TEKNILLINEN TIEDEKUNTA

Material requirements and recycling of wind turbines

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TIIVISTELMÄ

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Työn ohjaajat yliopistolla: Eva Pongrácz, Jenni Ylä-Mella

Työn tavoitteena on selvittää mitä materiaaleja tuuliturbiinissa on käytetty, sekä miten näitä materiaaleja kierrätetään ja millaisille materiaalivolyymeille kierrätysinfrastruktuurin kapasiteetti riittää. Työssä pyritään myös selvittämään eroja eri materiaalien kierrätysten välillä, sekä löytämään sellaisia materiaaleja, joiden kierrätyskapasiteetin tai kierrätystekniikan kanssa tulee mahdollisesti ongelmia tulevaisuudessa.

Kansallisen ilmastostrategian tavoitteena on, että Suomi on hiilineutraali vuoteen 2035 mennessä. Tämä tarkoittaa energiantuotannossa sitä, että tuotannon täytyy siirtyä uusiutuviin energian muotoihin. Energiastrategiassa tuulivoiman lisääminen on yksi keskeisimmistä keinoista kasvattaa uusiutuvan energian osuutta tuotannossa. Tuulivoiman lisääminen tarkoittaa kuitenkin lisää turbiineja ja niiden käyttöiän tullessa loppuun myös kierrätettävää materiaalia on enemmän. Tähän mennessä Suomessa vuotuiset turbiinin kierrätysmäärät ovat olleet alle kymmenessä turbiinissa, kun alle kolmenkymmenen vuoden kuluttua kierrätettävien turbiinien määrät nousevat useisiin satoihin vuodessa.

Materiaalilaskennassa aluerajauksena käytettiin Pohjois-Pohjanmaata, joka tuottaa noin puolet Suomen tuulivoimasta. Turbiinit jaettiin kahteen eri kokoluokkaan rakennus vuosien mukaan siten, että jakajana käytettiin vuotta 2018. Ennen vuotta 2018 rakennetut tuulivoimalat ovat keskimäärin pienempiä kuin sen jälkeen rakennetut. Tämän pohjalta laskettiin kierrätykseen tulevat materiaalivirrat vuoteen 2053 asti. Materiaali määrät tulevat kasvamaan huomattavasti ja joidenkin materiaalien osalta jo pelkästään Pohjois-Pohjanmaan alueelta syntyvien määrien kanssa kierrätyskapasiteetin raja tulee ylittymään.

Huomioon täytyy ottaa, että laskenta suoritettiin vain tietylle alueelle Suomessa. Todellisuudessa valtakunnalliset materiaalimäärät ovat yli kaksinkertaiset tässä työssä laskettuihin määriin nähden. Kierrätyslaitosten kapasiteettia ei kuitenkaan rajattu maakunnallisesti, joten kierrätyskapasiteetti tulee valtakunnallisesti täyteen aikaisemmin, kuin tässä työssä on esitetty.

Asiasanat: tuulivoima, materiaalit, kiertotalous

ABSTRACT

Material requirements and recycling of wind turbines

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University of Oulu, Degree Programme of Environmental Engineering

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The goal of the national climate strategy is for Finland to be carbon neutral by 2035. In energy production, this means that production must shift to renewable forms of energy. In the energy strategy, increasing wind power is one key approach to increasing the share of renewable energy production. However, increasing wind power means more turbines, and, when they reach the end of their useful life, there will be substantial waste material flows. So far, the annual turbine recycling volumes in Finland have been less than ten turbines annually, while in less than thirty years, the number of turbines to be recycled will rise to several hundred per year.

The aim of this work was to find out the material requirements of wind turbines, how these materials are recycled, and is the capacity of the recycling infrastructure sufficient to receive future waste flows. The work also investigated the differences between recycling rates of turbine materials and find materials, to highlight potential future challenges regarding recycling capacities.

The material flow calculation were done for Northern Ostrobothnia alone, which produces about half of Finland's wind power. The turbines were divided into two sizes according to the building years, with 2018 as the divider. Wind turbines built before 2018 are, on average, smaller than those built after. On this basis, material flows for recycling were calculated until 2053. The material flows will grow considerably, and, for some materials, with the amounts generated in the North Ostrobothnia region alone, the recycling capacity limit will be exceeded in 2047(?). Considering the total national wind capacity, the amounts of waste turbine materials are more than double than calculated in this work. Therefore, the recycling capacity will be filled considerably earlier.

Keywords: wind power, wind turbine, material flows, circular economy, recycling

ALKUSANAT

Haluan kiittää työni ohjaajia Eva Pongráczia ja Jenni Ylä-Mellaa tuesta ja avusta työn teon aikana. Lisäksi haluan kiittää työnantajaani Carelin Oy:tä siitä, että sain tehdä työni teille. Carelinilla haluan erityisesti kiittää Juha Parkkaria, joka toimi Carelinin puolelta työni ohjaajana. Lisäksi haluan kiittää kaikkia muita, jotka ovat auttaneet minua matkalla sekä perhettäni tuesta ja kannustuksesta.

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Anna-Kaisa Isolahti

TIIVISTELMÄ

ABSTRACT

ALKUSANAT

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LABELING AND ACRONYMS

LABELING AND ACRONYMS

EU	European Union
kg	kilogram
kV	kilovolt, unit of voltage
MW	megawatt, the unit of power
MWh	megawatt hour
OHL	overhead line
SF6	sulphur hexafluoride

1 INTRODUCTION

The aim of this work is to research how much materials wind power needs for wind turbines and how materials are recycled after the turbine is at the end of its life cycle. To achieve that goal in this work, material requirements are calculated from the two different size turbines that are average sizes in the timeline that turbines are built in the Northern-Ostrobothnia area. The dividing year is 2018 when no turbines were constructed in the area. After that year, turbine sizes started to grow rapidly, so before 2018, the calculation used a smaller 3,0 MW turbine and, after 2018 a bigger 6,2 MW turbine.

To find out the future situation with materials that need to be recycled, work will observe future scenarios in 2050. The scenario will be based on the European Union climate strategy and the statistics about wind turbines on the building stage, in action or planning now. The scenario is made from the Northern Ostrobothnia area.

The interest in the work comes from the national climate strategy, the main goal of which is that Finland will be carbon neutral in 2035 in the energy sector. That means that energy production must increase the production share of renewable energies. In the strategy, wind power is one of the main ways to achieve the transition goal towards renewable energy.

Research questions:

- What are the material requirements of wind turbines?
- How are wind turbines currently recycled?
- What are the expected waste material flows from wind turbines in 30 years in Northern Ostrobothnia?

2 ENERGY STRATEGIES

European Union's climate and energy strategies are based on international agreements like the Paris Agreement and the United Nations Framework Convention on Climate Change (UNFCCC). In the UNFCCC agreement, almost all countries have agreed that it is necessary to take some action to protect people and the environment and decrease greenhouse gas emissions. With the Paris Agreement, UNFCCC parties renewed their commitment to the agreement and made new targets for limiting emissions. In the Paris Agreement, parties agreed to limit the rise of temperature to 1.5 Celsius when compared to the pre-industrial time. EU countries have agreed that the EU economy will be the first climate-neutral economy by 2050. (European Council, 2023b)

2.1 The European Green Deal

The European Green Deal is the program for the EU Commission to keep the economic growth with less resource use and be carbon neutral by 2050. The basic idea of the Green Deal is that all the different parties are working together for a shared responsibility and goal. The deal affects all areas of politics and decision-making, every law and regulation should support the carbon neutrality and 2050 goal. (European Commission, 2023)

In the energy sector, changes are significant. Europe's energy production has been relying on coal in the past. 77% of EU greenhouse gas emissions came from energy production in 2019. (European Parliament, 2021) The energy sector needs to make the biggest changes that the 2050 carbon neutrality goal can be achieved. At the same time as changes in production are made, the energy sector should take care of energy security and affordable energy. The energy sector should be based on renewable energy sources in the future. The goal is to support the development and usage of new ways to produce and store energy; for example, green hydrogen and offshore wind are these technologies. (European Council, 2023a)

The industry sector needs time to change and develop. New ways to do things and innovations are not in use immediately. The industry relies heavily primarily on materials and resources. Green Deal is guiding the industrial sector towards the circular economy; with that, it is possible to reduce the usage of primary materials and make more sustainable products. Fear is that changes in the EU area will lead to some industries taking their production to countries where laws and regulations are not at the same level as in Europe. (European Council, 2023a)

2.2 National climate and energy strategy

Finland has a national climate and energy strategy that sets the base for energy and climate politics and actions that need to be done in the future. This strategy is based on the European Union's climate and energy strategy. In the EU energy and climate strategy, the target is carbon neutral by 2050, but Finland's target is carbon neutral by 2035. The strategy gives the big guidelines for how Finland will reach targets. (Työ- ja elinkeinoministeriö, 2022)

National climate and energy strategy goes through widely different fields of carbon sources and carbon and energy markets. It studies how this strategy will affect the economy and people's lives. The focus is still on energy production and distribution of energy. That is because energy production is our biggest source of carbon emissions. (Työ- ja elinkeinoministeriö, 2022)

The energy strategy of the national climate and energy strategy is based on producing renewable energy. The largest share of production will come from wind power. Another significant source of renewable energy will be solar power. Nuclear energy will also be an essential way to produce energy. In solar power, the focus is on the industrial-scale land-installed plants, and in nuclear power, innovations and small-scale plans like modular nuclear power plants are the focus in the future. (Työ- ja elinkeinoministeriö, 2022)

Irregularity of renewable energy sources is acknowledged in the Finnish strategy. The strategy searches for and presents solutions to irregularity challenges. One solution that is given in the strategy is green hydrogen. With hydrogen, it is possible to store wind energy during high production and use the storage energy during low production. Another solution to the irregularity is battery storages. The issue with them is that their capacity should be significantly larger than it is now. It would make a difference, and they are quite expensive to build compared to their capacity. (Työ- ja elinkeinoministeriö, 2022)

Energy production is guided towards renewable production with different types of financial support. These supports will be guided to smaller renewable production sources like industrial-scale solar power projects. Also, the energy storage projects and green hydrogen projects can get support. Support is not only for building but also for research. This way, the government tries to improve the share of renewable energy. (Työ- ja elinkeinoministeriö, 2022)

2.3 Wind power in Finland today

In Finland, there were 1393 wind turbines at the end of 2022. The total capacity was 5677 MW. The building of wind power has increased yearly in the last 15 years. After 2013, cumulative capacity has grown significantly, as seen in Figure 1. (Suomen tuulivoimayhdistys, 2023b). Growth has been possible because the 2012 feed-in tariff law was enacted. Feed-in tariff was support paid to the wind power producers until the total production capacity was over 2500 MVA, which means 2500 MW. (2010/1396 6 §) The total energy production of wind power was 11,5 TWh in 2022. Finland's energy production is relying on wind power all the time. At the moment, wind power in the windy days is as significant a source of electricity as nuclear power. On windy days, electricity production in Finland is showing a surplus. (Suomen tuulivoimayhdistys, 2023b)

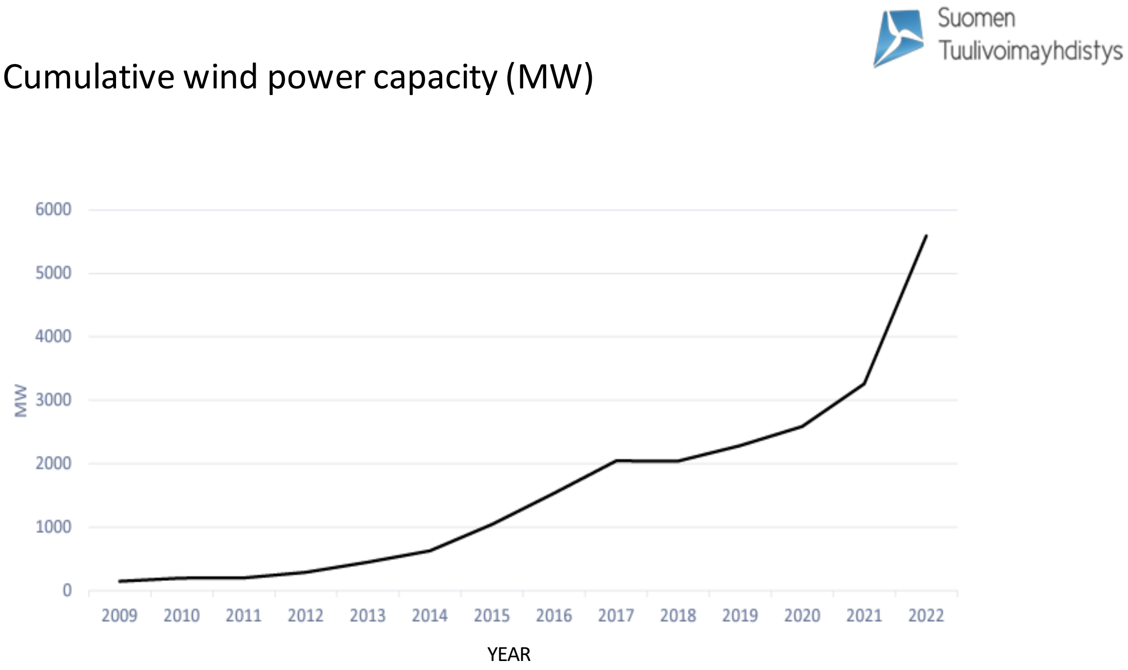

Figure 1. Cumulative wind turbine capacity (MW) development in Finland (Suomen tuulivoimayhdistys, 2023b)

Wind conditions are propitious in Finland for wind power production. The best wind condition is on the west coast and north Lapland, as shown in Figure 2. Darker red means stronger wind in Figure 2. The best conditions are in the sea area. Overall, the wind conditions are suitable for the whole country. (Ilmatieteenlaitos 3023)

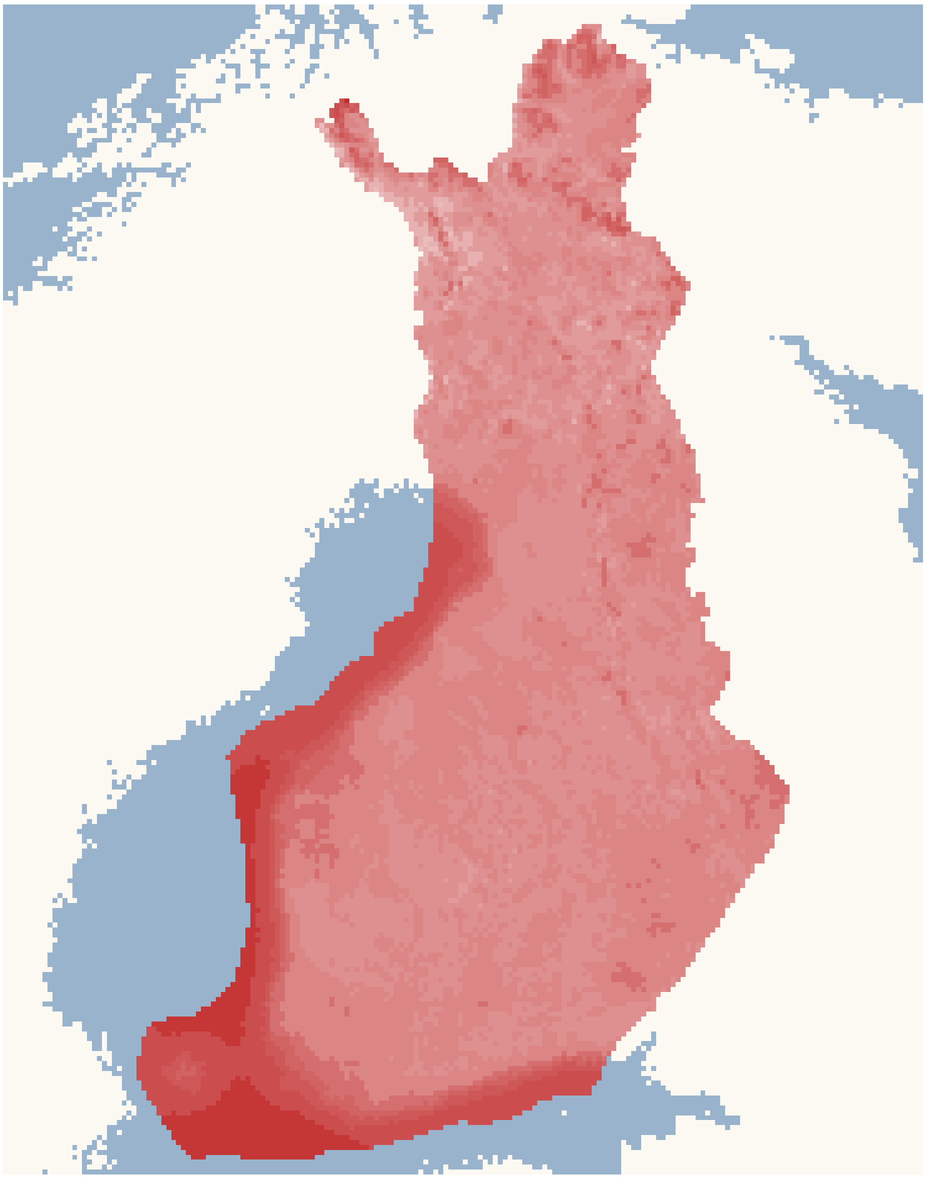

Figure 2. Wind conditions in Finland (Ilmatieteenlaitos, 2023)

Wind power production in Finland is divided unevenly. As we can see from the Figure 3, the production hot spot is on the west coast; 46% of production capacity is in the Northern-Ostrobothnia area in 2022.

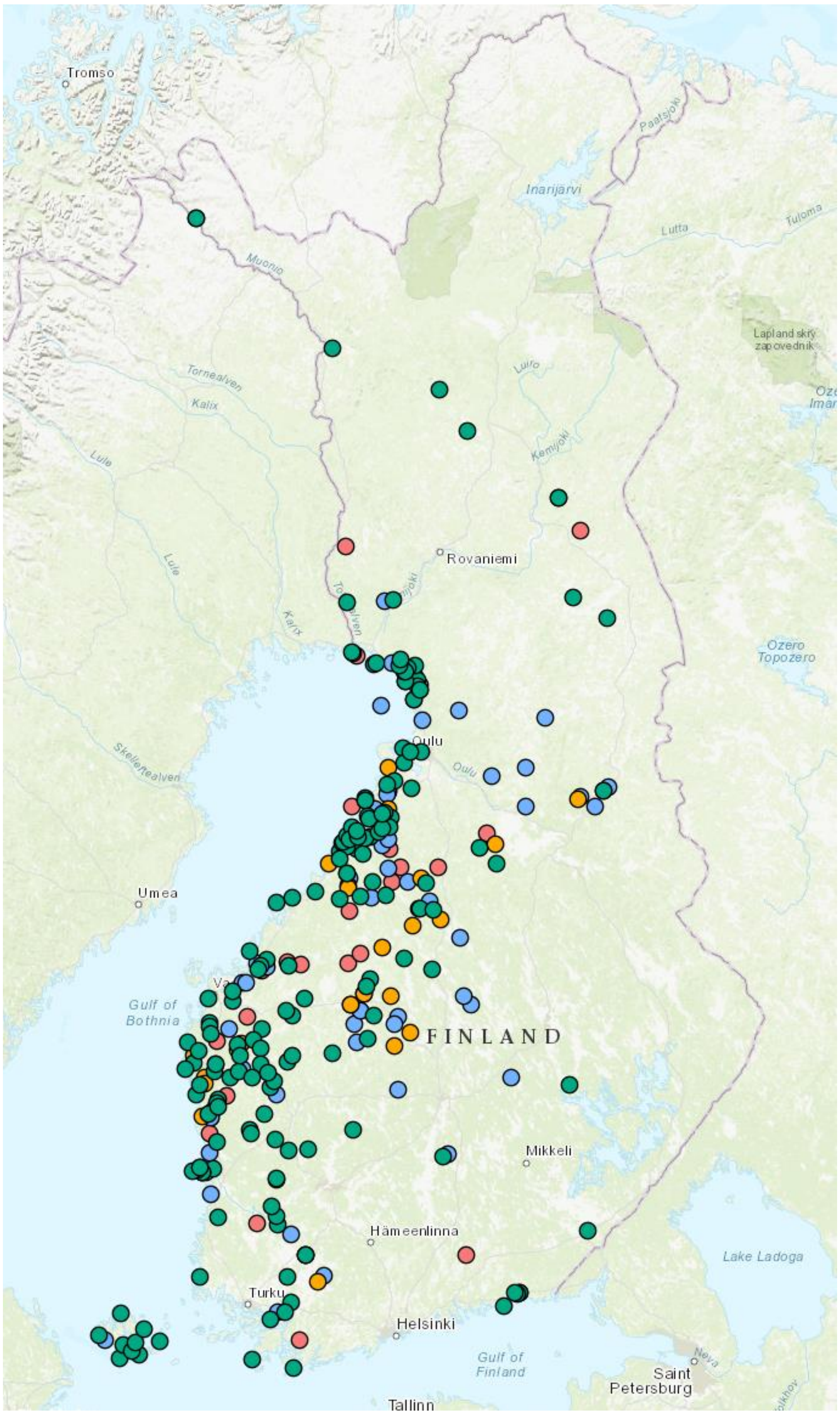

Figure 3. Wind turbines in Finland (Maanmittauslaitos,2023)

In the Figure 3 green dots presents wind turbines that are in production. Yellow ones are under the construction and blue ones are fully permitted turbines, which means these will be built next. Red marks indicate that land use plan stage is finished.

In eastern Finland, there are few wind turbines. For 2023-2025, investment decisions are in the West Coast area; the biggest share, 24%, is in the Northern-Ostrobothnia area. (Suomen tuulivoimayhdistys, 2023b) The Lapland region is a good example of an area with good wind conditions but with geographical limitations. Most of Lapland's wind power production is in the southwest part, and in the east, there are none in the northern parts, very few wind parks, and even the wind conditions are suitable for wind power production in the whole region. There are multiple reasons for the unevenness. Large national parks and wilderness areas in the Lapland area prevent wind power building (1991/62). In east Finland, a long border zone is giving limitations to building. Also, the eastern part of the country has many large lake areas and nature preserves. (Maanmittauslaitos,2023)

In 2022, 437 wind turbines were installed, and 5 wind turbines were dismantled. The power unit’s numbers were 2430 MW installed and 9 MW dismantled. These numbers show that the size of the wind turbines has increased, and wind technology has been developing with markable steps. For example, before 2014, the median size of installed wind turbines was under 3 MW. In 2022, the median size of the installed wind turbine was about 5,5 MW. This growth is possible with higher towers and bigger rotors and drive drains. (Suomen tuulivoimayhdistys, 2023b)

The degree of domestic ownership was 47% in 2022. This means that over half of the wind production capacity is owned by non-domestic enterprises. The four biggest owners of wind turbines in Finland are Taaleri Energia (Finland), Neoen (France), EPV Tuulivoima Oy (Finland) and Exilion Tuuli Ky (Finland). From the turbine delivers Vestas is the biggest with 61% of all turbines in Finland. Next is Nordex Acciona with 23%. The rest of the suppliers have under 10% of the market. (Suomen tuulivoimayhdistys, 2023b)

3 WIND POWER PRODUCTION

Wind power production is an old way to produce energy. Today, it is used mainly to produce electricity. Wind power production usually happens in wind parks. A wind park is a unit that consists of multiple wind turbines.

3.1 Wind park

Park sizes vary between one and 69 turbines today in Finland. In the future, bigger parks are possible, especially offshore. One park can be calculated so that all turbines with the same grid interface point belong in one park. The largest parks in Finland have approximately 403 MW production capacity. On the other hand, small old parks have a capacity under 10 MW. (Suomen tuulivoimayhdistys, 2023f)

3.1.1 Layout

A wind park consists of four components: turbines, an internal grid, a substation, and an overhead line or underground cable. Wind turbines need space between them, and they cover only a few percentages of the whole park area. With a 140-meter rotor, the distance between the turbines must be at least 700 meters. (Suomen tuulivoimayhdistys, 2023i) One example of the wind park layout is presented in Figure 4. Road networks can also be calculated as one component. The basic structure is similar in all wind parks. Turbine generators produce the electricity fed to the wind park's electrical network. (Suomen tuulivoimayhdistys, 2023g)

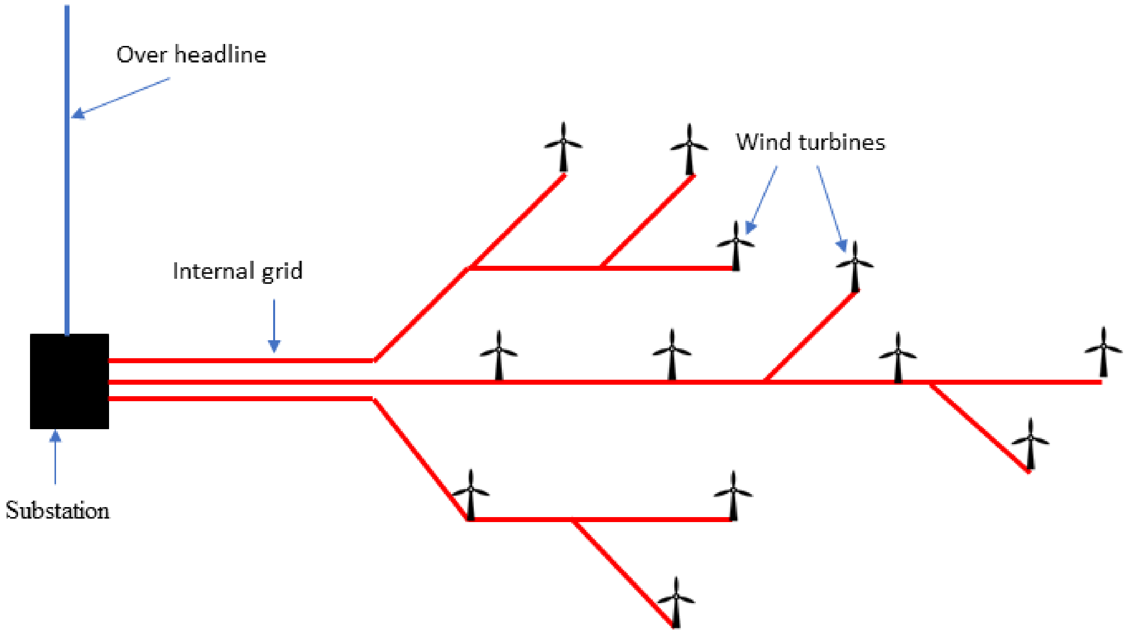

Figure 4. Wind Park layout example

Electricity is led from the turbines to the substation in the park via the internal grid. The internal grid is, in most cases, underground cables. Like the example in Figure 4, turbines are connected in groups with the same cable connection. In this example, in the internal grid, the voltage usually varies between 10 kV and 35 kV. In the substation, electricity is transformed to the correct voltage for the overhead line. The most common voltage for the OHL is between 100 and 150 kV. (Wind energy the facts, 2023) From the substation, electricity is transferred to the Fingrid substation with an overhead line or ground cable. The overhead line can be tens of kilometers long. From the Fingrid substation, it is fed to the national gird. This Fingrid substation is the grid interface point. (Fingrid Oyj, 2023)

3.1.2 Planning, building, and operating a wind park

Wind park projects can start in multiple ways. For example, wind park owners can have an area in the offing suitable for wind power, or the landowners can contact a company willing to build. After the area is found, the developer makes contracts with landowners. After the contracts, the company will install the anemometer mast in the area to find the exact wind conditions. The next stage is land use planning. During land use planning, the wind park area is inspected, and for example, the Finnish Defence Forces can give their opinion, usually from the height of the flight obstacles. An environmental impact assessment is done during the land use plan stage if needed. When the land use plan is accepted, the next stage is to apply for building and other required permits. After the permitting phase, competitive tendering is organized by the builder to find suitable contractors and turbine supplier. When contracts are made, construction can start, and the first roads and hard stands are made in the area. Then, foundations, inner grid, and substation are built. The overhead line is made at the same time as these. The next stage is the turbine delivery, installation, and commission of the turbines. After the turbine installation, the wind park is ready to produce electricity. (Suomen tuulivoimayhdistys, 2023h)

Companies often have multiple parks in production and are building and developing new ones. It is also possible that the developer will sell the park after the permitting phase to forward it to a different owner who is building it. Parks can also change their ownership during the operation phase. (Suomen tuulivoimayhdistys, 2023h)

3.2 Wind turbine

Wind energy has been used for thousands of years for different purposes. First, it was used in water pumps and for grinding the grains. The first wind turbine that produced electricity was built in Scotland in 1887. After that, wind turbines developed, and the invention was more widely used than before. One megawatt mark in turbine capacity was broken in 1941. After that, wind power technology and ability have been developing steadily. (U.S. Department of Energy, 2023)

A wind turbine is a power plant that converts wind kinetic energy to electricity. Wind is a rotating wind turbine rotor, and wind kinetic energy is converted to mechanical energy. This mechanical energy is transmitted to the generator that will produce the electricity. The efficiency of the wind turbine depends on the rotor's size and the tower's height. The higher tower usually means better wind conditions for energy production. For example, the earth's topography, vegetation, and buildings are not affected as much as closer to ground level. (IRENA, 2023)

Rotors consist of hub and blades. Blades are aerodynamically designed. When air flows across the blade, movement causes different air pressures on two sides of the blade. That pressure difference causes the blade to start to move in the direction of negative pressure. The blade is then turning the whole rotor. That pressure difference stays if the air flows through the blade and the rotor rotates. (U.S. Department of Energy, 2023)

Wind turbine maximum production capacity can vary from some kilowatts up to seven megawatts (Vestas) in onshore turbines. Offshore turbines capacity is 8-12 MW. The wind turbines that are built today onshore are around six and seven megawatts. The capacity is highly developed, and it is growing constantly. (U.S. Department of Energy, 2023) Bigger turbines are more economically efficient than smaller turbines. Bigger turbines can produce more energy in the same land space than smaller ones. That is important when thinking of land use.

3.2.1 Wind turbine components

Wind turbines consist of four main components. Those components are the tower, nacelle, drive drain, and rotor. The rotor consists of blades that are attached to a hub. Figure 5 presents the main components of wind turbines.

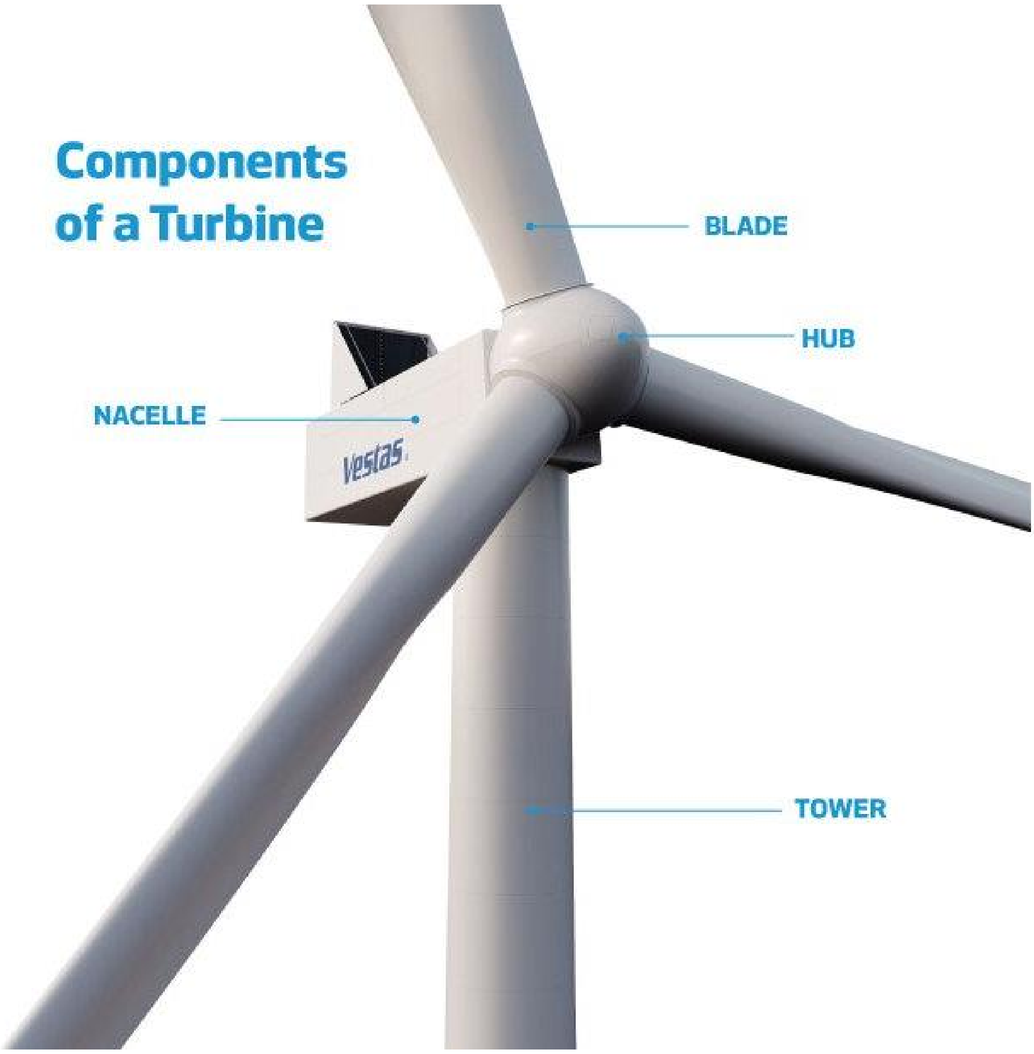

Figure 5. Wind turbine main components (Vestas, 2023)

The tower is the largest and heaviest part of the wind turbine. The tower supports the parts above. The tower can be made in a couple of various ways. The most common way is to use all steel towers; in this case, steel is over 80% of the material used in the turbine. Another solution is to use a concrete-steel hybrid tower. In this model, the lower part of the tower is concrete, and the upper part is steel. (Suomen tuulivoimayhditys, 2023d)

The nacelle is located at the top of the tower. The nacelle cover is usually made from fiberglass, and the support structure is made from steel. Between the nacelle and tower is a system that turns the rotor towards the wind. This system is called yawn. Electricity is produced in a generator in the drive drain, the biggest component inside the nacelle. Other components in the drive drain are gearbox, shafts, and controllers. Turbine layout and components can vary between the manufacturers. Figure 6 presents the layout of the nacelle. (Suomen tuulivoimayhditys, 2023d)

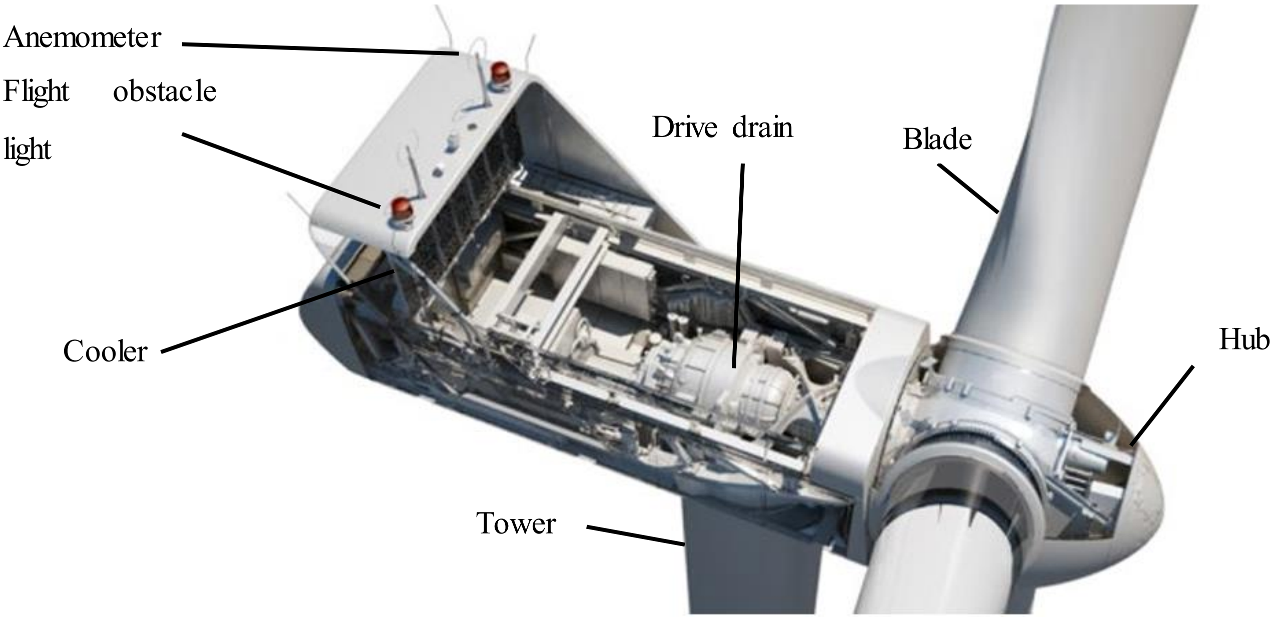

Figure 6. Nacelle layout (Modified from Vestas, 2023)

On top of the nacelle is an anemometer that measures the wind speed. A wind vane is in the back of the nacelle roof and monitors the direction of the wind. Nacelle protects most of the turbine electronics, like the control system and parts that are producing electricity. (Suomen tuulivoimayhditys, 2023d)

The brake, gearbox, and generator are located in the drive drain. The generator is the part that transforms the blade's kinetic energy into electricity. Electricity is produced with magnets containing rare metals counted as critical materials. Criticality means that only a very limited amount of those materials are available. Drive drain also contains many other metals and components. There is also hydraulic oil and other lubricants, coolants, and other liquids in the diver drain, the hub, and the nacelle. (Suomen tuulivoimayhditys, 2023d)

The hub is the part that connects the blades to the nacelle and especially to the drive drain, which produces the electricity. The inside of the hub is made from steel and covered in composite material, usually glass fibre. (Suomen tuulivoimayhditys, 2023d)

Blades are attached to the hub. They are made from the composite materials. The most used material is glassfibre and carbon fibre; different epoxies and polyester are used. Blades supporting structure is made from relatively light but durable material. These kinds of materials can be wood or lighter metals. Blade structure varies with each producer. The whole turbine, especially the blades, is well-earthed because of their height. Earthing is usually made with copper wires and bands. (Suomen tuulivoimayhditys, 2023d)

3.3 Materials in wind turbines

Wind turbines contain multiple materials from various material groups. The largest group of materials is metals and alloys. The turbine contains various metals, and almost all components contain some. Steel is used in the tower and cables, and copper and aluminium are used in earthing. Smaller amounts of rarer metals like molybdenum, chromium, lead, and silver are used in electronics and magnets. (Vestas, 2023a)

Another big material group is polymer and composite materials. These kinds of materials are fiberglass, carbon fibre, and resin. Typically, most of these materials are in the blades. Composite materials are light and durable, which is important in blades. Heavyweight blades would cause too big a load for the nacelle and tower, especially during the high winds, and the whole turbine would be hard to balance. (Vestas, 2023a)

Foundations are made from concrete and steel. Usually, when foundations are made, the constructor tries to use rock material as close to the construction site as possible. In this way, costs and environmental impacts are smaller. Foundations are calculated as demanding concrete works. (Vestas, 2023a)

Turbines also need different fluids to work. There are coolants, hydraulic liquids, and lubrication oils. The largest share of there is hydraulic liquid, and one turbine holds hundreds of litres. Coolant is usually some alcohol; glycol is one that is used. Fluids need to be added and changed during the turbine's lifetime. (Vestas, 2023a)

3.3.1 Metals and alloys

Metals and alloys are used in wind turbines due to their suitable properties. Metals are durable and strong, but they are quite easy to reform, and they are not as hard as needed in the structures of turbines. Metals are also vulnerable to corrosion. With alloys, these kinds of issues can be decreased. For example, steel holds its shape well, which is important when turbine parts are transferred long distances, and steel can stand corrosion better than pure iron. (Teräsrakenneyhdistys, 2023)

The most used alloy in the wind turbine is steel. It is the primary material of the tower. Steel is a mixture of iron and coal. It can contain other additives that form its properties. The most used additives are manganese, aluminium, phosphorus, silicon, nitrogen, niobium, copper, vanadium, cobalt, and tungsten, and in stainless steel, chromium, and nickel are used. All additives have their purpose. Additives affect the properties like strength, corrosion durability, and tensile strength. (Teräsrakenneyhdistys, 2023)

Magnets in turbines contain light rare earth metals. Turbine magnets are permanent magnets. These rare earth metals occur in low concentrations, and mining them is not very profitable. Most of the production is in developing and politically unstable countries, which contributes to reducing their availability. (Huoltovarmuuskeskus 2020)

3.3.2 Polymer and Composite Materials

Polymers consist of monomers. Monomers are small particles that can react with other monomers that react similarly. Polymers can have chain-like or web-like structures. They can be fully synthetic or natural polymers like starch of cellulose. Polymer materials are combinations of polymers and additives. Plastic, elastomers, coatings, grouts, and glues are the most important polymer groups. (Muoviteollisuus ry, 2023c)

Composites consist of two parts, reinforcement, and cavity, with different chemical properties. These components are mixed, and they make a mixture without mixing. This combination is called composite. The cavity can be some polymer, and reinforcement can be something like glass fibre or carbon fibre. Composites are as material light and durable.

They have good resistance against corrosion, and they work well in changing temperatures. (Muoviteollisuus ry, 2023a)

3.3.3 Liquids

Wind turbine contains a couple of types of different liquids. For example, coolant moves the excess heat from the drive drain and leads it to the cooler. In cooler coolant temperature drops, it circulates back to the drive drain. This circulation prevents overheating. Coolants are usually some types of glycols; for example, ethylene glycol can be used. (Kiiskinen, 2023)

Hydraulics are used in the wind turbine to adjust the blades. Hydraulic systems work with force and pressure changes; the transmitter is usually hydraulic fluid. One turbine can hold hundreds of litres of hydraulic fluids. Hydraulic fluids can be oil or water-based. Oil-based can be made from mineral oil or vegetable oil. One option is that they are synthetic and made from some hydrocarbons. (Metropolia, 2009)

3.3.4 Concrete

Concrete is used in wind turbine foundations, the most used material. The amount of concrete used depends on the turbine foundation type. Gravity foundation is the biggest foundation type. It stands in soil freely, and its mass is so large that it will hold the weight of the turbine. Another common type is a rock anchor foundation. The Rock anchor foundation is cast on top of the rock and anchored into the rock with metal wires. This type of foundation needs much less concrete because its diameter is smaller than gravity foundations. (Skoda, 2023)

As a building material, concrete is durable and long-lasting. It is suitable for different purposes because it can be cast in the desired shape. Concrete three main ingredients are rock material like sand, cement, and water. Other materials that can be used are additives, usually used in low concentrations. Concrete is mixed in batches after the ingredients are measured. Then, concrete is cast, then it will dry and become solid. (Betoniteollisuus, 2023)

Concrete used in wind turbine foundations is high-strength concrete. This gives quality requirements to materials also. For example, water used is monitored in a laboratory, and all water is not suitable for making concrete. Used sand must be a certain grain size, and the wanted mixture must be mixed from various fractions. (Betoni, 2023)

4 CIRCULAR ECONOMY

European parliament defines circular economy: “ The circular economy is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible.” The practice behind the circular economy is to extend the product and the material life cycle. The purpose is to reduce waste; material circulates longer, and that reduces the need for virgin materials. The circular economy also gives value to the used materials. (European Commission, 2020)

The circular economy is acknowledged in the wind power industry, and the industry tries to develop according to circular economy principles. Circular economy issues in the wind industry are also acknowledged outside of the industry and are displayed in the media. Turbine lifetimes are expanding when new models are developed. The industry tries to find new materials for turbines and new ways to recycle the existing turbine components.

The biggest issue in point of circular economy in the wind power industry is the composites and composite materials. They are hard to recycle, and there are few ways to do it. Most of the composite recycling options lower the degree of processing. Materials like metal and alloys are easier to recycle, and many companies pay for metals. (Tuulivoimayhdistys, 2023j)

4.1 Life cycle of wind turbine

Figure seven opens the life cycle of the wind turbine. The whole life cycle starts with the materials. Materials can be raw materials or recycled. Materials are mined or made chemically or produced somehow, and then material suppliers transport them to turbine component factories. (Vestas, 2023)

During the manufacturing, turbine components are produced. Different components, like blades and towers, can be produced in various places. In manufacturing, components are made in the point that they are easy to install, and there is as little work on the erection phase as possible. (Vestas, 2023)

After the manufacturing, components are transported to the wind park, where they are installed. Usually, transportation is done with ships as close to the site as possible. Due to component sizes, especially blade size, the harbour needs to be large enough. Blades are transported to the wind park with special trucks from the harbor. After that, transportation turbines are installed on the top of the foundations, and all the interior installations are done before the turbine can produce electricity. After the installation, turbines are commissioned and inspected to be safe to use and produce as they should. After the turbines work as they should, the park is ready, and production can start. (Vestas, 2023)

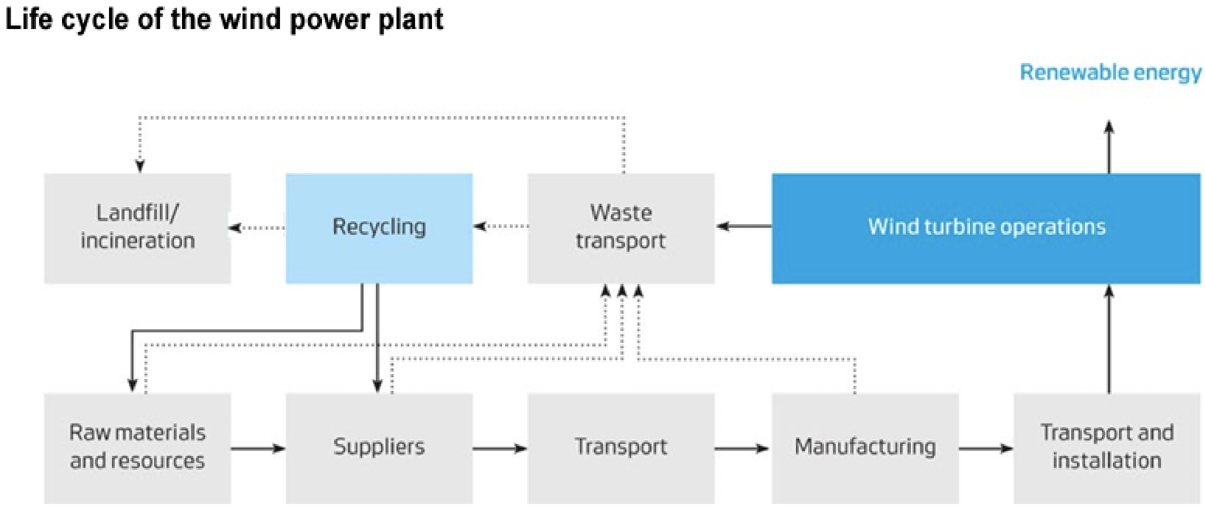

Figure 7. Vestas’s life cycle assessment V-162-6.2 MW wind plant (Vestas, 2023)

In the operating stage, the wind turbine produces electricity. Wind turbines are highly automated and do not need active operation like, for example, nuclear power plants would need. Turbines adjust the rotor and blades position based on the wind speed and direction to maximize electricity production. Most operations that are made during operation are related to service and repair. There are many moving parts, and the turbine works with hydraulic. The systems need steady maintenance. Wind turbines are cleaned from time to time, and that cleaning requires specialists. (Vestas, 2023)

After the turbine's lifetime, they are dismantled. Parts are taken down and transferred to recycling or disposal, for example, to landfills. Most of the turbine components are recyclable, but for example, using composite materials is challenging. Ten turbine park demolishing costs vary between 60 000 and 120 000 euros per turbine. Most of the demolishing expenses come from the crane and component transportation. (Tuulivoimayhdistys, 2023j)

4.2 Repairing and maintenance of wind turbines

Wind turbines need maintenance during their lifetime, like all machines. Maintenance of the turbines is already in the planning stage of the whole wind project. That is important because wind turbines need turbine specialists for maintenance and inspections. Wind turbine as a working environment is dangerous and logistically challenging. (Palmu, 2016)

Wind turbines contain many moving parts and are under mechanical stress like all other machines. This causes wear of the components and, at some point, minor breakdowns during the turbine's lifetime. Things like sensors and other small parts are easy to fix or change. Hydraulic liquids and cooling agents are added when the level in the system is too low. Turbines also need cleaning inside and outside if the turbine seems dirty; for example, oil leaks can cause fouling that needs cleaning. Wind turbines are monitored around the clock, and this way misfunctions are noticed quickly. Turbines are inspected once a year. (Palmu, 2016)

Most of the faults are in electrical sensors and other electrical components. Also, leaks in coolant systems and hydraulic systems are pretty common. In the gearbox, most faults are in the bearing. The longest time in the year goes in the electrical system faults. These are common, but they are quick to repair. Gearbox faults cause the longest stops for production. The repair costs rise if there is a need for a crane. For example, in the drive drain, there is some problem that requires taking it down. The first thing is to take the blades and hub down, and then it is possible to operate with the drive drain. This is one reason why bearing faults take longer to repair. (Palmu, 2016)

Big components like wings are not that common to break. Most of the blade breaks are caused by lightning or manufacturing defects. After these total breaks, blades are changed, and repairing is too expensive and, in most cases, impossible. Another type of damage is smaller surface damage. The most common surface damage is erosion. Blades are moving at high speed. The speed causes all the particles in the air to affect the blades. The biggest cause for the erosion is rain. Erosion in the blades can be seen a year after the installation. Due to erosion, blades need maintenance and repair. (Mishnaevsky et al., 2023)

4.3 Recycling of wind turbines

According to the manufacturers, the wind turbine recycling rate is between 80 and 85 percent. (Vestas, 2023) The wind power industry is acknowledging the recyclability issues and trying to find new solutions. One of the biggest issues is that waste will be significantly larger in the future than now. Today, a couple of turbines are recycled in a year, and in 30 years, hundreds of turbines will need to be recycled. An example of the industry's willingness to develop is that in 2021, Wind Europe, which is the European Wind Power Association, hopes that taking blades to landfill will be forbidden by 2025.

Reusing the old components in new turbines is impossible. Used components can still be used as spare parts in the same model turbines. Turbine size is growing rapidly, and component sizes are growing, too. For example, old foundations are made of smaller diameter towers and are too light to keep new turbine weight standing. The drive drain size is also growing constantly, and new drive drains do not fit in old nacelles. In some cases, wings have been changed to longer ones after the old ones needed to be changed anyway. Turbine production is increasing while the rotor diameter grows, and less wind is needed to spin the rotor.

Wind turbine metal parts are the easiest components to recycle. Steel towers, copper parts, aluminium, etc., have already working recycling systems. For example, Kuusakoski Oy can recycle almost 100 % of metals. Metal recyclability is good and can be used again in similar products. (Kuusakoski, 2023) There are also critical metals, for example, in magnets. If critical metals are in alloys, they are hard or impossible to separate from other metals in alloys. If they are used purely in components, then recycling would be easier. Most of the critical material is in electronics and is magnets. Magnet recycling in Europe is very low. Rare earth metals are critical material in turbines because, without them, wind turbine does not work. (Huoltovarmuuskeskus, 2023)

Electronic components have good recyclability in Finland. Finnish authorities have approved several electrical waste organizations to do it. They can utilize almost 99 percent of the material for reproduction. (SER-kierrätys, 2012)

The hardest part of recycling is the blades. That is because the blade is made from various composite materials, and separating the materials from each other is challenging. In Finland, most of the blades going into recycling are moved abroad. In 2022, three turbines were dismantled; three blades were left as spare parts, and six were recycled in Finland. Blades, in other words, composite material recycling is. Most of the blades end up in landfills, the lowest solution on the waste hierarchy, or in energy usage, meaning they are burned. They are also used, for example, in the highway noise barriers. Energy use is problematic because the composite heating value is low, and much ash is generated from burning. (Tuulivoimayhdistys, 2023j)

Many projects are trying to find ways to recycle composite materials. One project, KiMuRa, uses crushed blade material as a raw material for cement. The goal is that with blade material, concrete's CO2 emissions would be much smaller than they are now. (Uusiouutiset, 2022) KiMuRa's capacity now is 2000-4000 tons per year, and at the end of the summer of 2024, it will start a new recycling plant that can process 10 000 tons of material in a year. Some projects are trying to find a way to utilize composite materials for new composite materials. This could be possible with chemical processes and with pyrolysis, where composite can be taken apart, and fibres can be reused. The biggest issue with this method is that the fibres are less durable than before recycling. The method is still expensive. (Paalatie H, 2020) One of the new pilot chemical process projects is the Vestas, Olin Exposy, and Stena Recycling project, where they are trying to find a way to use the old blades to make new ones. (Stena Recycling, 2023)

5 WIND TURBINE MATERIAL BREAKDOWN

Material breakdown groups and the data for the turbine materials are from Vestas´ lifecycle assessment for wind turbines. Turbine materials are divided into eight categories; some of these groups are divided into more specific ones. One turbine component contains materials from various groups. Eight main groups are:

- Steel and iron materials
- Light alloys, cast alloys, and wrought alloys
- Nonferrous heavy metals, cast and wrought alloys
- Polymer materials
- Other materials and material compounds
- Electronics
- Lubricants and liquids
- Not specified

Figures 8 and 9 show the upper-class material breakdown for both turbine sizes. Figure eight shows a 3,0 MW turbine material breakdown, and Figure nine shows a 6,2 MW turbine material breakdown. The charts show that steel and iron materials are considerably the biggest group in both turbine types. The share of polymers and other materials in smaller turbines is smaller than in the 6,2 MW one.

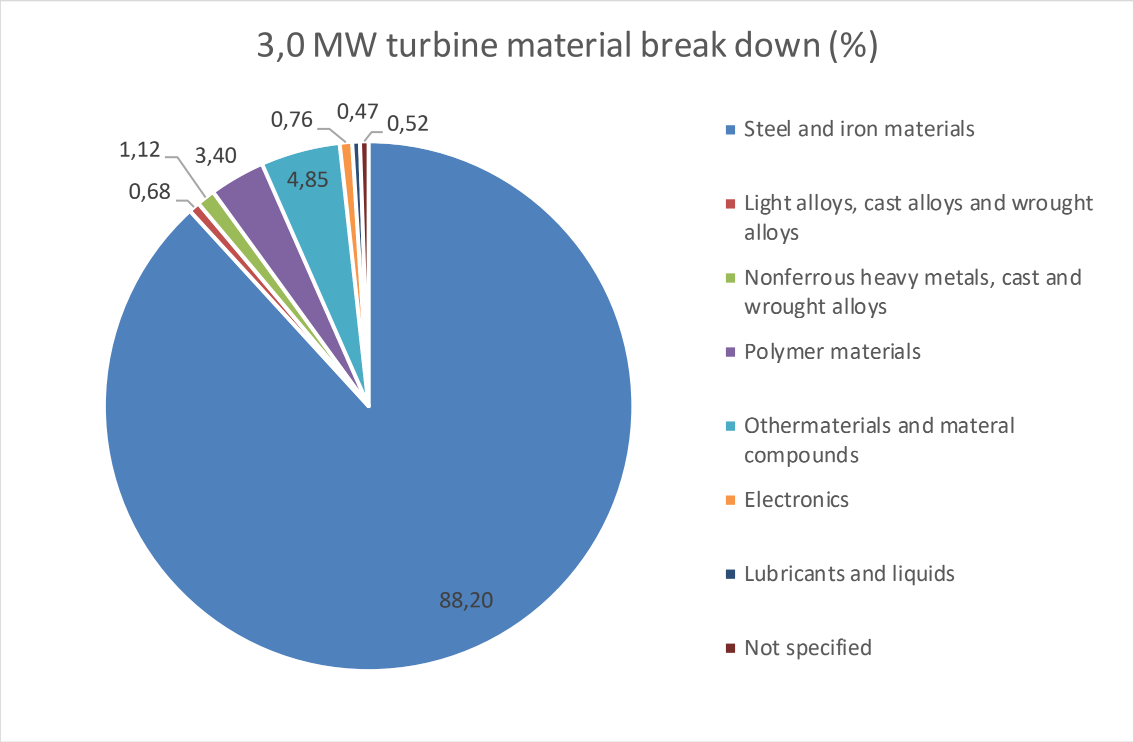

Figure 8. Main group material breakdown of 3,0 MW turbine.

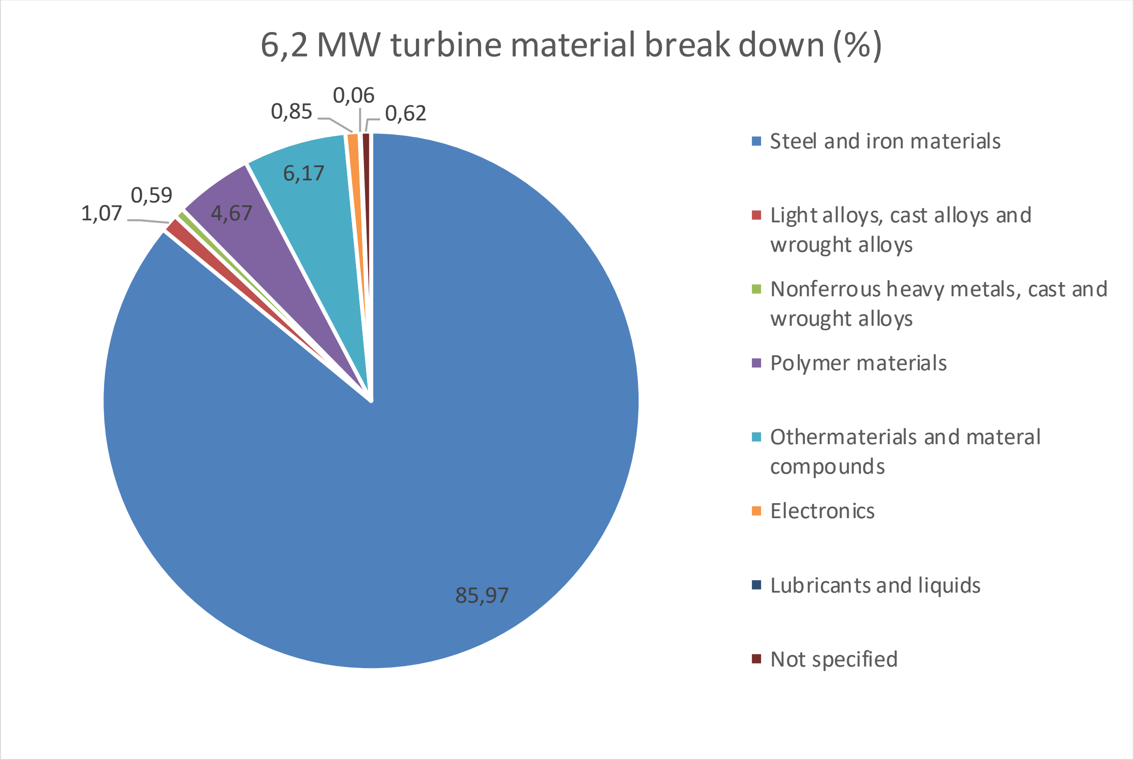

Figure 9. Share of turbine material of 6,2 MW.

The main material groups are divided into sub-groups. Table one presents material classes and sub-classes if there are any. Subgroups give more specific information about what each main group contains. With subgroups, it is possible to calculate more accurate material amounts.

Table 1. Material classification

Steel and iron materials	unalloyed, low alloyed
	highly alloyed
	cast iron
Light alloys, cast alloys, and wrought alloys	light alloys, cast alloys, and wrought alloys
Nonferrous heavy metals, cast and wrought alloys	copper
	zinc alloys
Polymer materials	polymer materials
Other materials and material compounds	modified organic
	natural materials
	ceramic/glass
	SF6 gas
	magnets
	other
Electronics	electronics
	electrics
Lubricants and liquids	lubricants
Not specified	not specified

5.1 Wind turbine material calculations

Material calculations are based on the two different Vestas turbines. Types are Vestas V162-6.2 MW and Vestas V90-3.0 MW. The material classification and amount are found from the life cycle assessment done by Vestas. In the 6,2 MW turbine lifecycle assessment, materials were assessed for 100 MW, and in the 3,0MW turbine, materials were assessed for 90 MW.

Material amounts are calculated first for the one MW and then for one turbine. Then are calculated percentages. The main group's material breakdown can be seen in Table 2. Material breakdown with sub-groups is presented in attachment one.

Table 2. Material breakdown for main groups.

	6,2 MW				3,0 MW			
	t/ 100 MW	t per MW	t per turbine	%	t/ 90MW	t per MW	t per turbine	%
Steel and iron materials	11082	110,82	687,1	85,97	6749	75,0	225,0	87,92
Light alloys, cast alloys, and wrought alloys	138	1,38	8,6	1,07	52	0,6	1,7	0,68
Nonferrous heavy metals, cast and wrought alloys	76	0,76	4,7	0,59	86	1,0	2,9	1,12
Polymer materials	602	6,02	37,3	4,67	297	3,3	9,9	3,87
Other materials and material compounds	796	7,96	49,4	6,17	371	4,1	12,4	4,83
Electronics	109	1,09	6,8	0,85	58	0,6	1,9	0,76
Lubricants and liquids	8	0,08	0,5	0,06	23	0,3	0,8	0,30
Not specified	80	0,8	5,0	0,62	40	0,4	1,3	0,52

From Table 2, it can be seen that steel and iron material are a major part of the materials that are used in both turbine types; they cover over 85 percent. Steel and iron material group includes unalloyed, highly alloyed, and cast iron. The second group comprises other materials and compounds, including modified organic materials, glass, ceramics, and magnets. The third group is polymers. These three groups cover over 96 percent of all materials used in turbines.

From subgroups, the biggest one is unalloyed and low alloyed steel and iron materials. This contains most of the tower and other supporting structures. The second biggest is cast iron, mostly from the hub and drive drain. After that, metal materials, the next biggest group is glass ceramics and polymer materials. These are mainly used in the blades and covers, like nacelle covers and electric wire covers.

Even though some groups are not as significant in volume, they are still in big part if looked at from the environmental or the economic point of view. For example, magnets are only 0.1 percent of the weight of the whole turbine. Still, they contain rare and expensive earth materials, and the availability of these materials is limited. Another example of an environmental point of view is SF6 gas (sulfur hexafluoride). It is used as an electrical insulator and for cutting off electrical power. From the mass of the 6,3 MW turbine, 0,001% or from 3,0 MW, 0,003% is SF6 gas. Sulfur hexafluoride is 23 500 times more effective greenhouse gas than carbon dioxide. In the 6,2 MW turbine, 0,001% means 1106 kg of sulfur hexafluoride. (Fingrid, 2020)

6 WIND PRODUCTION AND MATERIAL NEEDS IN NORTHERN OSTROBOTHNIA IN 2050

Northern Ostrobothnia as an area is in the north part of the Bothnic Bay, and it is the second largest region in Finland. It has a long coastline, and it extends from Bothnic Bay to the Russian border. The region's area is 36 818 m^3, which is 12 % of the area of Finland. 7,5 % of the population of Finland lives in the Northern Ostrobothnia area. (Pohjois-Pohjanmaan liitto, 2023)

Regions' wind conditions are well-suitable for wind power production due to good wind conditions. From Figure 1, it can be seen that the coast of Northern Ostrobothnia is one of the windiest areas in Finland. The region’s topography is also shallow, and for that reason, wind conditions are also profitable inland for wind power. In the northeast is an area with hills of 100 meters to 300 meters. (Paikkatietoikkuna, 2023)

6.1 Wind power production in Northern Ostrobothnia

At the end of 2022, there were 564 turbines in Northern Ostrobothnia. Production capacity was 2,3 GW. The first turbines were built in 1993, as shown in Figure 10. After that, only a few turbines were built per year until 2011. In 2012, the feed-in tariff was used, as seen from the figure in the first exponential growth phase between 2012 and 2017, when the feed-in tariff ended. After that, 2018 was a year in which zero turbines were installed in the region. In 2019, six turbines were built, and after the profitableness was confirmed, started new building growth. (Suomen tuulivoimayhditys, 2023f)

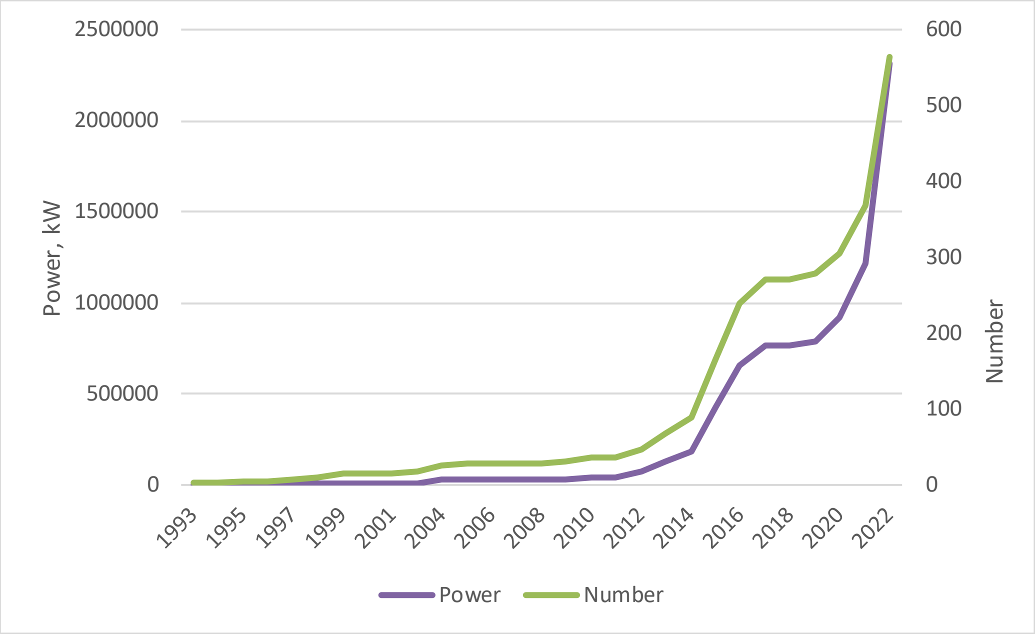

Figure 10. Cumulative capacity and number of wind turbines in Northern Ostrobothnia

The turbine's capacity has been growing more rapidly than the unit number of turbines. That is caused by turbine technical development. One turbine production capacity was 2,9 MW on average during the feed-in tariff growth. After the tariff, the turbine size grew up to 6,0 MW. Turbines that are under construction can be even bigger. (Suomen tuulivoimayhditys, 2023f)

In the pre-planning, permitting, and building phase, there are 3021 turbines in the Northern-Ostrobothnia region. This means 24,1 MW in capacity. Figure 11 is the cumulative capacity of the pre-production wind turbines that have already planned production starting the year. Of the 3 021 turbines, 1 409 do not have an estimated year of onset yet. Also, new turbine models or updated versions of existing ones can be on the market before, in the planning stage, turbines become the final investment decision. New turbine models and updated versions have better production capacity. (Suomen tuulivoimayhditys, 2023f)

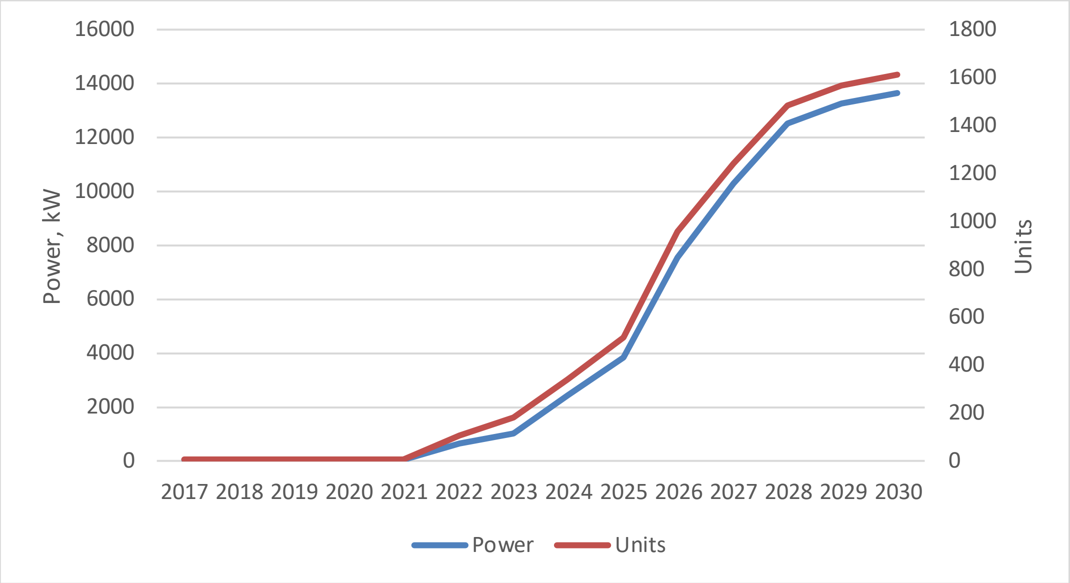

Figure 11. Cumulative capacity and units of pre-production phase turbines until 2030

Figure 12 presents the wind park project stages and how many turbines are in each stage. From the figure, we can see that most of the projects are in preplanning, which means that these projects have just found the area for the building, and even all the landowners are not involved yet. These are also projects in which realization is the most unsure. In the building stage, turbines are under construction. The second safe to say that turbines will be built are the permitting-ready ones. Those turbines have all the permits ready, and they probably have the building contractor's competitive tendering ongoing or starting soon. They might start to build within a year. (Suomen tuulivoimayhditys, 2023f)

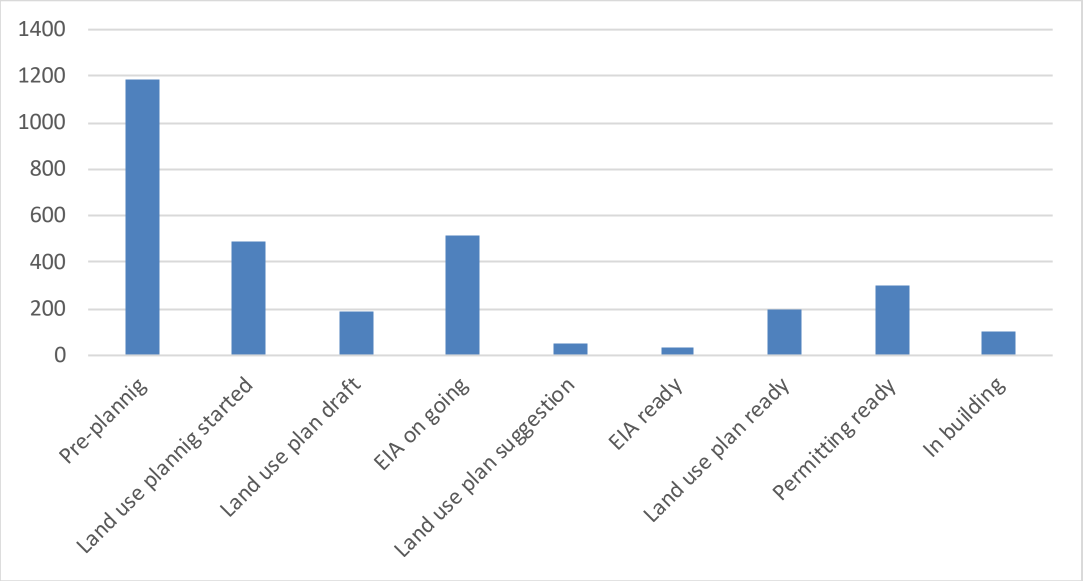

Figure 12. Turbine numbers in different pre-production stages

6.2 End of life turbines by 2050

Before the year 2018, built turbines in this scenario were assumed to have a 20-year lifetime, and after 2018, built turbines are assumed to have a 25-year lifetime. With this life expectancy, the first noticeable growth in the turbines coming to demolishing age is between 2033 and 2037, as seen in Figure 13. After that, there will be a couple of quieter years, and then after the 2044 waste, there is a large growth in the number of turbines, especially in the amounts of produced materials. In Figure 13, the blue line is wind turbines that are in production. The red line means that turbines are not yet built. Some might be, but some are in planning, and building time is not locked, and it can change. Also, some turbines are never built, and new projects can come.

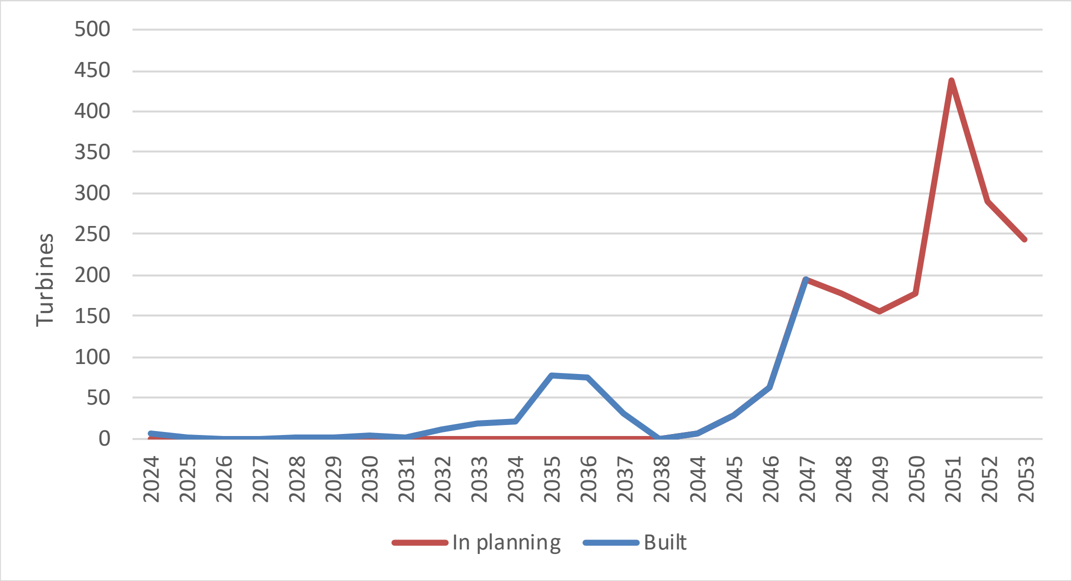

Figure 13. Yearly dismantled turbine numbers

Groving material amounts can cause overheating in all materials recycling. The better today, easily recyclable materials like steel, copper, and other metals have the most certain capacity to recycle growing amounts of material. The biggest challenges will likely be recycling glassfibres, carbon fibres, and composite materials.

6.3 Tentative material flow of waste from dismantled turbines

In 2022, only five turbines were dismantled. Figure 14 shows that dismantling amounts will not rise significantly until 2034 when the feed-in tariff parks come to the dismantling age. The waste amounts will stay at a manageable level. After the year 2045, the number of demolished materials will grow rapidly.

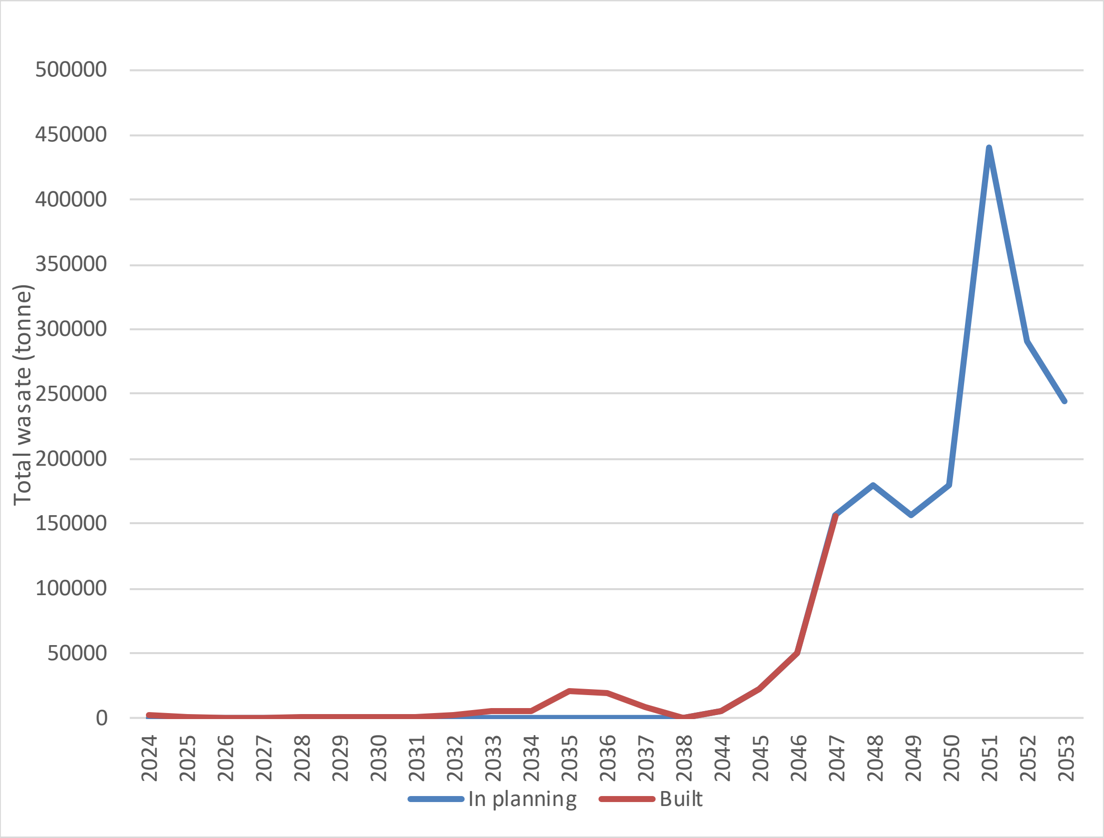

Figure 14. Total material amount from turbines that are coming to the recycling.

After 2045, the turbine sizes are also much bigger than earlier. This causes material amounts to grow more rapidly than the actual number of demolished turbines. After 2048, the amount of dismantled is unsure because those turbines are not built yet, and they are somewhere in the permitting stage, and there might become some things that all the turbines are not built. Also, the highest peak in Figure 14 can even out if the project timings change, which can happen easily.

Appendix 2 presents the yearly demolished material amounts by classes 2024 forward. All the material groups will grow, and the recycled material amounts will be a significant part of the total recycling of certain groups. For example, in 2010, 856 700 t of recyclable metals were. (Melanen et al. 2000) In 2035, 17 908,8 t of metals will come from demolished turbines in the recycling. That is two percent of the 2010 recycled metal amount. In 2048, the amount of recyclable metals from turbines will grow to 124 662,65 t. Percentage growth means that in 2048, 14 % of recyclable metals come from turbines compared to 2010.

6.3.1 Case study- Blades

Blades contain most of the material from the glass/ ceramics group, and some from the polymers group modified organic materials are used in the blades. In many cases, the organic materials group is the balsa wood used in the blade's structure frame. 3.0 MW turbine rotor weight 41.0 t. (wind-turbine-models.com) Hub weight is about half of it, so one blade weighs about 7 000 kg. Also, one 3,0 MW turbine has 22,3 t of glass/ceramics, organics, and polymers. When that is roughly divided into three parts comes 7 000 kg, and a little over one ton is left. The blade also contains some steel parts that which it is attached to the hub. The excess material is nacelle covers and other plastic parts in a turbine. 6,2 MW turbine blade weighs about 22 000 kg, so three blades weigh 66 t. The total amount of glass/ceramics, organics, and polymers is 84,6 t. Figure 15 shows how the amount of material to be recycled will increase in the future.

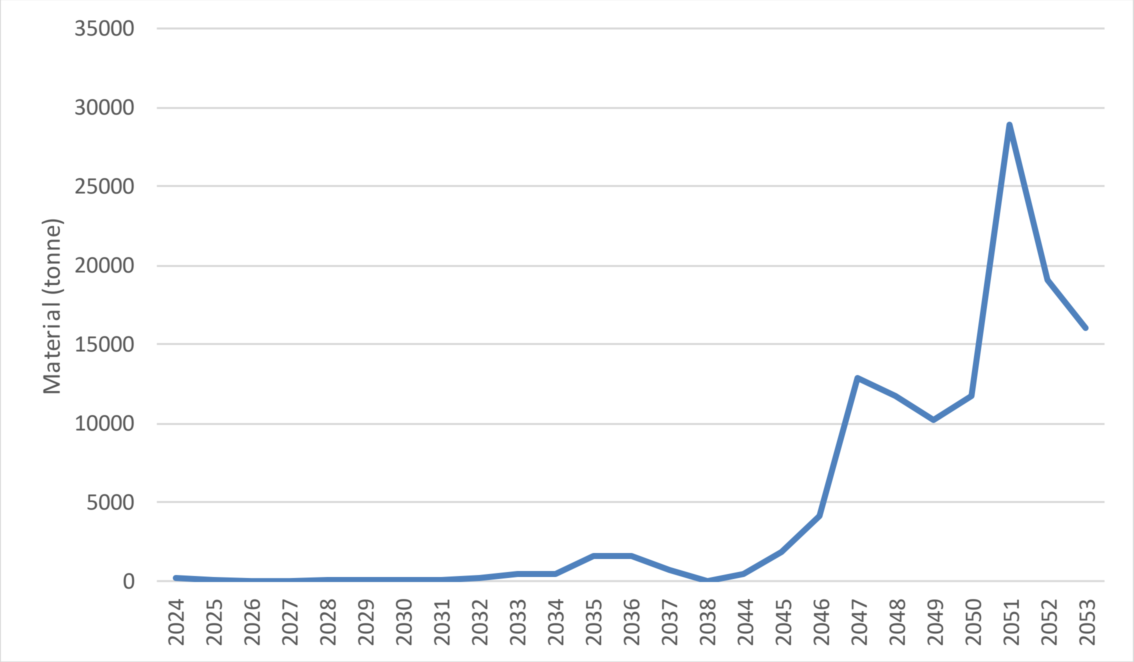

Figure 15. Blade material is to be recycled in the future.

Today's main recycling options for blade waste are burning and crushing concrete material. In Finland, the glassfiber composite recycling capacity is quite small. Today, the capacity is 2000-4000 t per year, and in 2024, a new 10 000 t recycling plant will be built. From Figure 15, it can be seen that 12 000 t will be reached in 2047. In 2051, 20 000t mark of blade waste will be broken.

7 DISCUSSION AND CONCLUSIONS

Increasing wind power capacity has become one of Finland's main ways to produce renewable electricity. Growth in wind power has been rapid since 2014. The jump in the electricity proruction has been significant with the growing wind turbine amounts and size capacity. The need for turbine materials has grown with growing turbine numbers and sizes. New turbine models have higher towers, and their blades are almost twice as long as in the old turbine models. This growth increases the material amounts in the future when turbines come into the demolishing age. In thirty years, the number of turbines to be recycled is growing from few to tens and even hundreds only in the Northen-Ostrobothnia area.

Today, 80-85 % of wind turbine materials are recycled. The rest of the materials are disposed of in landfills, which is not a sustainable way to handle these materials. The most important issue to consider in demolishing turbines is to increase the recycling percentage of waste materials. The quality of recycling is also important. In the best scenario, all the materials used to build a wind turbine would be used in a new turbine through recycling.

Recycling is already on a good level with some material groups used in turbines. One of such material group is metals and metal alloys. These already have good recycling possibilities. Metal recycling is also profitable because scrap metal has a good market value. This brings demolishing expenses down. Metals also keep their material properties well when recycled, and they can be used again in the new turbines. In metal and alloy recycling one target for the development is recycling of magnets in turbine motors. It is important that the rare earth metals contained in magnets can be reused, as their availability is low and, as demand increases, production from virgin materials cannot increase at the same rate.

The blades are one of the most problematic components of the wind turbine in terms of recycling. They are made from various materials that are hard to separate, and the materials are also hard to recycle. There are no proper ways yet to recycle blades in the ways that they would be reusable in as high-demand structures as they have been used in the first place. This problem is acknowledged in the industry, and there are projects and research that are trying to find ways to recycle blade materials.

With most materials, recycling capacity is not a problem, and there is already a recycling infra that can process all the material even if the volume is growing, such as with different metals. This is not the case for recycling the increasing volumes of blades. Current and under-construction blade recycling capacity will be sufficient until 2046 or 2047, depending on whether the older recycling plant is still in use. These material amounts are from the Northen-Ostrobothnia area only. In reality the recycling capacity will be insufficient much earlier.

In addition, the reuse of composites must improve to be able to give second life to materials already in use. Recycling would reduce the amount of virgin materials needed and thus reduce the environmental impact of the blades. In addition, recycled composite material would reduce the price of the blades, or at least the cost of dismantling the turbines, as the discarded blades could be treated as recondary raw material rather than waste. Even now, the cost of reselling the metal from the demolished power plants can be reduced.

Based on this work, the blade recycling challenge must be given more attention, and there is a need for new development and new research on how to recycle the blades in ways the material components could be utilized as a raw material for new blades. New materials for components is also a viable solution, such as organic, wood-based composites for blades or tower. In addition, development should targets magnets, to reduce or substitute the need for rare earth metals, or improve the recycling rate of rare earth from magnets. If wind power can develop in many ways there is a chance to solve these problems.

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APPENDIX 1. Material calculations

		6,2 MW				3,0MW			
		100MW Tonne	per mW Tonne	Per turbine tonne	%	90MW Tonne	Per MW Tonne	per turbine Tonne	%
Steel and iron materials	unalloyed, low alloyed	8583	85,83	532,1	66,58	4853	53,9	161,8	63,21
	highly alloyed	982	9,82	60,9	7,62	918	10,2	30,6	11,96
	cast iron	1517	15,17	94,1	11,77	979	10,9	32,6	12,75
Light alloys, cast alloys, and wrought alloys	light alloys, cast alloys, and wrought alloys	138	1,38	8,6	1,07	52	0,6	1,7	0,68
Nonferrous heavy metals, cast and wrought alloys	copper	76	0,76	4,7	0,59	79	0,9	2,6	1,03
	zinc alloys				0,00	7	0,1	0,2	0,09
Polymer materials	polymer materials	602	6,02	37,3	4,67	297	3,3	9,9	3,87
Other materials and material compounds	modified organic natural materials	35	0,35	2,2	0,27	33	0,4	1,1	0,43
	ceramic/glass	727	7,27	45,1	5,64	338	3,8	11,3	4,40

	SF6 gas	0,171	0,00171	0,0	0,00	0,22	0,0	0,0	0,00
	magnets	8	0,08	0,5	0,06	7	0,1	0,2	0,09
	other	25,829	0,25829	1,6	0,20	0	0,0	0,0	0,00
Electronics	electronics	27	0,27	1,7	0,21	3	0,0	0,1	0,04
	electrics	82	0,82	5,1	0,64	48	0,5	1,6	0,63
Lubricants and liquids	lubricants	8	0,08	0,5	0,06	23	0,3	0,8	0,30
Not specified	not specified	80	0,8	5,0	0,62	40	0,4	1,3	0,52

APPENDIX 2. Tentative material flow

	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036
unalloyed, low alloyed	1132,4	161,8	0,0	0,0	323,5	323,5	808,8	161,8	1779,4	3073,6	3397,1	12617,8	11970,7
highly alloyed	214,2	30,6	0,0	0,0	61,2	61,2	153,0	30,6	336,6	581,4	642,6	2386,8	2264,4
cast iron	228,4	32,6	0,0	0,0	65,3	65,3	163,2	32,6	359,0	620,0	685,3	2545,4	2414,9
light alloys, cast alloys, and wrought alloys	12,1	1,7	0,0	0,0	3,5	3,5	8,7	1,7	19,1	32,9	36,4	135,2	128,3
copper	18,4	2,6	0,0	0,0	5,3	5,3	13,2	2,6	29,0	50,0	55,3	205,4	194,9
zinc alloys	1,6	0,2	0,0	0,0	0,5	0,5	1,2	0,2	2,6	4,4	4,9	18,2	17,3
polymer materials	69,3	9,9	0,0	0,0	19,8	19,8	49,5	9,9	108,9	188,1	207,9	772,2	732,6
modified organic natural materials	7,7	1,1	0,0	0,0	2,2	2,2	5,5	1,1	12,1	20,9	23,1	85,8	81,4
ceramic/glass	78,9	11,3	0,0	0,0	22,5	22,5	56,3	11,3	123,9	214,1	236,6	878,8	833,7
SF6 gas	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,1	0,1	0,2	0,6	0,5
magnets	1,6	0,2	0,0	0,0	0,5	0,5	1,2	0,2	2,6	4,4	4,9	18,2	17,3
other	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
electronics	0,7	0,1	0,0	0,0	0,2	0,2	0,5	0,1	1,1	1,9	2,1	7,8	7,4
electrics	11,2	1,6	0,0	0,0	3,2	3,2	8,0	1,6	17,6	30,4	33,6	124,8	118,4
lubricants	5,4	0,8	0,0	0,0	1,5	1,5	3,8	0,8	8,4	14,6	16,1	59,8	56,7
not specified	9,3	1,3	0,0	0,0	2,7	2,7	6,7	1,3	14,7	25,3	28,0	104,0	98,7

	2037	2038	2044	2045	2046	2047	2048	2049	2050	2051	2052	2053
unalloyed, low alloyed	5176,5	0,0	3192,9	14900,1	33525,2	103768,5	94722,0	82482,6	94722,0	233079,9	153790,2	129311,5
highly alloyed	979,2	0,0	365,3	1704,8	3835,7	11872,4	10837,4	9437,0	10837,4	26667,2	17595,5	14794,8
cast iron	1044,3	0,0	564,3	2633,5	5925,4	18340,5	16741,6	14578,4	16741,6	41195,7	27181,6	22855,1
light alloys, cast alloys, and wrought alloys	55,5	0,0	51,3	239,6	539,0	1668,4	1523,0	1326,2	1523,0	3747,5	2472,7	2079,1
copper	84,3	0,0	28,3	131,9	296,9	918,8	838,7	730,4	838,7	2063,9	1361,8	1145,0
zinc alloys	7,5	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
polymer materials	316,8	0,0	223,9	1045,1	2351,4	7278,2	6643,7	5785,2	6643,7	16347,9	10786,6	9069,7
modified organic natural materials	35,2	0,0	13,0	60,8	136,7	423,2	386,3	336,4	386,3	950,5	627,1	527,3
ceramic/glass	360,5	0,0	270,4	1262,1	2839,7	8789,4	8023,2	6986,5	8023,2	19742,4	13026,4	10953,0
SF6 gas	0,2	0,0	0,1	0,3	0,7	2,1	1,9	1,6	1,9	4,6	3,1	2,6
magnets	7,5	0,0	3,0	13,9	31,2	96,7	88,3	76,9	88,3	217,2	143,3	120,5
other	0,0	0,0	9,6	44,8	100,9	312,3	285,0	248,2	285,0	701,4	462,8	389,1
electronics	3,2	0,0	10,0	46,9	105,5	326,4	298,0	259,5	298,0	733,2	483,8	406,8
electrics	51,2	0,0	30,5	142,4	320,3	991,4	905,0	788,0	905,0	2226,8	1469,3	1235,4
lubricants	24,5	0,0	3,0	13,9	31,2	96,7	88,3	76,9	88,3	217,2	143,3	120,5
not specified	42,7	0,0	29,8	138,9	312,5	967,2	882,9	768,8	882,9	2172,5	1433,4	1205,3