constant.

Silica (SiO_2) and Silicon (Si)

Next after oxygen, silicon (Si) is the element that is most abundant. In total, oxygen and silicon make up about three quarters (3/4) of the inorganic part of the Earth's crust. Silicon (Si) is a semi-metal chemical element in the carbon family, and it is not in a free state in nature (or rarely found alone in nature) but bounded to oxygen in silicate (SiO_2) minerals. Silica (SiO_2) occurs as sand, quartz, rock crystal, amethyst, and more, and silicon (Si) is produced from silica (SiO_2) in compact form by reducing quartz with coal (carbon) at 1700°C (Kofstad & Pedersen, 2019a).

The global silicon (Si) production amounted to an estimated total of 8,5 million tonnes in 2021, and according to the report from U.S. Geological Survey from 2022 (U.S. Geological Survey, 2022c, p. 151) the silica reserves in most major producing countries are ample in relation to demand, but quantitative estimates are not available. It's said that there's zero danger of ever running short of silicon, and that it would be more likely to run out of the energy needed to refine silicon from silica than to run out of silicon itself. However, Earth Magazine says that more than 25% of the Earth crust by weight is silicon and in a documentation written by ADS (Astrophysics Data System) it is mentioned that the total mass of the Earth's crust (oceanic + continental) is $2,77*10^{22}$ kg (Peterson & Depaolo, 2007) which would mean that 6,925 billion, billion ($6,925*10^{18}$) tonnes of the Earth's crust is silicon (Si). If considering the numbers and the calculation done here is close to correct, and the annual silicon production remains constant it will take about 815 billion years before all the silicon in the Earth's crust has been consumed, so it should be fair to say that there is unlimited of silicon to be used.

According to table 18 33.041 kg silica (SiO_2) and 3.367 kg of silicon (Si) are used to produce one wind turbine. According to the web page Sciencing (Merry, 2017) silica (SiO_2) contains 46,69% silicon (Si) by weight. By using this percent, the 33.041 kg of silica (SiO_2) contains 15.427 kg of silicon (Si), which gives a total of 18.794 kg of silicon (Si) used in one wind turbine. For the whole farm it will add up to 206.732 kg of silicon (Si) used. With an annual production of 8,5 million tonnes $2,43*10^{-3}$ % are used for the Hywind farm park.

Manganese (Mn)

Manganese (Mn) is the most common d-metal (partially filled d-shell) in the Earth's crust after iron. Since the metal is reactive, it exists in nature only in the form of chemical compounds. Important manganese ores are oxides or oxide hydroxides

(Kofstad & Pedersen, 2018). The most important deposits for manganese are the minerals pyrolusite (MnO_2) which is also called brownstone, and rhodochrosite ($MnCO_3$). In additional, there are minerals such as psilomelane (barium-containing MnO_2), cryptomelane (potassium-containing MnO_2), and manganite ($MnO(OH)$) (Kjemisk institutt UiO, n.d.-e).

The global production of manganese in 2021 was estimated to be 20 million tonnes, while the total global manganese reserves were estimated to be around 1,5 billion tonnes, with South Africa as the largest manganese reserves worldwide by far (U.S. Geological Survey, 2022c, p. 107).

In the production of one wind turbine, it has been estimated that 8.390 kg of manganese is used (ref. table 18). For the Hywind wind farm it will be used 11 times more manganese which equals to 92.290 kg of manganese. Looking at the worldwide production of manganese for 2021 this would be $4{,}61 * 10^{-4}$ % of the production.
If assuming the production of manganese from 2021 continues, it will be around 75 more years with manganese before it is empty.

Phosphorus (P)

Phosphorus (P) is the eleventh most abundant element on Earth, but it does not occur freely in nature. Essentially, the deposits consist of phosphate minerals (apatite) such as $Ca_5(PO_4)_3X$, where X can be F (fluorapatite), Cl (chloroapatite) or OH (hydroxyapatite). Here are also several other minerals that contain phosphorus, such as P_2O_5, aluminium phosphate and iron phosphate (Kjemisk institutt UiO, n.d.-a).

Today, phosphorus (P) is produces mainly from apatite. The production takes place either by dissolving the minerals in sulfuric acid so that phosphoric acid is formed, or by heating the mineral with sand and carbon so that free phosphorus is distilled out (Kjemisk institutt UiO, n.d.-a).

According to Kjemisk institutt at the University of Oslo (UiO) it is estimated to be a total of about 150 billion tonnes of phosphates (PO_4) on land and something similar in the sea (Kjemisk institutt UiO, n.d.-a). While the report from U.S Geological Survey from 2022 writes that overall, there are global phosphate rock reserves of approximately 71 billion tonnes, with Morocco having the largest reserve. The global production of phosphate rock in 2021 was around 220 million tonnes, where China had the largest production, with 85 million tonnes (U.S. Geological Survey, 2022c, p. 125). The general formula for pure phosphate rock is $Ca_{10}(PO_4)_6(X)_2$, where X is F-, OH-, or Cl-. These minerals are called apatites. The most common phosphate rock mined is fluorapatite ($Ca_5(PO_4)_3F$), which contains impurities like CO_3, Na, and Mg (Samreen & Kausar, 2019).

131 kg of phosphorus (P) (ref. table 18) is used in one wind turbine, which make 1.441 kg in all the 11 wind turbines in the farm. If assuming the phosphate rock

minded is fluorapatite ($Ca_5(PO_4)_3F$), the wight % of phosphorus (P) in the rock is 18,42% (molar mass $M_{Ca5(PO4)3F}$ = 504,298 g/mol where 3*30,97 g/mol = 92,91 g/mol is phosphorus, P -> 18,42% P). Assuming the annual production of phosphate rock is 220 million tonnes, then 40,524 million tonnes phosphorus (P) can be produces per year. Then from this annual production around $3{,}56*10^{-6}$ % are used in the Hywind Tampen farm. If assuming there are 71 billion tonnes of reserved phosphate rock in the world, and it is continued to be produced 220 million tonnes per year, then there would be around 323 years left with phosphate rock.

Sulphur (S)

Sulphur (S) is found both as pure sulphur and in many minerals. Pure sulphur is found at hot springs and at volcanoes. In addition, pure sulphur can be found underground. It's believed this is made by bacterial degradation of sulphates. Today, a large part of the sulphur is extracted from oil refineries and as a by-product of natural gas production. Sulphur is found in fossil fuels since it is formed from plant and animal remains. Oil can contain several percent sulphur. Going back in time, oil and petrol were a major source of acid rain, due to the sulphur in the oil and petrol.

A lot of elements form stable sulphidic minerals and sulphur is the most common element in minerals after silicon and oxygen. Iron forms pyrite (FeS_2), and other important sources of sulphur are chalcopyrite ($CuFeS_2$), bornite (Cu_5FeS_4), pentlandite ($(Fe,Ni)_9S_8$), and millerite (NiS). All of these are mainly sulphides of copper, iron, and nickel. Sulphur is also found as sulphates.

Pyrite is an iron sulphide where larger masses occur in many places in the Norwegian mountain ranges metamorphic rocks and were previously the basis for Norway's most important mining operations (Kjemisk institutt UiO, n.d.-g).

According to Store Norske Leksikon sulphur is assumed to make up 0,031% by weight of the Earth's crust (Kofstad & Pedersen, 2019b). Reserves of sulphur in crude oil, natural gas, and sulphides ores are large, and due to most of the sulphur production is a result of processing of fossil fuels, supplies should be adequate for the foreseeable future (U.S. Geological Survey, 2020, p. 2). The worldwide annual production of sulphur in 2021 was 79,65 million tonnes (Fernandez, 2022).

Table 18 shows that 132 kg sulphur is used in producing one wind turbine, which makes 1.452 kg for all the 11 turbines in the wind park. Using the annual production from 2021 the wind turbines in the farm will use about $1{,}82*10^{-6}$ % of the production.

Neodymium (Nd), Dysprosium (Dy), Praseodymium (Pr), Gadolinium (Gd)

Neodymium, dysprosium, praseodymium, and gadolinium are all so-called rare-earth elements (REE); however, they are not as rare as the name wants them to sound like. They are all a part of the 15 elements in the group called lanthanides in the periodic table, and the name "rare" occurred because lanthanoids are very well "spread" in the

Earth's crust and therefore it took a long time before they were discovered. Lanthanoids are found everywhere also in massive rocks such as basalts, granites, and gneiss, but then only in very small concentrations (10-300 ppm). However, the lanthanoids cannot be recovered from such low concentration source. Instead, all the elements are extracted from the two most important minerals; monazite ((Ce,La,Nd,Th)(PO_4,SiO_4), a phosphate mineral) and bastnasite ((Ce,La)CO_3(F,OH), a fluoride carbonate mineral). Both contains all the lanthanoids, but lanthanum (La) and cerium (Ce) dominate. In total, about 70,000 tonnes of monazite and bastnasite are produced each year. Only a small part of this is used to produce the various elements purely since most are used as a mixture of lanthanides called mixed metals (Kjemisk institutt UiO, 2019).

In 2021 the rare earth mine production worldwide was, according to the web page Statista, 277.100 tonnes, with China as the world's largest producer of REE by a large margin with 168.000 tonnes (Garside, 2022d). And according to estimates, the total worldwide reserves of rare earths amount to about 120 million tonnes (Garside, 2022g).

Neodymium (Nd) is the second most abundant of the REE after cerium (Ce) and is almost as abundant as copper. The reserves of neodymium are estimated to be 8 million tonnes, and the world production of neodymium oxide is about 7.000 tonnes a year (Lenntech, n.d.-f).

Dysprosium (Dy) is one of the more abundant lanthanide elements and is more than twice as abundant as tin (Sn). Dysprosium is not encountered as a free element but found in many minerals. The world's production of this lanthanide is around 100 tonnes per year (Lenntech, n.d.-c).

Praseodymium (Pr) is also one of the more abundant of the rare-earth elements, and it is four time more abundant than tin (Sn). The reserves of praseodymium are estimated to be around 2 million tonnes, and the worldwide production of praseodymium is about 2500 tonnes per year (Lenntech, n.d.-g).

Gadolinium (Gd) is an abundant rare-earth element, which is not found as a free element in nature but containing in many rare minerals. The reserve for gadolinium is expected to exceed one million tonnes, and the worldwide production of pure gadolinium is about 400 tonnes per year (Lenntech, n.d.-d).

Referring to table 18, it shows that about 346 kg Nd, 128 kg Dy, 12 kg Pr, and 2 kg Gd is used per wind turbine, and with 11 of them it will give each element a total of 3.806 kg Nd, 1.408 kg Dy, 132 kg Pr, and 22 kg Gd. Considering that 7.000 tonnes of Nd is mined for each year, the Nd used for the Hywind farm will be 0,0544% of the annual production. When it comes to Dy 1,41% of the annual production is used for the wind farm, which is a lot more of the annual production than what has been calculated for other elements in this thesis. For Pr it would be $5,28*10^{-3}$ % of the annual production, and for Gd it will be 0,0055%. Considering the worldwide mining production in 2021 of REEs, Hywind Tampen consumes $1{,}94 \cdot 10^{-3}$ % of this.

The estimated reserves for Nd have been set to 8 million tonnes, if considering a yearly production of 7.000 tonnes a year, it will take around 1143 years before it is empty. For Dy it has not succeeded the author finding out the estimated reserves for this element, but as it is said to be a more abundant lanthanide element, it should be reasonable to think it would be a place between 1 million tonnes and 2 million tonnes as it is for the two other more abundant lanthanide elements Gd and Pr respectively. Also, the yearly minding of Dy is less than for Pr and Gd, so it should not be way off to think that Dy will be lasting somewhere between Pr and Gd. For Pr it has been estimated reserves of 2 million tonnes, with an annual production of 2500 tonnes per year, this will last for another 800 years, and Gd will last for another 2500 years.

Boron (B)

Boron (B) is a semi-metal and a semiconductor, and next after diamond, it is the hardest of all elements. Boron makes up only 0,001% of the Earth's crust, so based on that it can be characterized as rare, but boron minerals are in some places concentrated in large quantities, especially such as borax and kernite (Kofstad & Pedersen, 2021a). Boron is not present in nature in elemental form. It is found combined in borax ($Na_2B_4O_7*10H_2O$, natural mined mineral), boric acid (H_3BO_3, processed borax), kernite ($Na_2B_4O_7*4H_2O$, source of borax), ulexite ($NaCaB_5O_6(OH)_6*5H_2O$, borate mineral), colemanite (B_4CaO_7), and borates. Vulcanic spring waters sometimes contains boric acids (Lenntech, n.d.-a).

The world's production of borates (boron-oxygen compounds) is about 2 million tonnes per year (Lenntech, n.d.-a), and the worldwide reserves are estimated to be around 1,343 billion tonnes in 2021, with Turkey having the largest reserves globally estimated to be 1,2 billion tonnes (Garside, 2022h).

Around 16 kg of boron is used to produce one wind turbine, this gives 176 kg for all the 11 wind turbines. With a production of 2 million tonnes of borates per year this would be $8{,}8 \cdot 10^{-6}$ % of the annual production. However, borates are a compound of boron (B) and oxygen (O), which means that it is not pure boron. If assuming a borate got the formular BO_3 then the molar mass of BO_3 would be M_{BO3} = 58,807 g/mol, where 10,81 g/mol would be boron. This would mean that from the borates production 18,38% is boron (B). Out of the 2 million tonnes of borates produced each year 367.600 tonnes would be pure boron (B). Then the boron usage would be 0,0479% of the annual production. With an estimate of 1,343 billion tonnes of worldwide reserves of borates (= 246,84 million boron (B)) it will last for about 672 years.

Niobium (Nb)

In pure form, niobium (Nb) appears as a light grey metal, it is soft and malleable, and can be easily rolled and forged. The metal is very corrosion resistant in acidic water because a thin, protective oxide film forms on the surface. The mineral columbite has long been the most important for the production of niobium. It is a mineral oxide containing iron, manganese, niobium, and tantalum: (Fe, Mn) $(Nb, Ta)_2O_6$. When the niobium (Nb) content dominates in relation to tantalum (Ta), the mineral is called columbite, and when the tantalum content dominates, it is called tantalite. Columbites being rich on niobium occurs particularly in Nigeria and Congo, tantalite in Brazil and Australia.

Later, pyrochlore, with the chemical formula $NaCaNb_2O_6F$, took over as the most important niobium raw material. This is now the starting point for more than 90 percent of the niobium market. Another niobium-containing mineral is euxenite, (Y, Ca, Ce, U, Th) $(Nb, Ta, Ti)_2O_6$ (Kofstad & Pedersen, 2021c).

The mining production of niobium in 2021 was estimated to be close to 75.000 tonnes worldwide (Garside, 2022c), while the worldwide niobium reserves are estimated to be around 17 million tonnes (Garside, 2022f).

Only around 1 kg niobium is used in the production of one wind turbine, which will be 11 kg in total for all the 11 wind turbines in the farm. This gives a usage of $1{,}47*10^{-5}$ % of the annual niobium production. Considering the niobium reserves and the yearly production continues, it will take around 227 years before it is empty.

Calcium oxide (CaO) - also called lime or quicklime

Calcium oxide (CaO) is a chemical compound of calcium and oxygen not found pure in nature but rather is contained in various abundant minerals. It is a white crystalline solid manufacture by heating limestone, coral, seashells, or chalk, which are mainly calcium carbonate ($CaCO_3$) to drive off carbon dioxide (O_2) (scifun, n.d.).

The annual worldwide production of calcium oxide (CaO) was around 430 million tonnes in 2021, where China was by far the world's largest producer, with a total of around 310 million tonnes that year. No estimate has been provided for the world's reserves of limestone and dolomite suitable for calcium oxide manufacturing, except for saying that it is very large (U.S. Geological Survey, 2022a, p. 2).

Around 4.205 kg calcium oxide is used to produce one Hywind Tampen wind turbine, with 11 of them it will be used a total of 46.255 kg of calcium oxide, this means that $1{,}08*10^{-5}$ % of the worlds yearly production is used for this wind farm.

Magnesium oxide (MgO)

Magnesium oxide (MgO) is a white solid found in nature as the mineral periclase. Periclase most often occurs in metamorphic limestones and dolomites and can be very widespread in the Earth's mantle. Magnesium oxide is also formed when magnesium, either in the form of powder or strips, burns in air (Pedersen, 2020).

As it is unknown to the author if the mineral periclase is used as magnesium oxide in the production of the fibreglass, or if it is magnesium burned in air that is used, and it is unknown how much periclase is mined for every year, it will be assumed that magnesium (Mg) burned into magnesium oxide (MgO) is used.

Magnesium (Mg) is the eight most abundant element and constitutes about 2% of the Earth's crust by weight, and it is the third most plentiful element dissolved in seawater. It's very abundant in nature, and it's found in important quantities in many rocky minerals, like dolomite, magnetite, olivine, and serpentine. It's also found in seawater, underground brines, and salty layers. It's the third most abundant structural metal in the Earth's crust, only exceeded by aluminium and iron (Lenntech, n.d.-e).

The annual production of magnesium (Mg) in 2021 was 950.000 tonnes, and the reserves for this metal is said to be sufficient to be supplied for in current and future requirements (U.S. Geological Survey, 2022b). However, the web page Statista has estimated the magnesite ($MgCO_3$) reserves for the major countries worldwide to be 4,669 billion tonnes in 2021 (Garside, 2022e). Magnesite is a mineral that belongs to the calcite group, and by high temperature (calcination) magnesium oxide (MgO) is formed.

The chemical equation for burning magnesium into magnesium oxide is:
magnesium + oxygen -> magnesium oxide: $2Mg + O_2 \rightarrow 2MgO$
From the equation it is shown that 2 mol magnesium (Mg) gives 2 mol magnesium oxide (MgO). To find the mass of Mg burned with oxygen, and the mass of the resulting MgO the following formula is used: m = M*n, where M is the molar mass of the molecule, and n is the amount of mole. $M_{Mg} = 24{,}305$ g/mol, $M_O = 16$ g/mol and $M_{MgO} = 24{,}305$ g/mol + 16g/mol = 40,305 g/mol (ref. periodic table).
$m_{Mg} = M_{Mg} * n = 24{,}305 \text{ g/mol} * 2 \text{ mol} = 48{,}61 \text{ g}$
$m_{MgO} = M_{MgO} * n = 40{,}305 \text{ g/mol} * 2 \text{ mol} = 80{,}61 \text{ g}$

This calculation shows that we get more than 1,658 times as much MgO than what was started out with of Mg ($1{,}658\, m_{Mg} = m_{MgO}$).

In table 18 it shows that 5.188 kg of Magnesium oxide (MgO) was used in the fibreglass for one wind turbine, which should mean that 5.188 kg/1,658 =3.129 kg of magnesium (Mg) was used to make 5.188 kg magnesium oxide (MgO). For all the 11 wind turbines this would be 34.419 kg of magnesium (Mg), which means $3{,}62*10^{-3}$ % of the annual production.

Magnesite ($MgCO_3$) burns to magnesium oxide (MgO) according to the following equation:

$$MgCO_3 \rightarrow MgO + CO_2$$

M_C = 12 g/mol (ref. periodic table)
M_{MgCO3} = 24,305 g/mol + 12 g/mol + (3*16g/mol) = 84,305 g/mol
M_{MgO} = 40,305 g/mol
m_{MgCO3} = M_{MgCO3}*n = 84,305 g/mol *1 = 84,305 g
m_{MgO} = M_{MgO}*n = 40,305 g/mol * 1 = 40,305 g

The above calculations show that it is produced 0,478 times less MgO than the $MgCO_3$ started out with (0,478 m_{MgCO3} = m_{MgO}). If the worldwide reserves for magnesite ($MgCO_3$) is 4,669 billion tonnes, it would mean that out of this it can be burned 0,478*4,669 billion tonnes = 2,232 billion tonnes of MgO. From before it has been calculated that 1,658 m_{Mg} = m_{MgO}, this would mean that 2,232 billion tonnes of MgO/1,658 = 1,346 billion tonnes of magnesium (Mg) are in the reserves.

With a continuous yearly production of magnesium (Mg) of 950.000 tonnes, it would mean there are magnesium and then also magnesium oxide for another 1417 years, which is pretty much covering the current and the future requirements.

Cobalt (Co)

Most of the cobalt is found in the Earth's core, and then a relatively low abundance is in the Earth's crust and in natural waters, from which it is precipitated as the highly insoluble cobalt sulphide, CoS. Cobalt is not found as a free metal and is generally found in the form of ores. Most of the cobalt extracted is a by-product of nickel and cobber production. The main ores of cobalt are cobaltite, erythrite, glaucodot, and skutterudite. The world's major producers of cobalt are the Democratic Republic of the Congo, mainland China, Zambia, Russia, and Australia (Lenntech, n.d.-b).

The total worldwide production of cobalt in 2021 was estimated to 170.000 tonnes, with the Democratic Republic of the Congo as the world's leading cobalt producer, producing 120.000 tonnes in 2021 (Garside, 2022a). The total global reserves of cobalt were estimated to 7,6 million tonnes in 2021. Cobalt is ranking 32nd in the global abundance among metals, and it has become an increasingly important commodity due to its use in batteries, as well as alloys, chemicals ceramics, cemented carbides, and more (Garside, 2022b).

In the production of a wind turbine in the Hywind Tampen farm it is used about 47 kg of cobalt, for the whole farm it will be 517 kg. This would be $3{,}04*10^{-4}$ % of the annual production in 2021. If the production continues as of 2021 there will be about 45 years left with cobalt in the world.

Sodium oxide (Na_2O)

In the production of the Epoxy used to manufacture a wind turbine it is used sodium oxide (Na_2O), which is a chemical compound with oxygen (O) and sodium (Na). Sodium oxide is not found in nature but mostly produced through the reaction of sodium hydroxide (NaOH) with metallic sodium. This reaction produces hydrogen as a side product:

$$2NaOH + 2Na \rightarrow 2Na_2O + H_2$$

A second method is the thermal decomposition of sodium carbonate (Na_2CO_3, also called soda ash) up to 850°C, to produce carbon dioxide (CO_2) and sodium oxide (Na_2O):

$$Na_2CO_3 \rightarrow Na_2O + CO_2$$

(Softschools, n.d.).

Approximately 2,6% by wight of the Earth's crust is sodium, and it is the sixth most abundant element in the crust. Since the metal is very reactive, it exists only in chemical compounds. In the solid Earth's crust, sodium is found primarily in silicates and feldspar. When the minerals weather, sodium is washed out into the sea, and on average 1 kg of seawater contains 26,82 g of sodium chloride (NaCl), which corresponds to 10,55 g of sodium (Na) (Kjemisk institutt UiO, n.dn).

In the research trying to find out how much sodium is produced every year and how much is left for us to use, a report from U.S Geological Survey from 2022 was found, however this report only talks about soda ash also called sodium carbonate (Na_2CO_3), so it is assumed that the sodium in seawater is not included. This report states that in 2021 17 million tonnes of natural soda ash (Na_2CO_3) was produces and it has been estimated to be around 25 billion tonnes with reserves around the world (U.S. Geological Survey, 2022c, p. 155).

The equation $Na_2CO_3 \rightarrow Na_2O + CO_2$ shown above shows that 1 mole Na_2CO_3 gives 1 mole Na_2O and 1 mole CO_2. By using the formular $m = M*n$ it is possible to find out how much Na_2O is given from Na_2CO_3, where the molar mass $M_{Na} = 22,99$ g/mol, $M_C = 12$ g/mol, and $M_O = 16$ g/mol (M is found in the periodic table).
$M_{Na2CO3} = (2*22,99 \text{ g/mol}) + 12 \text{ g/mol} + (3*16 \text{ g/mol}) = 105,98 \text{ g/mol}$
$M_{Na2O} = (2*22,99 \text{ g/mol}) + 16 \text{ g/mol} =61,98 \text{ g/mol}$
$m_{Na2CO3} = M_{Na2CO3}*n = 105,98 \text{ g/mol} * 1 = 105,98 \text{ g}$
$m_{Na2O} = M_{Na2O}*n = 61,98 \text{ g/mol} * 1 = 61,98 \text{ g}$

This means that from 105,98 g of Na_2CO_3 you will get 61,98 g Na_2O which is the same as $(61,98 \text{ g}/105,98 \text{ g})*m_{Na2CO3} = m_{Na2O} \rightarrow 0,58*m_{Na2CO3} = m_{Na2O}$

In 2021 the production of Na_2CO_3 was estimated to be 17 million tonnes, with the findings from the calculation above this would give about 0,58*17 million tonnes = 9,86 million tonnes of sodium oxide (Na_2O) that year if all had been converted into Na_2O and CO_2.

From table 18 it shows that about 109 kg sodium oxide is used in one wind turbine, which would be 1.199 kg for all 11 wind turbines. This is about $1,22*10^{-5}$ % of the annual production of Na_2O in 2021, assuming all the Na_2CO_3 was converted into

Na_2O and CO_2. If continuing the yearly production of 17 million tonnes, and assuming reserves of 25 billion tonnes (= 14,5 billion tonnes Na_2O), there will be soda ash and sodium oxide for another 1470 years.

Potassium oxide (K_2O) also called potash

In the Epoxy used for the wind turbine it is used potassium oxide (K_2O) (in Norwegian also called normal oxide), which is a chemical compound between potassium (K) and oxygen (O). Potassium oxide is formed when metallic potassium reacts with oxygen:

$$4K + O_2 \rightarrow 2K_2O$$

Potassium peroxide (K_2O_2) is also formed during this reaction, and by adding potassium it will produce potassium oxide:

$$K_2O_2 + 2K \rightarrow 2K_2O$$

(Riya I, 2022).

Potassium (K) is a silvery-white metal that is so soft that it can be easily cut with a knife. Pure potassium is not itself particularly useful as it reacts so quickly with air and water, even in room temperature, and therefore it is rarely to be seen in pure form. Around 2,4 mass percentage of the Earth's crust is potassium where it occurs as chemical compounds with other elements. The most common potassium-containing minerals are orthoclase, $KAlSi_3O_8$, and muscovite $KAl_3Si_3O_{10}(OH)_2$. When weathering these silicates, potassium ions are absorbed in the soil (Pedersen, 2021a). Potassium is also available in large salt deposits for example in the Ural Mountains, Canada, Germany, and France (Kjemisk institutt UiO, n.d.-c).

According to the report given by U.S. Geological Survey in 2022 (U.S. Geological Survey, 2022c, p. 129) the mine production of potassium oxide (potash) was 46 million tonnes worldwide in 2021, and the world's reserves were estimated to be more than 3,5 billion tonnes.

In table 18 it shows that 273 kg potassium oxide (K_2O) is used in the epoxy for one wind turbine, which will be 3.003 kg for all the 11 wind turbines in the farm. This is around $6{,}53 \cdot 10^{-6}$ % of the world's production in 2021. If the production from 2021 continues, there will be around 76 years left with potassium oxide assuming the world's estimated reserves are correct.

Lithium (Li) and Lithium oxide (Li_2O)

Lithium oxide (Li_2O) is used in the epoxy produced for the wind turbines, which is a chemical compound of lithium (Li) and oxygen (O). Lithium oxide can be produced by burning lithium (Li) with oxygen (O):

$$4Li + O_2 \rightarrow 2Li_2O$$

(Thpanorama, n.d.).

Lithium (Li) is a silvery-white metal, and it is the lightest of all the metals. It is light enough to float in water, and soft enough to be cut, and it does not occur in pure form in nature, for that it is too reactive. Lithium reacts with water and produces hydrogen gas, and it reacts with oxygen gas in the air producing lithium oxide, so therefore it must be stored air-free. The most important lithium mineral is spodumene, with the chemical formula $LiAlSi_2O_6$. Some other lithium minerals are lepidolite, $K(LiAl)_3(SiAl)_4O_{10}(OH,F)_2$, and petalite, $LiAlSi_4O_{10}$ (Kjemisk institutt UiO, n.d.-d) (Pedersen, 2021b).

The world’s production of lithium (Li) in 2021 was around 100.000 tonnes (excluding the U.S production), and the estimated worldwide reserves are calculated to be 22 million tonnes (U.S. Geological Survey, 2022c, p. 101).

The lithium (Li) used in the epoxy has been calculated to be about 355 kg per wind turbine, which will be 3.905 kg for all the wind turbines in the farm. With the world’s production of 100.000 tonnes in 2021, this would be $3{,}91 * 10^{-3}$ % of the annual production. If assumed the production from 2021 continues, and the estimated reserves are close to correct, then there is 220 years left with lithium (Li).

Titanium dioxide (TiO_2) also called Titanium(IV) oxide

Titanium dioxide (TiO_2), also called titanium(IV) oxide, is a chemical compound between titanium (Ti) and oxygen (O) and is the most important titanium compound. It is a solid with a strong white colour. Large-scale industrial production of titanium dioxide takes place either by the sulphate process or the chloride process (Haraldsen, 2021).

Ilmenite ($FeTiO_3$) is an iron-black, heavy, metallic oxide mineral, composed of iron and titanium oxide, that is used as the major source of titanium (The Editors of Encyclopaedia Britannica, n.d.-b). Rutile is the most abundant of the three naturally occurring forms of titanium dioxide (TiO_2). Rutile is a commercially important titanium mineral, although most titanium dioxide is produced from ilmenite (The Editors of Encyclopaedia Britannica, n.d.-c).

In the sulphate process, ilmenite concentrate, $FeTiO_3$, is treated with concentrated sulfuric acid (H_2SO_4) at 150-200°C. This gives a solution of titanium(IV)- and iron(II) sulphate ($FeSO_4$), as shown in the following reaction equation:

$$FeTiO_3 + 2H_2SO_4 \rightarrow TiOSO_4 + FeSO_4 + 2H_2O$$

By boiling the titanium oxygen sulphate ($TiOSO_4$) in water, solid titanium(IV) oxide hydrate (TiO_2*aq) is formed, which is filtered off and annealed in a rotary kiln at approx. 1000°C to anhydrous titanium(IV) oxide:

$$TiOSO_4 + nH_2O \rightarrow TiO_2{*}aq + H_2SO_4$$

The chloride process is based on titanium(IV) chloride ($TiCl_4$) produced by chlorination of rutile concentrates. The chloride is combusted in vapor form with air or oxygen at 650-750°C:

$$TiCl_4 + O_2 \rightarrow TiO_2 + 2Cl_2$$

With this method you get the rutile modification directly. The sulphate method is mostly used in Europe, and the chloride method is mostly used in the United States (Haraldsen, 2021).

The worldwide mine production of ilmenite ($FeTiO_3$) in 2021 was estimated to be around 8,4 million tonnes, and of rutile it was around 9 million tonnes. The estimated reserves for ilmenite are calculated to be 700 million tonnes, and for rutile around 49 million tonnes. Ilmenite accounts for 90% of the world's consumption of titanium minerals, and the world resources of anatase (another mineral form of titanium dioxide (TiO_2)), ilmenite, and rutile total more than 2 billion tonnes (U.S. Geological Survey, 2022c, p. 179).

As ilmenite accounts for 90% of the world's consumption of titanium minerals, this will be used in the calculation finding out how much of titanium dioxide is used in the wind turbines, and how much more is left for us to use. From the equation
$FeTiO_3 + 2H_2SO_4 \rightarrow TiOSO_4 + FeSO_4 + 2H_2O$
it shows that 1 mole $FeTiO_3$ together with 2 mole H_2SO_4 will produce 1 mole $TiOSO_4$, 1 mole $FeSO_4$, and 2 mole H_2O (water). In this equation it is $FeTiO_3$ and $TiOSO_4$ that are of interest. Again, the formular m = M*n is used to find how much of each molecule is needed and how much is made, where M is the molar mass for an atom found in the periodic table and n is the amount of mole.

M_{Fe} = 55,845 g/mol, M_{Ti} = 47,867 g/mol, M_O = 16 g/mol, M_H = 1,008 g/mol, and M_S = 32,065 g/mol.
M_{FeTiO3} = 55,845 g/mol + 47,867 g/mol + (3*16 g/mol) = 151,712 g/mol
M_{TiOSO4} = 47,867 g/mol + 16 g/mol + 32,065 g/mol + (4*16 g/mol) = 159,932 g/mol
m_{FeTiO3} = M_{FeTiO3}*n = 151,712 g/mol * 1 = 151,712 g
m_{TiOSO4} = M_{TiOSO4}*n = 159,932 g/mol * 1 =159,932 g

From this calculation it shows that it is produced a bit more $TiOSO_4$ than the $FeTiO_3$ started out with: m_{TiOSO4} = 1,054 m_{FeTiO3}.

Then the equation:
$TiOSO_4 + nH_2O \rightarrow TiO_2{*}aq + H_2SO_4$
says that 1 mole $TiOSO_4$ makes 1 mole TiO_2*aq which is dried off to be pure TiO_2.
M_{TiOSO4} = 159,932 g/mol
M_{TiO2} = 47,867 g/mol + (2*16 g/mol) = 79,867 g/mol
m_{TiOSO4} = M_{TiOSO4}*n = 159,932 g/mol * 1 =159,932 g
m_{TiO2} = 79,867 g/mol * 1 = 79,867 g

This calculation shows that from the amount of $TiOSO_4$ that is used it produces about 0,499 times TiO_2: $m_{TiO2} = 0{,}499\ m_{TiOSO4}$.

In other words, starting out with 151,712 g $FeTiO_3$ will through these two processes produce 79,867 g TiO_2, which would be approximately the same as:
$m_{TiO2} = 0{,}526\ m_{FeTiO3}$

In one wind turbine it is used about 71 kg TiO_2 which would be 781 kg for all the 11 wind turbines. In 2021 the worldwide production of ilmenite ($FeTiO_3$) was 8,4 million tonnes, which would produce 4.418.400 tonnes or 4.418.400.000 kg of TiO_2 according to the formula $m_{TiO2} = 0{,}526\ m_{FeTiO3}$. This means that the Hywind Tampen wind farm would use about $1{,}77*10^{-5}$ % of the annual production in 2021.
If assuming the mining for ilmenite ($FeTiO_3$) continues with 8,4 million tonnes per year, and the reserves worldwide is 700 million tonnes (=368,2 million tonnes TiO_2), there are about 83 years left with ilmenite ($FeTiO_3$) and then also titanium dioxide (TiO_2). But since there are other minerals like anatase and rutile that also can be used to produce titanium dioxide it should be correct to assume that the years with titanium dioxide are a bit more.

Nickel (Ni)
Nickel (Ni) is a silvery metallic element that can be easily forged, rolled, and drawn. Nickel is ferromagnetic at normal temperatures, but its magnetic properties are far weaker than those of iron (Fe). Pure nickel is slowly oxidized in air at temperatures up to 400-500 ° C. It is also very resistant to corrosion in seawater, concentrated alkali solutions and molten alkalis (Kofstad & Pedersen, 2021b).

Nickel is mainly used in alloys, to make them more resistant to corrosion, and as a coating on metal objects, for the same reason. Nickel occurs in nature as sulphides, arsenide and antimonides, often together with iron (Fe) and copper (Cu). Of particular importance is copper-cobalt-nickel-containing pyrrhotite ($Fe_{1-x}S$). It contains copper as chalcopyrite, $CuFeS_2$, and nickel as pentlandite, $(Ni, Fe)_9S_8$. The nickel content of these ores varies from 0.4 to 3 percent (Kofstad & Pedersen, 2021b).

Interestingly, most of the globe's nickel is inaccessible to us - the hot, molten iron / nickel core in the earth's interior is believed to consist of approx. 10% nickel (Kjemisk institutt UiO, n.d.-f).

In the report from U.S. Geological Survey from 2022 the worldwide estimated production of nickel (Ni) in 2021 was 2,7 million tonnes, and the table show that more than 95 million tonnes are estimated as worldwide reserves. However, it also states the following "*Identified land-based resources averaging approximately 0.5% nickel or greater contain at least 300 million tons of nickel, with about 60% in laterites and 40% in sulfide deposits. Extensive nickel resources also are found in manganese crusts and nodules on the ocean floor*." This is a bit confusing as the table states reserves of >95 million tonnes (U.S. Geological Survey, 2022c, p. 115). As the author has found several other web sites with articles claiming that there is nickel (Ni) for further use for another 150 years, it will be assumed in this master's thesis that the nickel reserves on Earth in 2021 was estimated to be 300 million tonnes.

Only 0,62 kg of nickel is used in one wind turbine (ref. table 18), and this is used in the NdFeB magnet. For all the wind turbines in the farm it will then be used 11*0,62 = 6,82 kg, rounded up to 7 kg of nickel in total. Out of the annual production in 2021 of 2,7 million tonnes this will be around 2,59*10^{-7} % of the annual production. Assuming the annual production continues with a 300 million tonnes worldwide reserves, there are around 111 years left with nickel.

Nitrogen (N)

Nitrogen is a colourless and odourless gas, and the nitrogen molecule has the chemical formula N_2. In dry air, nitrogen makes up 78 percent of the volume and its boiling point is −195.8 degrees Celsius (° C). Solid nitrogen forms white crystals with a density of 1,026 g/mL at a temperature of −252 ° C. At normal temperature, nitrogen is very unreactive. This is because the atoms in the nitrogen molecules are very tightly bound to each other. However, the reactivity increases with increasing temperature. At high temperatures, nitrogen reacts directly with metals to form nitrides (Pedersen, 2021c).

Nitrogen is mainly produced from air. The air is cooled to liquid air, and nitrogen is separated from the other main component of air, oxygen, by fractional distillation. Because the boiling point of nitrogen (−195.8°C) is somewhat lower than that of oxygen (−183°C), nitrogen is more volatile than oxygen and evaporates preferably in the first fractions (Pedersen, 2021c).

In the report from U.S. Geological Survey from 2022 the nitrogen production in 2021 is reported in the form of ammonia (NH_3), and the availability of nitrogen from the atmosphere for fixed nitrogen production is unlimited (U.S. Geological Survey, 2022c, p. 119). Due to this information in addition to the nitrogen used in one wind turbine is very small, 0,01 kg, which would be 10 g, the calculation of nitrogen will not be included in this master's theses as the author find it irrelevant/not important as the usage is very small and the reserves are set to be unlimited.

Crude oil

Crude oil is a naturally occurring, liquid mixture of hydrocarbons that is found in reservoirs in the bedrock and is extracted as a raw material in the petroleum industry. Crude oil is a form of petroleum and is formed together with natural gas by maturation of organic material in sedimentary rocks. Crude oil is processed into petrol, kerosene, diesel, and heating oil, as well as plastic and synthetic fibres.

Crude oil is a very complex mixture of a large number of chemical compounds, and the composition varies from field to field. (Lundberg, 2021).

From Statista's web page it shows that in 2020 around 88,4 million barrels of oil was produced every day, considering 2020 being a leap year with 366 days, this would give 2020 an annual production of 32,35 billion barrels (Sönnichsen, 2021b). In a web article written by Discovery Magazine in 2021 it says that according to the British Petroleum's 2019 "Statical Review of World Energy", the total proved reserves of the planet's oil at that time was 1.733,9 billion barrels. Then the yearly global consumption in 2019 was around 35,9 billion barrels. Assuming the proved reserves do not grow, and the consumption remains constant the magazine calculates with 48 years left of oil (Learn, 2021).

According to the calculations done in this master's thesis about 14.816.317 kg of Johan Sverdrup crude oil could have been used to produce one wind turbine, which is equal to 16.779.521 litre of oil or about 105.540 barrels of crude oil. To produce all the 11 wind turbines in the farm it would have taken 1.160.940 barrels of crude oil (=162.979.487 kg) from Johan Sverdrup. If assuming the daily production in 2020, but without it being a leap year, then the annual production would be 32,27 billion barrels (=$4{,}53*10^{12}$ kg), which would mean that around $3{,}6*10^{-3}$ % of the yearly production is used for the Hywind Tampen wind farm. In 2019 (assuming end of year) it was estimated to be around 1.733,9 billion barrels of oil reserves, if subtracting the production in 2020 (32,35 billion barrels), and the production in 2021 assuming the daily production from 2020 continues (32,27 billion barrels), the oil reserves in 2021 (end of year) would be $1{,}67*10^{12}$ barrels of oil (=$2{,}34*10^{14}$ kg). When calculating the remaining crude oil left in table 19 below, it has been calculated to be around 52 years in end of 2021, so more than what the Discovery Magazine calculated it to be in 2019 (assumed end of year). This is due to the assumed reduction in the annual production from 35,9 billion barrels in 2019 to 32,27 billion barrels in 2021.

4.4. Material usage, annual production, and reserves overview

Table 19 below shows an overview of the calculations done in section 4.3. It shows the raw materials used to produce the 11 wind turbines for the Hywind Tampen farm, the yearly estimated worldwide production of each raw material, the estimated worldwide reserves left, and estimated years left before empty per end of year 2021(considering no change in the annual production).

Material/Element/ Metal	**Raw Material usage for Hywind Tampen [kg]**	**Estimated Raw Material annual production [kg]**	**Material used as a percentage of annual production [%]**	**Estimated worldwide reserves [kg]**	**Years left with raw material when assuming constant production**
Iron cast (Fe)	6.786.615	1.500.000.000.000	0,000452	230.000.000.000.000	152 (153 in 2020)
Copper (Cu)	203.709	21.000.000.000	0,000970	880.000.000.000	42
Aluminium oxide / alumina (Al_2O_3)	291.324	136.760.000.000	0,000213	11.880.000.000.000	90
Balsa Wood	17.160	No data found	No data	Renewable	Renewable
Plywood	17.160	No data	No data	Renewable	Renewable
Carbon (C)	11.506	853.000.000.000	0,00000135	1.049.000.000.000.000	1230
Silicon (Si)	206.732	8.500.000.000	0,00243	$6,925*10^{18}$	Unlimited
Manganese (Mn)	92.290	20.000.000.000	0,000461	1.500.000.000.000	75
Phosphorus (P)	1.441	40.524.000.000	0,00000356	13.078.200.000.000	323
Sulphur (S)	1.452	79.650.000.000	0,00000182	Unknown	Adequate for the foreseeable future.
Neodymium (Nd)	3.806	7.000.000	0,0544	8.000.000.000	1143
Boron (B)	176	367.600.000	0,0479	246.843.400.000	672
Niobium (Nb)	11	75.000.000	0,0000147	17.000.000.000	227
Dysprosium (Dy)	1.408	100.000	1,408	Unknown, but it is said to be one of the more abundant lanthanide elements	Estimated to be somewhere between 800 to 2500 years.
Calcium oxide (CaO) (From $CaCO_3$)	46.255	430.000.000.000	0,0000108	Unknown, but said to be very large.	Unknown
Magnesium (Mg)	34.419	950.000.000	0.00362	1.346.000.000.000	1417
Cobalt (Co)	517	170.000.000	0,000304	7.600.000.000	45
Sodium oxide (Na_2O)	1.199	9.860.000.000	0,0000122	14.500.000.000.000	1470
Potassium oxide (K_2O)	3.003	46.000.000.000	0,00000653	3.500.000.000.000	76
Lithium (Li)	3.905	100.000.000	0,00391	22.000.000.000	220
Oxygen (O)	4.499	Not produced	No data	Assumed unlimited	Unlimited
Titanium dioxide (TiO_2)	781	4.418.400.000	0,0000177	368.200.000.000	83+
Praseodymium (Pr)	132	2.500.000	0,00528	2.000.000.000	800
Gadolinium (Gd)	22	400.000	0,00550	1.000.000.000	2500
Nickel (Ni)	7	2.700.000.000	0,000000259	300.000.000.000	111
Nitrogen (N)	0,010	Not calculated	No data	Assumed unlimited	Unlimited
Crude oil	162.979.487	4.530.240.763.000	0,00360	234.342.742.500.000	52
Miscellaneous	102.982	No data	No data	No data	No data

Table 19 An overview of the raw material usage for Hywind Tampen, annual production, and reserves

4.5. Analysis of the material usage and the environmental impact

One part of this master's thesis, and what Equinor asked for was an analyse of the material used to make the Hywind Tampen wind farm, make an overview of how much is used from the annual production, and then make a conclusion on how sustainable and environmentally friendly the production of these wind turbines really is.

In this section the author will be analysing observations and findings made in section 4.2 and 4.4 and use these findings to look at the impact the material usage has on the environment and the human beings. Table 18 gives a good overview of the raw materials used in the production of one Hywind Tampen wind turbine, and table 19 gives a good overview of the material used for all the wind turbines in the Hywind Tampen farm and the reserves we have for each raw material.

Rare Earth Elements (REEs)

By looking at table 19 it shows that all the REE elements Nd, Dy, Pr, and Gd are highly representative when it comes to the percentage used from the annual production. All the four REE elements are among the top 5 elements with the highest usage compared to annual production, but on the other hand the estimated worldwide reserves are big compared to the annual production, and therefore will last for a long time if it is assumed that the annual production will not increase. But will that be realistic to assume?

Even though the REEs are not as rare as the name wants them to sound like, actually we got a lot of it all across the globe, the challenge when mining for them is that they normally do not occur in concentrated deposits. They are often found mixed together with other minerals which makes it difficult to separate the REEs from the other minerals. And in some of the rocks the content of the REE is so small that it is impossible to separate it. Due to the difficulty of separating the REEs from the other elements, it also makes them very expensive elements to mind for. This might be the reason why China, as of today, is the marked leader of mining REEs with around 97% of the production, as they have a low mining and procession cost, in addition to less stringent environmental standards. Since Europe do not extract much for these elements, the REEs have been classified as critical for the European industry.

That China pretty much got monopoly on the mining of REEs could be a problem for the rest of the world. The fact that basically only one country in the world is mining for these elements, makes the rest of the world very vulnerable, especially when the usage of REEs is increasing, as we use them more and more in new technology such as electrical cars, mobile phones, tablets, laptops, computers, batteries, wind turbines, and so on. Some of these technologies are manufactured to lower the worlds carbon footprint, and therefore the demand will increase as we are turning around for a "greener" world. The war that started when Russia invaded Ukraine in February 2022 is an example of how vulnerable the world is when one or two countries stands for a big part of the export of one or more products. Russia is one of the biggest exports of wheat and oil in the world, and Ukraine

exports wheat. This caused food problems in many countries during the war, and it caused problems for the countries supporting and trying to help Ukraine as it was difficult for them not to buy oil and gas from Russia, which again contributed to the financing of Russia's war.
The monopoly also let China have more control when it comes to the cost of REEs, as they are the biggest producer.

As mentioned above, the usage of REEs is increasing as the world tries to lower the carbon footprint, which should result in a bigger demand of REEs. It is therefore not reasonable to assume that the annual production of the REEs will remain constant, or decrease, it's all pointing in the direction of increasing. In an article found on the Energy&Nature (Emblemvåg, 2021) web page it is mentioned that in the USA alone, it has been estimated that as much as 4.600 million tonnes of REE will be used if the growth targets for the wind industry are to be achieved, and only this alone is a concern if the total worldwide reserves of REEs has been estimated to be approximately 120 million tonnes according to the Statista web page. If these numbers are correct, we do not have enough REEs in the world to meet the worlds demand of wind energy, and we are forced to rethink and come up with new solutions to meet our carbon emission goals.

The article from the Energy&Nature web site is also pointing out another very important aspect, and that is that the extraction and refining of REEs takes place under terrible conditions. BBC has described the world's largest and most important area – Bayan Obo, which contains about 70% of the global REE deposits, as "hell on Earth". There is also great concern in relation to the emission of radioactive waste since the REE deposits contain thorium and/or uranium. Surprisingly, miners who extract REE for the renewable industry are exposed to 40-80 times higher doses of radiation than miners in the nuclear power industry. This mining also threatens wildlife. Mining for materials for renewable energy sources is more threatening to protected and remaining wilderness than mining for other purposes.

Copper (Cu) and Cobalt (Co)

Copper and cobalt are central elements in many of the upcoming technologies manufactured for a lower carbon footprint and a "greener" environment. Copper is for instance used in batteries, electrical wires, cables, solar cells, electrical vehicles, magnets, and transformers, while cobalt, among other, are used in batteries, magnets and in many alloys used for manufacturing. According to the calculations done in this master's thesis the 11 wind turbines for the Hywind Tampen farm will use around 203.709 kg of copper, and then the calculation does not include all the copper used for electrical wires and cables that also must be in place for transporting the electricity. So, it should be fair to say that a lot more copper than what has been calculated here will be needed in this wind farm. The big concern when it comes to these two elements is that they are the two elements that will run out first, if the consumption continues as of today. From table 16 it shows that with today's annual production there will be copper for another 42 years, and

cobalt for 45 more years. However, by the look at the direction the world is heading, with the productions of more and more renewable energy (wind turbines, solar cells, etc.) and low carbon emission equipment (electrical vehicles, batteries for energy storage, etc.) it is not likely to believe that the annual production will remain as of today. It will most likely increase, which would mean that the reserves of copper and cobalt will be emptied even sooner. The author might even still be alive when we run out of copper and cobalt.
Tesla CEO Elon Musk was already in 2019 expressing his concern of global shortages of nickel, copper, and lithium, due to the fact that we will be using a lot more of these elements in the future.

Crude oil
The 11 wind turbines in the Hywind Tampen farm have been estimated to use 162.979.487 kg of crude oil (from Johan Sverdrup), this equals to 1.160.942 barrels of oil (1,16 million barrels). In addition to this the oil under the section miscellaneous should be added as well, which is unknow to the author if includes the oil used for maintenance during the years the wind turbines are up and running. Most likely the wind turbines will turn out using more than the estimated 0,0036% (or 3,6‰) of the annual production of oil, and oil is the 8th most used raw material compared to the annual production. In table 19 it has been estimated that we will have crude oil for another 52 years, and it should be reasonable to believe that the annual production and consume of crude oil not necessarily will increase even though the world is focusing on more wind power because it should be reasonable to believe that the oil usage will decrease in other areas like in the need of petrol as we start using electrical vehicles, plastic as we have started to substitute this with for example wood, and so on. But nevertheless, oil is and always will be a limited resource to the world.

As we all know, pumping up oil and gas is not good for the environment due to its pollution, even though we are implementing solutions like carbon capture and storage to capture and store the CO_2 emissions from the industry. Another concern is that a causal relationship between exposure to benzene and the development of leukaemia has been established. As well as significantly lower white blood cell and platelet counts have been reported for workers exposed to benzene in the working environment, even at very low concentrations (Kirkeleit J, 2005). In other words, these are among the health issues that oil works might be exposed too.

Other exposed elements
Among the other exposed elements found in table 16 we have manganese (Mn), potassium oxide (K_2O), titanium (Ti)/titanium dioxide (TiO_2), aluminium (Al)/aluminium oxide (Al_2O_3), nickel (Ni), iron (Fe), and lithium (Li) even though the latter three have been calculated to last for another 111, 152, and 220 years respectively.

Manganese and potassium oxide got reserves left in the world for another 75 and 76 years, respectively, if today's annual production and consumptions are continued, according to this thesis calculations. Virtually all manganese produced today is used in steel or electric steel, only a small amount is used for cast iron, aluminium-, magnesium-, and copper alloys. While potassium oxide (K_2O) and potassium (K) are used in fiberglass, fertilizer, photocells, and nuclear reactors among other. If we look at manganese, that is mostly used for steel, and then look at how steel has developed production wise during that last couple of years, we can see from Statista's web page for world crude steel production from 2012 to 2021 (Statista Research Department, 2022) that the steel production has increased with 25% from 2012 to 2021, and 3,8% from 2020 to 2021. And with steel being the major ingridience in a wind turbine with approximately 522.730kg/Hywind Tampen wind turbine, it is reasonable to believe that the steel production will not decrease but rather increase as the years goes by. When it comes to potassium and potassium oxide it is also not likely to believe that the usage will decrease, but rather increase, as it is used in the fiberglass for the wind turbines which we plan to increase the production of, in addition to being used as fertilizers for food production in a world where the population is only increasing. This means that we are probably looking at less than 75 and 76 years with manganese and potassium/potassium oxide.

Aluminium (Al)/aluminium oxide (Al_2O_3) and titanium (Ti)/titanium dioxide (TiO_2) are two other elements/oxides that also don't look like having a promising future. Even though they have been estimated to last for another 90 and 83+ years respectively, the usage of them is related to the renewable industry among other. Aluminium and aluminium oxide is used for example in wind turbine magnets, fiberglass, electric steel, and solar cells, while titanium and titanium oxide are for example used in solar cells and fiberglass. This would mean that in a world hunting for more renewable energy more production of these elements/oxides are needed, which will result in reserves being emptied much faster.

Nickel (Ni), Iron (Fe), and lithium (Li) have also been mentioned even though they have been calculated to last for another 111, 152, and 220 years respectively. But with the increase in standard of living and the increase of population the demand for energy and electronic devices will increase, so this will probably only be one or two generations of resources. These elements are related to the world's green shift and lowering carbon footprint as they are used in batteries, magnets, and solar cells, so it is reasonable to believe that the annual production of these elements will increase.

When it comes to all the other elements being looked at in this thesis, they will not be looked at in more details, as they do not seem to be as crucial as the elements discussed above. Either the element has been estimated to last for a very long time, like magnesium (another 1417 years), or the usage in the 11 wind turbines compared with the annual production is so small that the author does not see the point in going into more details (an example would be niobium where 0,0000147% of the annual production is used in all the 11 wind turbines). The only element left that could be worth looking at is boron (B) as this is the 3rd most used element in the 11 wind turbines compared to the annual production. Even though it has been calculated to last for another 672 years, it is used in productions like wind turbine magnets and solar cells, and with an increase in these renewable energy sources, we will probably not have boron for this long either.

Balsa Wood and Plywood

From table 19 it shows that the 11 wind turbines in Hywind Tampen also consists of some wood, actually 17.160 kg of balsa wood, and 17.160 kg of plywood where in the latter it is unknown to the author what type of wood has been used. It has also not succeeded the author to find information about the annual production of balsa wood, nor the annual production of plywood as the wood type is unknown. However, it has been found information saying that balsa wood is a fast-growing tree, and that it is looked up on as sustainable because the balsa tree capture carbon from the atmosphere, while balsa products work as long-lasting carbon storage. And since it is such a fast-growing tree the timber is more sustainable than many other tropical timbers. Even though the tree type(s) used in plywood might not be just as fast growing, it should not be way off to consider it as being sustainable to a certain extent, as long as the harvesting does not get out of control. However, there has been reported about uncontrolled balsa harvesting in certain regions. As the demand for balsa wood has increased, and with that the harvesting, it has started to threaten ecosystems. Also, the COVID-19 pandemic we have been faced with during the last two years, has caused an increase of balsa wood harvesting. The pandemic has shut down the tourism industry in areas growing balsa wood, which in some places are the primary source of income, and to compensate for the outstanding money from the tourism the balsa wood harvesting has come out of control. The step in the balsa wood's life cycle that is probably dragging its sustainability most down is the transportation of the balsa wood to where it will be processed and used. Since most of the balsa wood comes from the jungles in Central and South America it is a long distance from the source to the place it will be processed, and then to the end user. There are emissions associated to the transportation of the wood. The end life of balsa wood is also sustainable if the wood is reused or burned as bioenergy. Using balsa wood for wind turbines can be sustainable thanks to the carbon capture during the products' relatively long life, but it is important that the wood is not illegally harvested, but rather logged in a controlled and sustainable way, that do not harm the forests' biosystem and accelerates climate change (Nguyen, n.d.).

Other factors and concerns related to the mining industry and wind turbine production

As already mentioned for the REEs, the mining industry do contribute to pollutive emission and radioactive radiation. Actually, the global metals and mining industry contributes to approximately 8% of the global carbon footprint. Mining per tonnes of the raw minerals bauxite and iron ore emit 0,03 tonnes of CO_2, and for the finished metal production of aluminium and steel 21,99 tonnes of CO_2 is emitted per tonne of production (Cox, Innis, Kunz, & Steen, 2022). If considering the numbers given above and then looking at the steel and pure aluminium used in the creation of one wind turbine: 522.730 kg steel and 7.808 kg pure aluminium, it gives a total of 530.538 kg (530,538 tonnes) of finished metals which emits 21,99 tonnes of CO_2 per tonne of production. This would mean that only the steel and pure aluminium used in one wind turbine emits around 11.667 tonnes of CO_2. In comparison 1 barrel (= 159 litre or 140 kg) of combusted oil emits about 400 kg CO_2 (Nøst, 2014) which would mean that 1 tonne of combusted oil emit around 2,86 tonnes of CO_2 which is a lot less than what is emitted when producing 1 tonne of steel and aluminium. This shows that the production of the materials needed to produce the Hywind Tampen wind farm, is not environmentally friendly. In addition to this, it is also CO_2 emission involved when transporting the minerals from the mines to where it will be processed, and all the way to the "end user", as well as the transportation involved when transporting the wind turbine pieces to its assembly destination. The author has not looked into any number related to this, but it goes without saying that it for sure is CO_2 emission related to this.

Another negative aspect related to the mining activity, are all the human suffering and civil wars that are related to natural resources and mining. In 2018 Denis Mukwege won the Nobel Peace Prize for the work he is doing helping people, especially women and children, that are victims of the terrible crimes done during war. In his speech for the Nobel committee and the rest of the world he blames the mining for natural resources as the main cause of war in his own country, Democratic Republic of the Congo. Here is an excerpt quoted from his speech:

> "*My name is Denis Mukwege. I come from one of the richest countries on the planet. Yet the people of my country are among the poorest of the world.*
>
> *The troubling reality is that the abundance of our natural resources – gold, coltan, cobalt and other strategic minerals – is the root cause of war, extreme violence, and abject poverty.*
>
> *We love nice cars, jewellery, and gadgets. I have a smartphone myself. These items contain minerals found in our country. Often mined in inhuman conditions by young children, victims of intimidation and sexual violence.*
>
> *When you drive your electric car; when you use your smart phone or admire your jewellery, take a minute to reflect on the human cost of manufacturing these objects.*
>
> *As consumers, let us at least insist that these products are manufactured with respect for human dignity.*
>
> *Turning a blind eye to this tragedy is being complicit.*
>
> *It's not just perpetrators of violence who are responsible for their crimes, it is also those who choose to look the other way.*" (Mukwege, 2018).

This is unfortunately the reality in many countries, the mining for natural resources cause war and human suffering, and it is very seldom the poor people living in the country benefits from the mineral richness of the country. In the book “Natural resources and violent conflict” I. Bannon and P. Collier writes that since the mid-1990s there has been an increase of research done related to the causes of civil wars. And one of the findings is that natural resources play a key role in triggering, prolonging, and financing these conflicts. Resource-related conflicts are specially a problem for the African countries. Out of the 17 resource-related conflicts mentioned in table 2.1 in the book, nine are in Africa. However, it is also mentioned that natural resources are never the only source of a conflict (Bannon & Collier, 2003, pp. 17-19).

These wars, conflicts, and human sufferings are also, sadly enough, the reality behind many of the minerals and materials used in wind turbines as well. Considering many of the African countries, the mining for these raw materials is not environmentally friendly neither from the nature nor at the human perspective.

4.6. Summary of analytical findings (4.1-4.5)

In section 4.1 calculations were done to get down to the raw materials used in each material used in the production of a Hywind Tampen wind turbine, and section 4.2 provides a table summing up all the materials used. It shows that we are using a bit of the Earth’s resources to make just one Hywind Tampen wind turbine. In section 4.3 calculations related to how much of the annual production the Hywind Tampen farm is consuming for each raw material is made, and an estimate of how many years we have left with the resources if we continue as of today. And section 4.4 provides a table with an overview of the finding in section 4.3. It can be seen that a few of the raw material do not have many years left, if continuing the annual production as we currently do, and some of the REEs used in wind turbines do not have a very high annual production. In the last section, 4.5, an analyse of the most outstanding materials found in table 18 and 19 are made, and some of the environmental impact the mining industry got. It shows that some raw materials are only extracted in some countries, which is not good in the case of conflicts and war, an article written about USA’s target for the wind industry will demand more REEs than what has been estimated that we have in our reserves, mining for REEs takes place under terrible conditions and the workers are exposed to 40-80 times higher doses of radiation than miners in the nuclear power industry, and the mining industry is a threat to the wildlife. In addition to the CO_2 emission coming from the mining and the production of a finished metal, and the war and conflicts related to the mining industry.

The amount of the different materials given in this master’s thesis are actual figures given by SGRE as the wind turbine vendor for Equinor’s Hywind Tampen project. Equinor can use and develop further the calculations done in this master’s thesis for other activities and tasks within the company.

5. Forecast areas for potential improvements and other recommendations

Even though the fact is that no matter what energy resource we use from today's technologies, we will be spending resources from Earth that eventually will go empty. However, we can take actions that might mitigate this from happening too soon, so it could be possible to supply resources for a longer time than what seems to be the timeframe at the moment. In this chapter it will be discussed forecast areas for potential improvements and other recommendations and initiatives that can be taken to mitigate the world from running out of resources too fast and too soon.

5.1. Reduction of non-sustainable raw material usage

In table 19 it can be seen that a lot of raw materials are used in the production of the Hywind Tampen wind farm, and that some of the materials are soon running out sooner than others. A potential area for improvement when it comes to the production of wind turbines could be to find more sustainable materials like wood to be used in the production. Or if possible, use more of the raw materials we have a lot of, to save the ones we do not have that much of. Looking at whether it is possible to make the material and components more efficient, could also be an option. Would it, for example, be possible to make the NdFeB magnet more efficient using the same or less raw materials?

Direct-driven drivetrain wind turbines uses PMGs (magnets) that consist of REEs, and they require a bigger generator than wind turbines using gear boxes. This means that more raw materials, and materials that are difficult to get, are used in direct-driven turbines. To save the raw material usage it might be an idea to use gear box instead of direct-driven. However, the downside of using gear box is probably more maintenance and the enormous, complexed gear boxes that might be required as the wind turbines becomes larger and more effective. It will probably be a choice between size, capacity, and maintenance cost, versus the raw material usage.

Oil is one of the raw materials that are used in the production of wind turbines, and it is a material that we might be running short of. An improvement could be to try to reduce the oil usage in Epoxy or substitute it with something that do not require oil if possible, and another non-oil material for lubrication and maintenance purposes.

5.2. Recycling and reuse

Probably the number one criterion when it comes to improve and defend the wind turbine production in order to achieve a more sustainable approach, is recycling and reuse. The total wight amount of material used to produce a Hywind Tampen wind turbine, including the tower, nacelle, and blades, is 756.787 kg (ref. table 3), in addition to the foundation and the wasted material during the production process. This is a lot of material to be recycled. In the future we will have many millions of tonnes of wind turbine waist, and we will have to build an industrial recycling technology that can handle all this waist. The main challenge when it comes to recycling of wind turbines is the blades. The blades made of fiberglass are difficult to recycle as it is difficult to separate the different materials, and the materials are difficult to reuse after being recycled. However, the Vanderbilt University in Nashville Tennessee USA has come up with a new recyclable resin (Epoxy) that will make wind turbines more sustainable, as the raisin used on the fibreglass of the blades can be melted down during recycling, and then the fiberglass can be reused in other manufacturing applications. This means that we do not have to throw the fiberglass away and put it in a landfill (Adams, 2018). A good and well working industry for recycling is alfa omega in the process of making wind turbines more sustainable.

Even though this thesis is related to wind turbines, this is of course the case for all renewable energy sources (solar power, hydropower, etc.) and devices made for lowering the carbon footprint, in addition to all the electrical devises that we use (electrical vehicles, batteries, iPhones, iPads, etc.).

5.3. Lifetime improvement

As of today, a good quality wind turbine will generally last for about 20-25 years, but this could be further extended with good maintenance and service procedures, replacement of worn-out parts, and material improvements. A good maintenance strategy and monitoring of the wind turbine components will help detect failure at an early stage, and to be proactive in the maintenance work. This would probably also prevent longer down time due to big mechanical failure or damage, which will increase the wind turbine efficiency. However, more frequent maintenance and monitoring tools will be costly, and the maintenance costs will increase as the wind turbine gets older as the worn-out parts will demand more maintenance as the years goes by. Technology that might be able to lower the maintenance and operational cost could be the use of drones and artificial intelligence.

Lifetime improvement is also applicable for other renewable energy technologies, not only for wind turbines. By improving both the lifetime and capacity of our existing hydropower technology for example, we should also be able to save the environment for the usage of raw materials and CO_2 emission.

5.4. Help reducing war and human suffering related to the mining industry

This recommendation is easy to say, but difficult to act on, as there are so many involving parts and, in many countries, missing transparency which in many cases leads to a lot of corruption and human exploitation. Most people in the world like to live in peace, but unfraternally many people don’t. As mentioned earlier, the mining industry is one of the sources to war and conflict in many African countries, and western companies should take more responsibility towards preventing this from happening. Companies should be more aware of where their minerals and metals are coming from and set some criteria to what they do not find acceptable. Child labour is very common in African countries as the labour is cheap, many people living in poverty depends on their children to work to help feed the family, in addition to children being small and then able to reach places in the mines where adults cannot. Making sure of no child labour and that employee of the mining industry got sufficient work clothes, protections, and safety in their working environment should be a minimum requirement, in addition to a viable salary. In addition to this, companies should look at the country's conflicts and war situation and try to avoid buying minerals and raw materials from countries in these situations. These countries should be on an unattractive list of countries from which minerals and raw materials are purchased. It should be a criterion that the resources coming from the country should benefit all its citizens, and corruptions should not be accepted, but this would be difficult to carry out unless all the companies in the world would have a common agreement on this. If only some companies follow up on this, the author is afraid they will lose out and get problems getting the raw materials and minerals they need, and the companies that do not care will win. Companies that do not care will have more raw materials and minerals to choose from, and they will probably be able to press the prizes even lower as the demand of these countries' products will go down, which will contribute to a worse situation for the mine workers. On the other hand, having some companies being the first working towards this, and showing that some things should not be accepted in this business, would be a start, and then maybe more would follow, but it can be tough.

5.5. Energy storage

Another technology worth mentioning in this concept is energy storage, which already got some attention these days. As most of the energy we produce today is so called "fresh produce", which means it must be used as it is produced as it cannot be stored, we are now working on technology that will store excess energy. How the situation is today in many countries is that we are able to produce the most energy when we need it the least. Like during the summertime there are a lot of sun and wind, which is used to produce electricity, but at this time some countries do not need that much electricity as it is warm outside and no need for heating up homes, at the same time as it is not so warm that a need for air conditioner. During this time, it would be smart to store the excess energy for the winter, when more energy is needed. However, the dilemma with this when considering the main objective with this master's thesis, is that to be able to store a big amount of energy we need a lot of huge batteries, which consist of raw materials looked at in this thesis, and which we soon will run out of if we are not doing anything about it. So even though storing the energy is a good though, it will require a lot of raw materials from the Earth, but on the other hand, it could be that storing energy would reduce the need of wind turbines and other renewable energy technologies. Then the question would be what is the best thing to do? To get an answer to that, considerations like what technology is using less raw materials and what is the lifetime for the technologies, as well as the recycling part, should be looked at. Would it be easier to recycle and reuse materials used in a big battery, or would it be better to recycle a wind turbine?

5.6. Energy efficiency and reduction

Together with recycling and reuse, the author believes that energy efficiency is the key to the problems we are about to face. This improvement recommendation is not related to improvement for the wind energy industry, but an improvement to be taken by us, the human beings living on this planet. The author would like to mention this, as this is such an important act to be taken. As we become more and more people on this Earth, we cannot continue to waist energy the way we are doing today. We need to sharpen up, especially the people from the rich part of the world, and other rich people living in other parts of the world. We cannot spend energy on heating up our driveways, cars, garages, private swimming pools and saunas, fly all over the world and so on just because we can afford it. We need to start thinking about all the energy we waist just because we can, and just because we want to have a better life. In addition, we need to use the energy more efficient. We need to build smarter and use the energy we already have, more efficient in our buildings. Examples could be the use of trombe wall, a heavy-weight wall behind a large window used to store and distribute the solar heat, and buildings built in such a way that it gets shade in the summer and warmth from the sun in the winter based on the sun’s different position during summer and winter time. And factories that are already producing heat through their production, which is waisted, could be laid in pipes and transported to areas in the need of some extra heating, instead of it going to waist.

6. Discussion and conclusion

The initial intention of this master’s thesis was to get an overview of the raw materials used in the production of one of Equinor’s wind farm projects, Hywind Tampen, and look at the wind turbines sustainability and the impact on the environment related to its production. As this thesis has shown, about 756.787 kg of materials are used just to produce one Hywind Tampen wind turbine. Information was gathered from different companies to be able to get down in details, as much as possible, to the raw materials used in the production. Then a search for each raw material’s annual production and reserves were made, to establish the productions sustainability regards to the Earth’s resources. In addition, research was done to find out the environmental and human impact the mining and production of the raw material and the final material used, have. A summary of all the raw materials used in producing one wind turbine are presented in table 18. And an overview of the total amount of raw materials used for the whole wind farm, the annual production of each raw material, the percentage used for the Hywind Tampen farm out of the annual production, estimated reserves for each raw material, and estimated years left with resources assuming a constant annual production, is present in table 19. Then an analyse of the raw material usage and the environmental impact was given in section 4.5. Before potential improvements and other recommendations are provided in chapter 5.

6.1. Practical challenges

The main challenge writing this master thesis was to gather information related to the natural raw materials used in the production of a wind turbine. SGRE could only provide information on a high level related to the wind turbine production, so interactions with companies producing products used was needed to get more detailed information about the raw materials used. SGRE could also not tell me who their subcontractors for the different products were, meaning that the companies helping with product information in this master's thesis might not be the exact same companies used in the production of the Hywind Tampen wind turbines.

A product that was not provided any detailed information about, was the plastic material polyurethane (PU), so in the case of this product no calculation has been provided.

Another challenge was when calculating the amount of crude oil used in different products. As the different oil qualities can be refined into different quantity of other products like benzene, ethane, and propane, depending on how the conditions have been in the reservoir when the oil was formed and how it has been stored, it will not be accurate calculated as only one crude oil sample taken from Johan Sverdrup in 2021 has been used in this thesis. By using another sample from a different oil field, could have resulted in less crude oil usage if the oil sample contained more benzene, ethane, and/or propane.

The calculation of propylene (also used in glycerine) was a challenge as well, as this product can be produced in more than one way and from more than one product, which gives different results. On Equinor's refinery at Mongstad they use catalytic cracking to produce petrol as the main product, and where propylene is a by-product called Refinery Grade Propylene (RGP) which got a purity of 70% propylene, and the rest is basically propane. However, steam cracking is a more efficient way of producing propylene. This propylene is produced at petrochemical plants and is called Polymer Grade Propylene (PGP) and contains 99,5% propylene and 0,5% propane, which is used in producing glycerine. The products used to steam crack propylene is ethane or propane which are gasses, or naphtha which is in liquid form. The calculation of propylene in this master's thesis is based on information given by a specialist in chemicals who used to work in the propylene business, where propane has been steam cracked into propylene using the crude oil data from the Johan Sverdrup sample in 2021.

Since it is unclear if this is the best way of producing propylene, and if the Johan Sverdrup reservoir is the optimal crude oil to be used producing propylene, the calculation of crude oil used in producing these wind turbines is probably not reflecting the true quantity, but more giving an idea of how much crude oil is used.

6.2. Learning points

This master's thesis has been a very interesting and educational journey, where the author has learned a lot about how wind turbines work, how they are built, the raw materials used, the minding of the raw materials, and the impact mining for these raw materials have on the environment and the humans. It is an extreme quantity of raw materials that are used in the production of one wind turbine, but one of the biggest surprises to the author was the amount of oil that is needed for one wind turbine. Even though another oil sample would have given less amount of oil, it is very surprising that if oil from a Norwegian oil field was used, it would have required 1,16 million barrels of oil only to produce the 11 wind turbines for the Hywind Tampen farm. This is a lot of oil which the author did not expect. Then the casual relationship between exposure to benzene and the development of leukaemia that has been found, and the significant lower white blood cell and platelet counts reported for workers exposed to benzene are somethings the author was not aware of.

Learning about the rare earth elements (REEs) have also been instructive as the author was not aware of such elements. And then to learn that they are not that rare after all, just difficult to separate from other minerals and lack of companies mining for them. That China is the leading market with 97% of the REEs production was also a surprise. And it was not at all known to the author that mining for REEs exposes you to 40-80 times higher doses of radiation than mining for elements used in nuclear power industry.

To produce 1 tonne of aluminium and steel a total of 21,99 tonnes CO_2 are emitted, and during the combustion of 1 tonne oil it emits about 2,86 tonnes of CO_2. It surprises the author that producing 1 tonne of aluminium and steel emits almost 8 times more CO_2 than the combustion of 1 tonne oil.

Then last but not least, the discovery of the key role natural resources has in triggering, prolonging, and financing wars and conflicts, and all the human suffering related to this. That a country blessed with the richness of natural resources should be a curse to most of the people in the country is a paradox, and really sad. And the most heart-breaking learning when working on this thesis was to read Denis Mukwege's speech after he won the Nobel Peace Prize. The author encourages everyone who has not read his speech to read it, it is really an eye opener.

6.3. Conclusion

To be able to make a conclusion, let us first look at the word “sustainability”, what does it really mean when “something” is sustainable? In the Summery chapter of this thesis a definition of the word “sustainability” is written, taken from the book “Energy and Climate change” written by D.A. Coley (Coley, 2008, p. 27). It says that something is sustainable when the resource is being replenished at roughly the same rate as it is being used.

So, what does this mean when it comes to wind turbines? Wind turbines are described as sustainable because they use the wind to create electricity, and the wind is being replaces at the same rate as it is being used. Meaning, it doesn’t matter how much wind we use because there will always be more as long as the sun is shining. But is the production of the wind turbines sustainable? The initial answer to that would be “no” because all the raw material we use to create them is not being replaced at the same rate as it is being used. Actually, it is not being replaced at all.

However, it could be possible to make them sustainable, or at least make them “more” sustainable by looking at the recycling process. As it has been shown in this master’s thesis a lot of raw materials found in the Earth’s crust is used to produce the wind turbines, and these elements are not unlimited and as far as we know, they will not be reproduced in the near future. If we are able to recycle and reuse most of the metals used in the production of wind turbines, we are a step closer to make wind turbines sustainable when it comes to material usage. However, it also depends on the usage and recycling ratio, meaning are we able to recycle a component 100% or will material be lost during the recycling process? It is reasonable to believe that material will be lost along the way, and that we are not able to recycle and reuse everything 100%, which would mean that we always will have to add new raw material to the production. However, the new added material will hopefully be a lot less than the material reused. In this way we will be using from the Earth’s resources, but we will be using less, and thus the Earth’s reserves will last longer.

The biggest problem, as of today when it comes to recycling wind turbines, is the wind turbine blades made of fibreglass. Fibreglass is difficult and expensive to recycle, and it is difficult to reuse the recycled product. However, as already mentioned in section 5.2, the Vanderbilt University in the USA is working on a new raisin to be used in the production of wind turbine blades, that will make the recycling of these even easier. There is one positive thing when it comes to the wind turbine blades and that is, next after the oil used in the Epoxy for the blades silica (SiO_2) is the second most used raw material in the blade, and silica has been estimated to unlimited when it comes to Earth’s reserves. But what has not been looked into here and is unknown to the author, which should be considered, is the amount of energy that might be needed in the recycling part. The recycling will definitely involve electricity and other energy sources which will most likely contribute to CO_2 emission, and electricity that could have been used for something else.

Depending on how good the recycling part is, it will have an effect on whether new mines are required or not. As noted in this thesis the mining industry is not good for the environment, wildlife, and the humans, so if we are able to recycle the wind turbines in an efficient way, we might not have to start up new mines, or be able to close one before a new one is started. In this way we will protect the environment more.

The only material that the author sees as a problem to be recycled and reused, is the oil spent in the production and the maintenance of the wind turbines. Most of the oil used in the production of a wind turbine is used in the Epoxy, so the question is how easily can the Epoxy used on the wind turbine blades be recycled and reused? And can it be reused as Epoxy for another wind turbine, or will it be used for something else? Today most of the wind turbine blades are buried in landfills underground, and a few are ground up (crushed) leaving a lot of ground up turbine blades which are difficult to reuse. This means that the oil used in the wind turbine blades are not recycled back to something that can be used in another wind turbine. In other words, the oil used in a wind turbine must be coming from new crude oil pumped up from below. If the raisin provided by the Vanderbilt University, which per the author's understanding, will be melted off the fiberglass of the wind turbine during recycling, can be reused in another raisin, is unknown to the author. If that is possible, then the author believes oil can be speared, but if that is not possible, then we will have to use freshly pumped crude oil to produce wind turbines, which will not be sustainable as oil is a limited resource. Then we will have to try and substitute the oil with something that can be recycled.

To be able to draw a conclusion whether wind turbines are sustainable or not, the author will look at: 1) A single wind turbine being produces, 2) Meeting the world's demand and goals in just a few years.

A single wind turbine being produced

If the author consider the wind turbine as just one product produced (or just a few in a farm like in Hywind Tampen) and assume that there are good recycling procedures in place which can recycle close to 80% and 90% of the material for reuse in another wind turbine, and the companies set some criteria for the countries producing the raw material, then the authors conclusion would be that wind turbines can be close to sustainable. The author will argue for this conclusion as follows: if good recycling procedures are in place, and the recycled materials can be used for new wind turbines, then it will not be a need for too much of freshly mined raw materials, which would mean that the mine industry will not need to increase due to wind turbine production, and the wind turbines will be using a lot less of the annual raw material production. That the author concluded "close to sustainable" is due to the fact that as long as we cannot recycle a wind turbine 100% and making a new wind turbine out of the recycled material, there will be used raw materials from the Earth's crust which is not an unlimited resource as it is not reproduced.

However, if our recycling procedures are not that good meaning that maybe only 50% of the wind turbine can be recycled, or if the oil used in the production cannot be recycled in such a way that it can be reused for Epoxy, then wind turbines will not be that sustainable, as it will be using more of the Earth's resources that eventually will go empty. Even if the wind turbine is more than 80% recyclable but very little of the recycled material could be used to produce a new wind turbine, wind turbines would not be sustainable as the production of new wind turbines to replace the decommissioned ones would require just as much freshly mined raw materials. In other words, if for example the turbine blades containing among other aluminium, magnesium, lithium, and Epoxy made from oil, is ground up and used in something totally different like concrete, then it would not be sustainable because concrete cannot be used in turbine blades. Meaning that it will save the Earth's reserves used for concrete, but the wind turbine production will continue to use the same amount of aluminium, magnesium, lithium, and oil to produce blades for the new wind turbines.

Meeting the world's demand and goals in just a "few" years

The author does not believe that one can justify the question of whether a wind turbine is sustainable or not just by looking at one single turbine or a small farm. The author believes that in order to assess this more fairly it must be looked at in a bigger picture. What is our goal for the next few years when it comes to shaping the future wind energy?

In a report called "Future of wind" written by IRENA (International Renewable Energy Agency) it is mentioned that the growth needed in wind power to archive Paris climate goals is that it must reach 6.000 GW - over 10 times the current level - by 2050, which would include 5.000 GW of onshore wind and 1.000 GW of offshore wind (Prakash et al., 2019). If considering this amount of power, and assuming that onshore and offshore wind turbines do require pretty much the same amount of raw material, which should not be way of assuming, then 750.000 Hywind Tampen wind turbines would be required within 2050 (one Hywind Tampen wind turbine is 8 MW). This also assumes that the wind turbines are producing 8 MW all the time, which is not the case. The wind is blowing at different speed meaning that sometimes it produces nothing (if no wind or if it has to be shut down due to too much wind or maintenance), other times below its capacity when little wind, and other times it produces its capacity. In other words, it will actually require more than 750.000 Hywind Tampen wind turbines, but the author will in this case assume 750.000 Hywind Tampen wind turbines. The author will also assume that the recycled turbines and their reuse of material during this time will be neglectable and the production start will be 2022.

If looking at neodymium (Nd) table 18 shows that one wind turbine requires around 346 kg Nd, to produce 750.000 it will require 259.500.000 kg Nd. From table 19 it is shown that the estimated reserve of Nd is 8.000.000.000, this would mean that about 3,24% of the world's reserves of Nd will be used to meet the Paris agreement, by 2050. If assuming a constant production every year, the annual production of Nd must be about 9.267.857

kg to meet the wind turbines requirements. This is 2.267.857 kg (~32,4%) more than the current annual production shown in table 19. To meet this demand, the mining industry would have to increase. Keep in mind that this is just the requirements for the wind turbines, in addition all the other products, devices, and constructions using Nd must be accounted for.

The same calculations can be done for dysprosium (Dy) where 96.000.000 kg will be necessary to produce the 750.000 wind turbines. Since the world's reserves for Dy is unknown to the author, it is not possible to estimate how much this would be out of the world's reserves, but with a constant yearly production during the 28 years from 2022 to 2050 the annual production of Dy must be 3.428.571 kg which is 3.328.571 kg (about 34 times) more than the current production. Meaning that mining for Dy must increase drastically.

For praseodymium (Pr) it will require around 9.000.000 kg of Pr, which would be 0,45% of the world's estimated reserves. With a constant annual production throughout the 28 years until 2050, the annual usage of Pr for the wind turbine production would be 321.429 kg. Meaning that the material used as a percentage of annual production of Pr in the wind turbine production will be 12,86%. When looking at the results for Nd and Dy above, where it clearly shows that an increase of annual production is needed to meet the future goal for wind power, it also tells me that right now we are producing far from what is needed to meet the Paris agreement. Therefore, it will be reasonable to believe that if 12,86% of the current annual praseodymium production will go to the next 28 years of wind turbines, the yearly mining for this element also would have to be increased.

Copper (Cu) is the element with the shortest lifetime, according to table 19, with 42 years. To produce 750.000 Hywind Tampen turbines around 13.889.250.000 kg copper would be needed, which is about 1,58% of the world's reserves. If a constant yearly production is preserved, then 496.044.643 kg will be required produced every year for the wind turbines. This would mean that around 2,36% of the current annual production of copper will go to wind turbines the next 28 years. For the same reason as for praseodymium, above, it is reasonable to believe that the yearly production of copper also needs to increase to meet the Paris agreement. So, then it goes without saying that we do not look at 42 years left with copper anymore.

The same as stated for the raw materials mentioned above, is reasonable to believe will yield for all other raw material used in wind turbines as well. As the findings for neodymium and dysprosium indicates that we, as of today, are far from the wind turbine production, which is needed to meet the Paris agreement, it would be reasonable to believe that most, if not all, of the raw materials in table 19 must increase its annual production to meet the Paris agreement. However, the author would still like to look at 3 more raw materials: steel, aluminium, and oil. Together with the elements calculated above the calculations of the 3 last raw materials will be given directly in the table below:

Material/Element/ Metal	Total raw material usage for 750.000 wind turbines [kg]	Annual raw material consumption for the wind turbines the next 28 years [kg]	Current estimated raw material annual production [kg]	Material used as a percentage of current annual production [%]	Material used as a percentage of estimated worldwide reserves [%]
Neodymium (Nd)	259.500.000	9.267.857	7.000.000	132,4	3,24
Dysprosium (Dy)	96.000.000	3.428.571	100.000	3428,57	Unknown
Praseodymium (Pr)	9.000.000	321.429	2.500.000	12,86	0,45
Copper (Cu)	13.889.250.000	496.044.643	21.000.000.000	2,36	1,58
Steel	392.047.500.000	14.001.696.430	Not calculated	Not calculated	Not calculated
Aluminium (Al)	5.856.000.000	209.142.857	Is given in Al_2O_3	Not calculated	Not calculated
Crude oil	11.112.237.930.000	396.865.640.400	4.530.240.763.000	8,76	4,74

Table 20 Raw material usage for 750.000 Hywind Tampen wind turbines

Table 20 above shows the total amount of raw material needed for 7 of the raw materials used in a wind turbine if 750.000 wind turbines were to be produced in the next 28 years, from 2022 to 2050. Then it shows annual material needed for the 750.000 wind turbines if a constant production during the 28 years, the current estimated annual production of the raw material, the material needed for the production as a percentage of the current annual production, and how much of the world's reserves the total materials needed for the 750.000 wind turbines are, in percentage. Material used as a percentage of the current annual production for neodymium and dysprosium shows more than 100%, that is because the raw material needed for the 750.000 wind turbines is more than the current annual production, meaning that currently the annual production of the raw material is too less to meet the demand.

The reason why the author wanted to look at steel and aluminium (note: only the pure aluminium usage has been looked at, and not the aluminium oxide) is because of the information given earlier mentioning that the production of 1 tonne of aluminium and steel emits a total of 21,99 tonnes CO_2. From table 20 it can be calculated that the total amount of steel and aluminium needed for the 750.000 wind turbines is 397.903.500 tonnes, which would mean that to produce the aluminium and steel needed for these wind turbines it will emit 8.749.897.965 tonnes of CO_2, or about 8,75 billion tonnes of CO_2. If considering a constant production during the 28 years, it would mean 312.496.356 tonnes CO_2 per year, or 312 million tonnes CO_2 per year. As a comparison, the annual combustion emissions of oil and gas from Norway are approximately 500 million tonnes CO_2 (Naturvernforbundet, 2019). And this is only for the steel and aluminium production, then the emission from the rest of the materials must be added as well.

The author also wanted to look at the numbers for the crude oil. As table 20 shows, these 750.000 wind turbines will require 4,74% of the estimated worldwide reserves, and 8,76% of the current annual production every year for the next 28 years. If during these 28 years other areas do not decrease their oil consumption, it would be reasonable to believe that we will have to increase the oil production to meet our goal. And that would be the opposite of what we currently are trying to do.

Summary

If looking at one wind turbine, or the Hywind Tampen farm as just one project, and assuming there are good recycling procedures, wind turbines would be close to sustainable, but if looking at the wind turbine industry globally and the demand for wind power to meet the Paris agreement, then initially the picture might look a bit different. A lot of the worlds resources will be used to meet this goal, and a bit of the problem here is that the wind turbines will substitute the electrical power generated from fossil fuel (oil, gas, and coal) to mitigate CO_2 emission, it will not be reducing the need for these raw material in other products, meaning the world will still need just as much and probably more of these raw materials in the future. Meaning by trying to solve one problem, the CO_2 emission, another problem has been created, the rapidly increased use of Earth's resources. In addition to this, more mining industries must be developed, causing more damage to the Earth and its people.

If the author only consider the resources used to produce all the wind turbines needed to meet the Paris agreement, and assume that a lot of the recycled material from a wind turbine can be reused in another wind turbine (80%-90%), then the author will still consider wind turbines as close to sustainable as we around 2050 probably will decommission and recycle our "first" created wind turbines, to be able to create new ones, which then should require less usage of freshly mined raw material. And even though the production of wind turbines does emit CO_2, and maybe even more than initially thought, the author believes that wind turbines are a better option than fossil fuel when it comes to CO_2 emission as 70-95% of the fossil fuels energy is converted to thermal energy, and then only 20-40% of this is converted into mechanical energy where 90-95% of this again becomes electrical energy, while 90-95% of the mechanical energy produced in a wind turbine is directly converted to electrical energy (Coley, 2008, p. 166). However, if the increase in the mining industry also is taken into consideration, ruining landscapes, and wildlife, and even being the cause of war and conflicts in some countries, in addition to the poor working conditions some of the works are exposed to at the moment, then maybe wind turbines will not be that sustainable after all. It is difficult for the author to conclude for sure, as it is not known how many more mines that would be needed to meet the demand, and how many more wars and conflicts this would generate, but that more raw material needs to be produced, that is for sure. There is also another definition of sustainability that says: "*Sustainability means meeting our own needs without compromising the ability of future generations to meet their own needs*" (University of Alberta, n.d., p. 1), and per that definition the author believes the wind turbine industry will fail, as the author believes we are compromising the ability of future generations to meet their own needs when we today are destroying wildlife, nature, and some countries due to war, to achieve our goal for wind power.

However, the fact is that we need energy like electricity and heat, and we need to get it from somewhere. And if the choices stands between fossil fuel and wind turbines, the choice should be simple, in the author’s mind, not just only due to the lower CO_2 emission, but also due to the fact that fossil fuel energy is only using raw materials (oil, gas, coal) without being able to do any kind of recycling of the used fossil fuel, while wind turbines can be recycled, and no matter how much is recycled and reused, wind turbines should be more sustainable than fossil fuel due to the fact that wind energy can be recycled, and fossil fuel cannot. The danger with this renewable energy turnover that we are making, is that if the Earth’s resources for metals and lanthanides is becoming the new oil, then we can be facing problems if we are not able to recycle what we use back to its pure original raw material, or at least close to it.

Even though wind turbines are sustainable once they are up and running, as wind is reproduced all the time, it is not sustainable to produce them and to decommission them. Every one of us should understand and take inward that what we use from the Earth’s resources, no matter what it is for (wind turbines, hydro power, solar cells, electronic devices, batteries, etc.), are not reproduced or replaced. We can make our usage more sustainable by recycling, but we need to start recycling everything, not just the big constructions as wind turbines, but also the small devices as well like, iPhones, PCs, laptops, batteries, dishwashers, wash machines, TVs, cars, and so on. And we need to stop our over-consumption of electricity and purchase of electronic devises.

6.4. Future work

Future work and master’s thesis suggestions related to or building on this master’s theses could be:

- CO_2 emission related to the production and installation of a wind turbine.
- CO_2 emission related to the decommission of a wind turbine and/or the energy used for decommissioning.
- CO_2 emission related to the mining industry.
- The mining industries’ damage to landscape, wildlife, and humans living conditions.
- Wind turbines damage to the wildlife.
- Improving the production and lifetime of a wind turbine.
- Streamlining of wind turbines maintenance and service.
- Maintenance and service costs related to a wind turbine’s lifetime.
- The cost related to the production and installation of a wind turbine.
- Material waist during wind turbine production.
- Material usage for energy storage and its environmental impact.
- CO_2 emission related to energy storage.
- How efficient is the recycling of a wind turbine? How much of the materials are reused in other wind turbines?

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7. Appendix

7.1. Molar Mass M calculation of the different molecules/compounds in FR 2930543

The molar mass M is the mass m [g] of a given chemical element or chemical compound divided by the amount of substance n [mol]. The molar mass M [g/mol] of a compound can be calculated by adding the standard atomic masses (in g/mol) of the constituent atoms. 1 mole = $6{,}022 \cdot 10^{23}$ atoms, molecules, protons, etc.
Ref. (Lumencandela, n.d)

Molar mass M [g/mol] data fetched from the Periodic table of the elements:
periodesystemet – Store norske leksikon (snl.no)

Total Glass Fiber used: 54,614 tonnes:
Mass m of SiO_2 (60,5%) = (54,614*60,5%) / 100 = 33,04147 tonnes = 33 041 470g
Molar mass, **M_{SiO_2}** = M_{Si}+M_{O2} = 28,08g/mol + (2*16g/mol) = 60,08g/mol

Mass m of Al_2O_3 (19,9%) = (54,614*19,9%) / 100 = 10,868186 tonnes = 10 868 186g
Molar mass, **$M_{Al_2O_3}$** = M_{Al2}+M_{O3} = (2*26,98g/mol) + (3*16g/mol) = 101,96g/mol

Mass m of CaO (7,7%) = (54,614*7,7%) / 100 = 4,205278 tonnes = 4 205 278g
Molar mass, **M_{CaO}** = M_{Ca}+M_O = 40,08g/mol + 16g/mol = 56,08g/mol

Mass m of MgO (9,5%) = (54,614*9,5%) / 100 = 5,18833 tonnes = 5 188 330g
Molar mass, **M_{MgO}** = M_{Mg}+M_O = 24,31g/mol + 16g/mol = 40,31g/mol

Mass m of Na_2O (0,2%) = (54,614*0,2%) / 100 = 0,109228 tonnes = 109 228g
Molar mass, **M_{Na_2O}** = M_{Na2}+M_O = (2*22,99g/mol) + 16g/mol = 61,98g/mol

Mass m of K_2O (0,5%) = (54,614*0,5%) / 100 = 0,27307 tonnes = 273 070g
Molar mass, **M_{K_2O}** = M_{K2}+M_O = (2*39,10) + 16g/mol = 94,2 g/mol

Mass m of Li_2O (1,4%) = (54,614*1,4%) / 100 = 0,764596 tonnes = 764 596g
Molar mass, **M_{Li_2O}** = M_{Li2}+M_O = (2*6,94g/mol) + 16g/mol = 29,88g/mol

Mass m of TiO_2 (0,13%) = (54,614*0,13%) / 100 = 0,0709982 tonnes = 70 998,2g
Molar mass, **M_{TiO_2}** = M_{Ti}+M_{O2} = 47,87g/mol + (2*16g/mol) = 79,87g/mol

7.2. The moles n and mass m calculation of the different molecules/compounds in FR 2930543

For a quantity of substance with mass **m** consisting of **n** moles, the molar mass **M** is for this substance:
M[g/mol] = **m**[g] / **n** [mol] <-> **n**[mol] = **m**[g] / **M**[g/mol] <-> **m**[g] = **M**[g/mol] * **n**[mol]
Ref. (Wikipedia, n.d.)

$n_{SiO2} = m_{SiO2}/M_{SiO2}$ = 33 041 470g / 60,08g/mol = 549 957,8895mol
$m_{Si} = M_{Si}{*}n_{SiO2}$ = 28,08g/mol * 549 957,8895mol = 15 442 817,54g = 15,44281754 tonnes
$m_{O2} = M_{O2}{*}n_{SiO2}$ = (2*16g/mol) * 549 957,8895mol = 17 598 652,46g = 17,59865246 tonnes
Test: $m_{Si} + m_{O2} = m_{SiO2}$ = 15 442 817,54g + 17 598.652,46g = 33 041 470g

$n_{Al2O3} = m_{Al2O3}/M_{Al2O3}$ = 10 868 186g / 101,96g/mol = 106 592,6442mol
$m_{Al2} = M_{Al2}{*}n_{Al2O3}$ = 2*26,98g/mol * 106 592,6442mol = 5 751 739,08g = 5,75173908 tonnes
$m_{O3} = M_{O3}{*}n_{Al2O3}$ = (3*16g/mol) * 106 592,6442mol = 5 116 446,922g = 5,116446922 tonnes
Test: $m_{Al2} + m_{O3} = m_{SiO2}$ = 5 751.739,08g + 5 116.446,922g = 10 868 186g

$n_{CaO} = m_{CaO}/M_{CaO}$ = 4 205 278g / 56,08g/mol = 74 987,12553mol
$m_{Ca} = M_{Ca}{*}n_{CaO}$ = 40,08g/mol * 74 987,12553mol = 3 005 483,991g = 3,005483991 tonnes
$m_{O} = M_{O}{*}n_{CaO}$ = 16g/mol * 74 987,12553mol = 1 199 794,008g = 1,199794008 tonnes
Test: $m_{Ca} + m_{O} = m_{CaO}$ = 3 005 483,991g + 1 199 794,008g = 4 205 277,999g

$n_{MgO} = m_{MgO}/M_{MgO}$ = 5 188 330g / 40,31g/mol = 128 710,7418mol
$m_{Mg} = M_{Mg}{*}n_{MgO}$ = 24,31g/mol * 128 710,7418mol = 3 128 958,133g = 3,128958133 tonnes
$m_{O} = M_{O}{*}n_{MgO}$ = 16g/mol * 128 710,7418mol = 2 059 371,869g = 2,059371869 tonnes
Test: $m_{Mg} + m_{O} = m_{MgO}$ = 3 128 958,133g + 2 059 371,869g = 5 188 330,002g

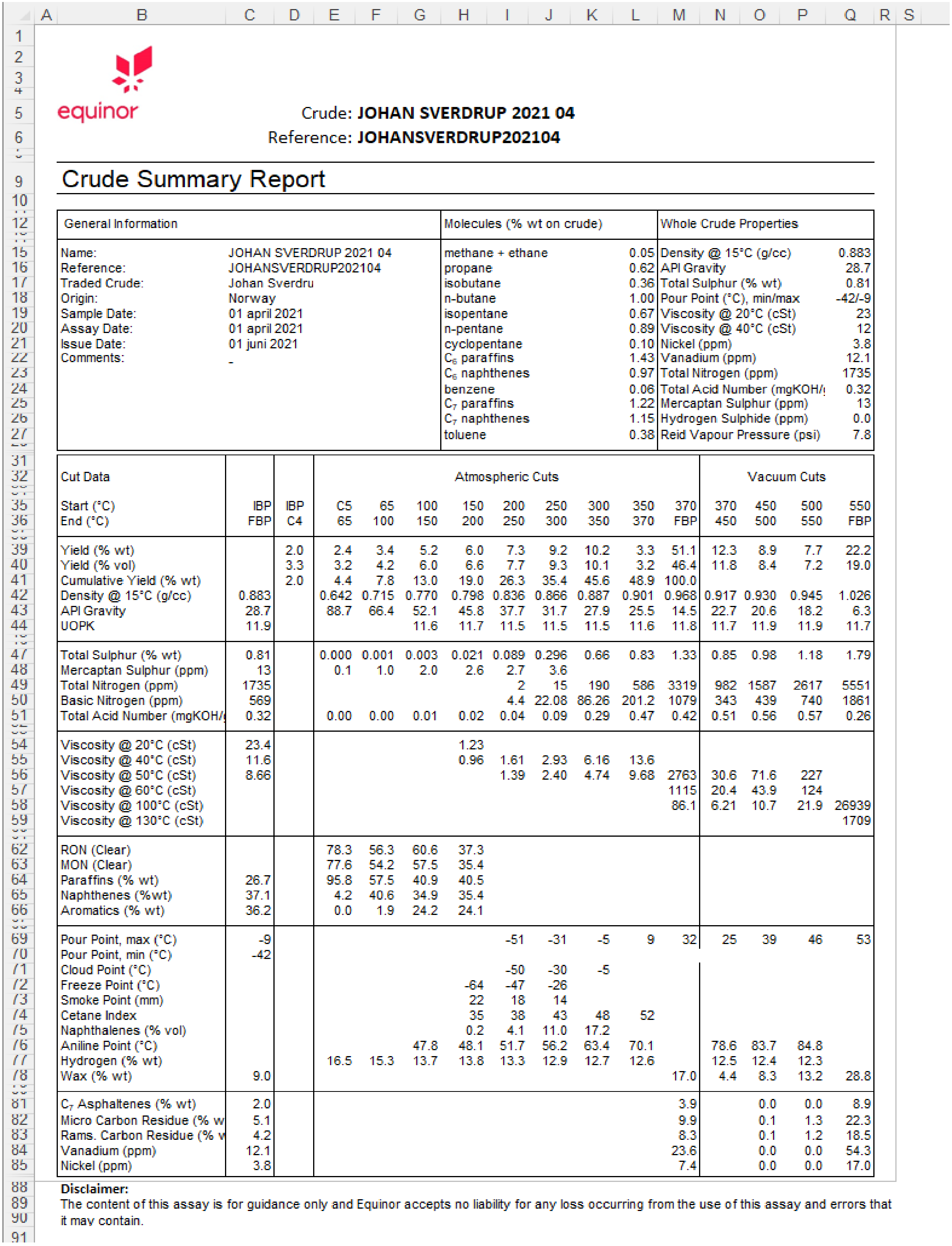
$n_{Na2O} = m_{Na2O}/M_{Na2O}$ = 109 228g / 61,98g/mol = 1 762,310423mol
$m_{Na2} = M_{Na2}{*}n_{Na2O}$ = (2*22,99g/mol) * 1 762,310423mol = 81 031,03325g = 0,08103103325 tonnes
$m_{O} = M_{O}{*}n_{Na2O}$ = 16g/mol * 1 762,310423mol = 28 196,96677g = 0,02819696677 tonnes
Test: $m_{Na2} + m_{O} = m_{Na2O}$ = 81 031,03325g + 28 196,96677g = 109 228g

$n_{K2O} = m_{K2O}/M_{K2O}$ = 273 070g / 94,2 g/mol = 2 898,832272mol
$m_{K2} = M_{K2}{*}n_{K2O}$ = (2*39,10) * 2 898,832272mol = 226 688,6837g = 0,2266886837 tonnes
$m_{O} = M_{O}{*}n_{K2O}$ = 16g/mol * 2 898,832272mol = 46 381,31635g = 0,04638131635 tonnes
Test: $m_{K2} + m_{O} = m_{K2O}$ = 226 688,6837g + 46 381,31635g = 273 070,0001g

$n_{Li2O} = m_{Li2O}/M_{Li2O}$ = 764 596g / 29,88g/mol = 25 588,88889mol
$m_{Li2} = M_{Li2} * n_{Li2O}$ = (2*6,94g/mol) * 25 588,88889mol = 355 173,7778g = 0,3551737778 tonnes
$m_O = M_O * n_{Li2O}$ = 16g/mol * 25 588,88889mol = 409 422,2222g = 0,4094222222 tonnes
Test: $m_{Li2} + m_O = m_{Li2O}$ = 355 173,7778g + 409 422,2222g = 764 596g

$n_{TiO2} = m_{TiO2}/M_{TiO2}$ = 70 998,2g / 79,87g/mol = 888,9219982mol
$m_{Ti} = M_{Ti} * n_{TiO2}$ = 47,87g/mol * 888,9219982mol = 42 552,69605g = 0,04255269605 tonnes
$m_{O2} = M_{O2} * n_{TiO2}$ = (2*16g/mol) * 888,9219982mol = 28 445,50394g = 0,02844550394 tonnes
Test: $m_{Ti} + m_{O2} = m_{TiO2}$ = 42 552,69605g + 28 445,50394g = 70 998,19999g

7.3. Oil sample from Johan Sverdrup 01.04.21



equinor

Crude: **JOHAN SVERDRUP 2021 04**
Reference: **JOHANSVERDRUP202104**

Crude Summary Report

General Information		Molecules (% wt on crude)		Whole Crude Properties	
Name:	JOHAN SVERDRUP 2021 04	methane + ethane	0.05	Density @ 15°C (g/cc)	0.883
Reference:	JOHANSVERDRUP202104	propane	0.62	API Gravity	28.7
Traded Crude:	Johan Sverdru	isobutane	0.36	Total Sulphur (% wt)	0.81
Origin:	Norway	n-butane	1.00	Pour Point (°C), min/max	-42/-9
Sample Date:	01 april 2021	isopentane	0.67	Viscosity @ 20°C (cSt)	23
Assay Date:	01 april 2021	n-pentane	0.89	Viscosity @ 40°C (cSt)	12
Issue Date:	01 juni 2021	cyclopentane	0.10	Nickel (ppm)	3.8
Comments:	-	C_6 paraffins	1.43	Vanadium (ppm)	12.1
		C_6 naphthenes	0.97	Total Nitrogen (ppm)	1735
		benzene	0.06	Total Acid Number (mgKOH/	0.32
		C_7 paraffins	1.22	Mercaptan Sulphur (ppm)	13
		C_7 naphthenes	1.15	Hydrogen Sulphide (ppm)	0.0
		toluene	0.38	Reid Vapour Pressure (psi)	7.8

Cut Data			Atmospheric Cuts									Vacuum Cuts			
Start (°C)	IBP	IBP	C5	65	100	150	200	250	300	350	370	370	450	500	550
End (°C)	FBP	C4	65	100	150	200	250	300	350	370	FBP	450	500	550	FBP
Yield (% wt)		2.0	2.4	3.4	5.2	6.0	7.3	9.2	10.2	3.3	51.1	12.3	8.9	7.7	22.2
Yield (% vol)		3.3	3.2	4.2	6.0	6.6	7.7	9.3	10.1	3.2	46.4	11.8	8.4	7.2	19.0
Cumulative Yield (% wt)		2.0	4.4	7.8	13.0	19.0	26.3	35.4	45.6	48.9	100.0				
Density @ 15°C (g/cc)	0.883		0.642	0.715	0.770	0.798	0.836	0.866	0.887	0.901	0.968	0.917	0.930	0.945	1.026
API Gravity	28.7		88.7	66.4	52.1	45.8	37.7	31.7	27.9	25.5	14.5	22.7	20.6	18.2	6.3
UOPK	11.9				11.6	11.7	11.5	11.5	11.5	11.6	11.8	11.7	11.9	11.9	11.7
Total Sulphur (% wt)	0.81		0.000	0.001	0.003	0.021	0.089	0.296	0.66	0.83	1.33	0.85	0.98	1.18	1.79
Mercaptan Sulphur (ppm)	13		0.1	1.0	2.0	2.6	2.7	3.6							
Total Nitrogen (ppm)	1735						2	15	190	586	3319	982	1587	2617	5551
Basic Nitrogen (ppm)	569						4.4	22.08	86.26	201.2	1079	343	439	740	1861
Total Acid Number (mgKOH/	0.32		0.00	0.00	0.01	0.02	0.04	0.09	0.29	0.47	0.42	0.51	0.56	0.57	0.26
Viscosity @ 20°C (cSt)	23.4					1.23									
Viscosity @ 40°C (cSt)	11.6					0.96	1.61	2.93	6.16	13.6					
Viscosity @ 50°C (cSt)	8.66						1.39	2.40	4.74	9.68	2763	30.6	71.6	227	
Viscosity @ 60°C (cSt)											1115	20.4	43.9	124	
Viscosity @ 100°C (cSt)											86.1	6.21	10.7	21.9	26939
Viscosity @ 130°C (cSt)															1709
RON (Clear)			78.3	56.3	60.6	37.3									
MON (Clear)			77.6	54.2	57.5	35.4									
Paraffins (% wt)	26.7		95.8	57.5	40.9	40.5									
Naphthenes (%wt)	37.1		4.2	40.6	34.9	35.4									
Aromatics (% wt)	36.2		0.0	1.9	24.2	24.1									
Pour Point, max (°C)	-9						-51	-31	-5	9	32	25	39	46	53
Pour Point, min (°C)	-42														
Cloud Point (°C)							-50	-30	-5						
Freeze Point (°C)						-64	-47	-26							
Smoke Point (mm)						22	18	14							
Cetane Index						35	38	43	48	52					
Naphthalenes (% vol)						0.2	4.1	11.0	17.2						
Aniline Point (°C)					47.8	48.1	51.7	56.2	63.4	70.1		78.6	83.7	84.8	
Hydrogen (% wt)			16.5	15.3	13.7	13.8	13.3	12.9	12.7	12.6		12.5	12.4	12.3	
Wax (% wt)	9.0										17.0	4.4	8.3	13.2	28.8
C_7 Asphaltenes (% wt)	2.0										3.9		0.0	0.0	8.9
Micro Carbon Residue (% w	5.1										9.9		0.1	1.3	22.3
Rams. Carbon Residue (% w	4.2										8.3		0.1	1.2	18.5
Vanadium (ppm)	12.1										23.6		0.0	0.0	54.3
Nickel (ppm)	3.8										7.4		0.0	0.0	17.0

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