UNIVERSITY OF GÄVLE

FACULTY OF ENGINEERING AND SUSTAINABLE DEVELOPMENT
Department of Building, Energy and Environmental Engineering

Wind turbine end-of-life:

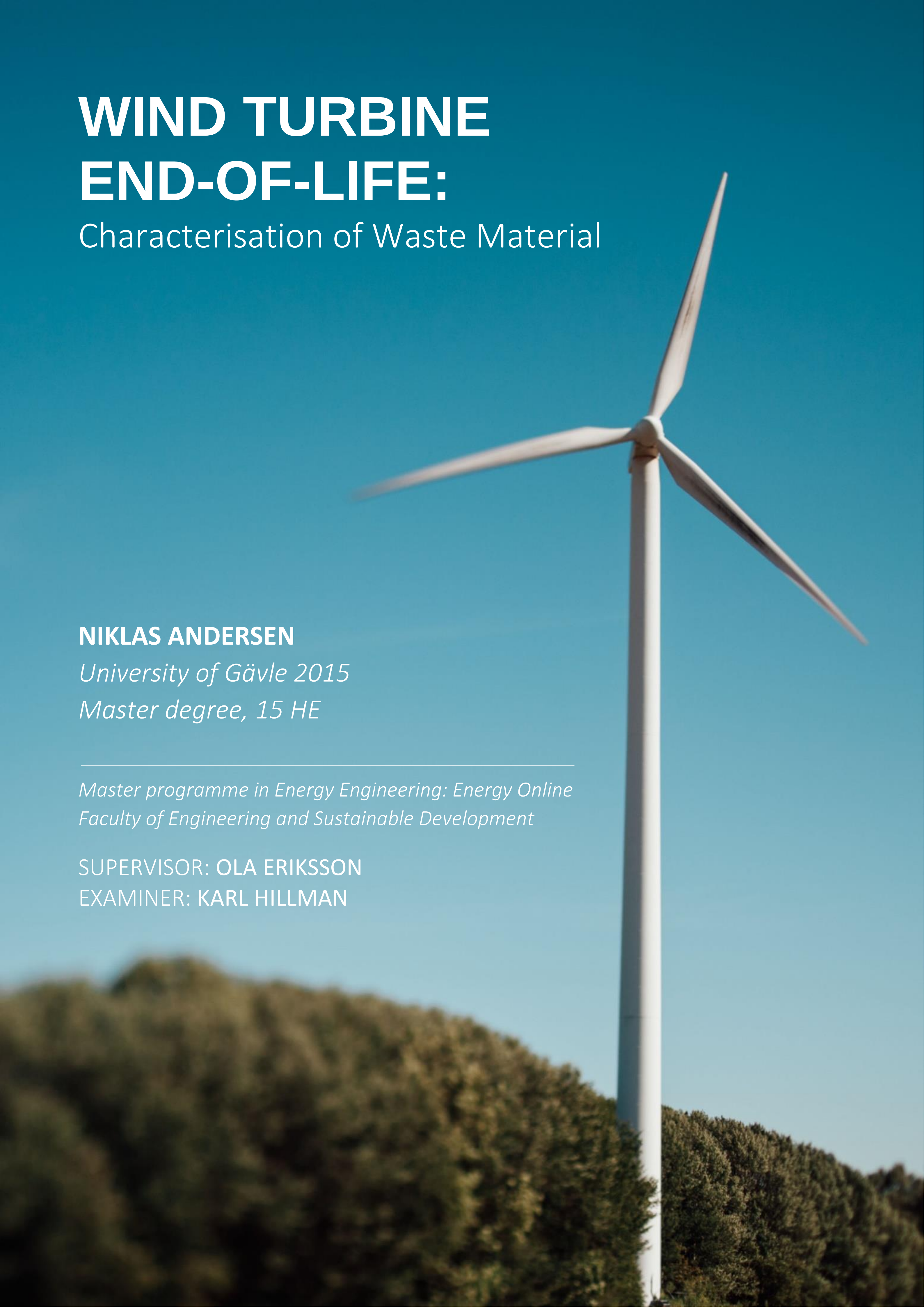
Characterisation of waste material

Niklas Andersen

2015

Student thesis, Master degree (one year), 15 HE
Energy Systems
Master Programme in Energy Engineering, Energy Online

Supervisor: Ola Eriksson
Examiner: Karl Hillman



WIND TURBINE END-OF-LIFE:

Characterisation of Waste Material

NIKLAS ANDERSEN

University of Gävle 2015

Master degree, 15 HE

Master programme in Energy Engineering: Energy Online
Faculty of Engineering and Sustainable Development

SUPERVISOR: OLA ERIKSSON
EXAMINER: KARL HILLMAN

ABSTRACT

Wind power is growing fast all over the world, and in Sweden alone thousands of turbines has been installed the last few decades. Although the number of decommissioned turbines so far is very low, the rapid installation rate indicates that a similar rapid decommissioning rate is to be expected shortly. If the waste material from these turbines is not handled sustainably the whole concept of wind power as a clean energy alternative is challenged.

This study aims to present an accurate estimate of the amounts of waste material that will be generated from wind turbines in Sweden during the coming decades, allowing the waste management industry to plan for this and by extension prevent unnecessary energy losses through imperfect waste treatment. It should also present helpful information on how problematic waste can be reduced or avoided.

VindStat's annual report, presenting installation date and other relevant data for most installed turbines in Sweden, has been used as the base for the calculations. Information on material composition in different types and sizes of wind turbines has been extracted from various life cycle assessments, and by using the available parameters in the data base each turbine has been assigned a specific amount of steel, iron, copper, aluminum, blade material and electronics. An average life time of 20 years has been assumed, based on prior research and comparison with empiric data, and the material of each turbine is therefore seen as generated waste 20 years after installation date.

To calculate the amount of waste material from replacing faulty components, empiric data over replacement rates in further developed markets has been combined with a prognosis over future development of installed wind capacity in Sweden based on a method described by prior research. As no sufficient way to predict how the future second hand market for turbines and components has been found, three different possible scenarios have been investigated to see how this may affect waste amounts.

The results show that annual waste will grow slowly at about 12 % increase per year until around 2026, and then the average increase is 41 % per year until 2034. By then, annual waste amounts are estimated to have reached 237 600 tonne *steel and iron* (16 % of currently recycled amounts), 2 300 tonne *aluminium* (4 %), 3 300 tonne *copper* (5 %), 343 tonne *electronics (<1 %)* and 28 100 tonne *blade material*. There is no industrial scale recycling method for commonly used blade materials, and a high strength steel developed by Sandvik is proposed as a fully recyclable material to consider for further research. A well-functioning second hand market is shown to possibly have a major impact on waste amounts, at least in postponing it until better recycling systems are in place.

SAMMANFATTNING

Vindkraft är en snabbt växande energikälla världen över och enbart i Sverige har tusentals vindkraftverk installerats under senaste decennier. Även om antalet nedmonterade verk än så länge är relativt lågt, indikerar det stora antalet årliga installationer att ett liknande antal nedmonteringar är att vänta inom kort. Om avfallsmaterialet från dessa verk inte hanteras på ett hållbart sätt riskeras att syftet med vindkraft som ett miljövänligt alternativ utmanas.

Målet med studien är att presentera en noggrann uppskattning om vilka mängder avfallsmaterial som kommer att genereras från vindkraftverk i Sverige under kommande årtionden, vilken kan användas för att planera avfallshantering och på så vis i förlängningen undvika onödiga energiförluster genom felaktiga processer. Information om hur problematiskt avfall kan undvikas eller minskas ska även presenteras.

Vindstats årliga rapport, vilken presenterar installationsdatum och annan relevant information för de flesta installerade vindkraftverk, har använts som bas för beräkningar. Information över materialfördelning i olika typer och storlekar av vindkraftverk har extraherats från ett antal livscykelanalyser och genom att använda tillgängliga parametrar i databasen har varje enskilt vindkraftverk tilldelats en specifik mängd stål, järn, koppar, aluminium, bladmaterial och elektronik. En genomsnittlig livslängd på 20 år har antagits, baserat på tidigare forskning och jämförelse med empirisk data, och materialet i vindkraftverken har därför setts som genererat avfall 20 år efter installationsdatum.

För att beräkna mängden avfallsmaterial från utbytta komponenter har empirisk data över utbytningsfrekvenser hos mer utvecklade marknader applicerats på en prognos över över möjlig framtida utbyggnad av vindkraftskapacitet i Sverige som skapats enligt en metod beskriven i tidigare forskning. Eftersom ingen fullständig metod har funnits för att förutse hur framtida andrahandsmarknad för vindkraftverk och komponenter så har tre möjliga scenarion undersökts för att se hur detta kan komma att påverka avfallsmängder.

Resultaten visar att de årliga avfallsmängderna förväntas växa med ca 12 % per år fram till 2026, och därefter i genomsnitt 41 % per år fram till 2034. Då förväntas avfallsmängderna uppnått 237 600 ton *stål och järn* (16 % av nuvarande återvunnen mängd), 2 300 ton *aluminium* (4 %), 3 300 ton *koppar* (5 %), 343 ton *elektronik* (<1 %) och 28 100 ton *bladmaterial.* Det finns ingen metod för att återvinna vanligen använda bladmaterial på industriell skala, och ett extra starkt stål utvecklat av Sandvik föreslås som fullt återvinningsbart alternativ att undersöka. En väl fungerande andrahandsmarknad visar sig kunna ha en betydande inverkan på framtida avfallsmängder, åtminstone genom att skjuta upp behovet av hantering tills ett mer effektivt system finns på plats.

CONTENT

1. INTRODUCTION

1.1 BACKGROUND

Increased awareness of environmental issues linked to using fossil fuels during the recent decades has driven the development of renewable energy resources with lower environmental impact such as hydro-, solar- and wind power. For these to remain sustainable alternatives it is important that the entire life time of components involved is managed as well as possible; from production and installation, through operation until decommissioning and removal.

Wind power is one of the fastest growing energy sources in the world [1], and the market in Sweden is certainly following that trend as more than 3000 turbines has been installed over the last decade and the annual electricity generation from wind power plants has grown more than ten times from around 0.9 TWh in 2004 to almost 11.5 TWh by 2014 [2] [3]. Assuming that the life span of a wind turbine is 20 years (the most common assumption in literature [4]), and considering that the more serious wind power development in Sweden began around 25 years ago, the logical conclusion is that the number of annual decommissioned wind turbines is going to increase substantially during the coming decades.

To properly handle all waste from the wind power industry, it is important to know what amounts to expect from each different material and when decommissioning demand will increase to make sure there is sufficient capacity in place.

1.2 PROBLEM

The waste generated from the aging wind turbines in Sweden has to be taken care of in a sustainable way for wind energy to remain a relatively environmentally friendly alternative. As wind energy developed relatively rapidly there is a risk that an equally sudden increase in waste material from decommissioned turbines will prove difficult to handle unless the industry is prepared.

1.3 AIM

The presented result should be an estimate of the amounts of waste material that will be generated from wind turbines in Sweden during the coming decades. These estimations should be as precise as available data allows. Material that could potentially be particularly problematic should be identified and methods to reduce amounts or lower the negative environmental impact of these proposed.

1.4 PURPOSE

The estimated amounts of waste generated from Swedish wind power will hopefully be used in planning for future waste management. This could avoid disposal of material that can be re-used, recycled or energy recovered since the proper system can be introduced in time. By extension this should prevent unnecessary energy losses and negative environmental impact from wind power.

1.5 RESEARCH QUESTIONS

> *What types of waste material is generated when wind turbines are decommissioned or turbine parts are replaced?*

> *How much of each material will be generated from both decommissioned and operating wind turbines in Sweden during the coming decades?*

> *Which materials are problematic to handle sustainably and how can the negative environmental impact from these materials be reduced?*

1.6 LIMITATIONS

The study is limited to the Swedish wind power market. Precise data for each installed wind power plant is not available in the data bases used, and hence some information has to be extrapolated and factored to be enable projections.

Grid connections, transformers and similar infrastructures are excluded from the study since it is assumed they are often reused for new turbines or for other projects. Turbines smaller than 50 kW is not available in the data base used and is therefore not included in this study as well as turbines that are not of three bladed horizontal axis design. Some material that are actually present may be left out of this report as they are used in minor amounts or only present in specific models by certain manufacturers.

The weight and design of the tower foundation is dependent on the surrounding environment, and no such information is available in the data used in this research, nor has it been found elsewhere. Attempts to estimate the foundation weight based on other parameters has proven inaccurate. It is also unclear how much of it, if any, that has to be removed from the site after decommissioning since it is often largely hidden underground. Therefore the foundation weight and material included within it has been completely excluded from the estimation results.

As offshore wind power is such a small fraction of the total installed power in Sweden and the uncertainty about how much has to be removed applies here as well, no particular measure has been taken for these turbines. The relatively new technology of permanent magnet generators have not been taken into account in this study as it is difficult to predict how the market for these will develop even in the near future.

2. METHOD

Literature previously used for relevant courses, journal articles, written reports and studies on relevant subjects have been read and analysed to ensure as precise prediction methods as possible from the available information. These have mainly been acquired through appropriate online search engines as the university online library search, Google Scholar and journal websites. Data over installed wind power in Sweden has been gathered from VindStat's annual reports and compared with other data bases as the Swedish Energy Agency and Swedish Wind Energy. Information on installed wind power in other countries has as far as possible been gathered from their respective energy agencies or BP's statistical review of world energy, although some data for early years has been collected from other reports.

Material amounts in entire turbines and specific turbine parts have been extracted from life cycle assessments. Rather than evaluating the quality of data of each assessment, a quantitative approach has been used where the lowest and highest value is noted along with the average of all values. These have then been then used to estimate the amount of material in specific turbines as well as to produce typical weight percentages for estimations regarding unknown models. The acquired values has then been combined with the VindStat data base, applied directly in cases where values for the specific model has been available and estimated for others.

As VindStat does not cover 100% of Swedish turbines, a scaling factor (based on comparison with actual installed power) have been used for each year to compensate. The average life time has been estimated through comparing the most common assumption with empirical data, and the result has been used to estimate when the material in each turbine will turn into waste. To find the amount of waste material generated from replaced components, a prognosis over future wind power development has been modelled and combined with historic data over component replacement as well as typical material weights in these components. The final result has been presented as waste material amount per year for several material categories, and is then compared to the current amount of recycled material in Sweden. Three different scenarios of second hand market development has also been produced to investigate how this may affect the actual waste amounts. A possible alternative to the currently used material in wind turbine blades has been suggested and briefly investigated via a phone interview with an engineer working with the material.

All data processing, calculations and simulated predictions has been performed in Microsoft Excel and finally presented as charts and tables, while images and models have been created in Adobe Photoshop.

3. GLOBAL WIND POWER GENERATION

The concept of converting energy in wind into electricity has grown from a few experimental projects in the late 70's and early 80's to now being a serious contributor to the worlds electricity mix. Denmark and USA were the first to develop serious wind power markets and are still in 2013 two of the major markets; USA has the largest amount of actual wind energy use and Denmark has the largest percentage of wind energy based electricity in their system (see table 1). China has increased its wind power generation greatly over the last decade (from about 1 TWh in 2003 to 131 TWh in 2013) and already has the largest installed capacity by far [1].

Table 1: Wind energy use and percentage of wind energy in the electricity mix in 2014 for the top 12 countries, based on BP's statistical review from 2015. [1]

COUNTRY	WIND ENERGY USE [TWH]	PERCENTAGE OF NATIONAL ELECTRICITY MIX
USA	184	4%
CHINA	158	3%
GERMANY	56	9%
SPAIN	52	19%
INDIA	38	3%
UNITED KINGDOM	32	9%
FRANCE	16	3%
ITALY	15	5%
DENMARK	13	41%
PORTUGAL	12	23%
BRAZIL	11.9	2%
SWEDEN	11.5	7%
ALL COUNTRIES	706	3%

4. WIND POWER IN SWEDEN

Statistics on Swedish wind power is available from several sources [2, 3, 5]. There is an electricity certificate system in place where owners of wind power plants report their installed turbines and their production is monitored to provide the right amount of certificates. This is what the Swedish Energy Agency bases their yearly statistics on and it is assumed to cover all the existing plants [2]. Swedish Wind Energy is an association for the wind power companies and they report statistics every quarter based on the turbine supplier's data [3].

VindStat monitors every plant's production and operation each year for those reporting. More detailed information on the plants are available, such as height, rotor diameter, power, installation date etc. As this is not mandatory, not all turbines are represented and there is often a delay between installations and reporting. Especially during the latest years there is a large gap between reported and actual turbines [5]. The wind power development in Sweden since 1982 is presented in figure 1.

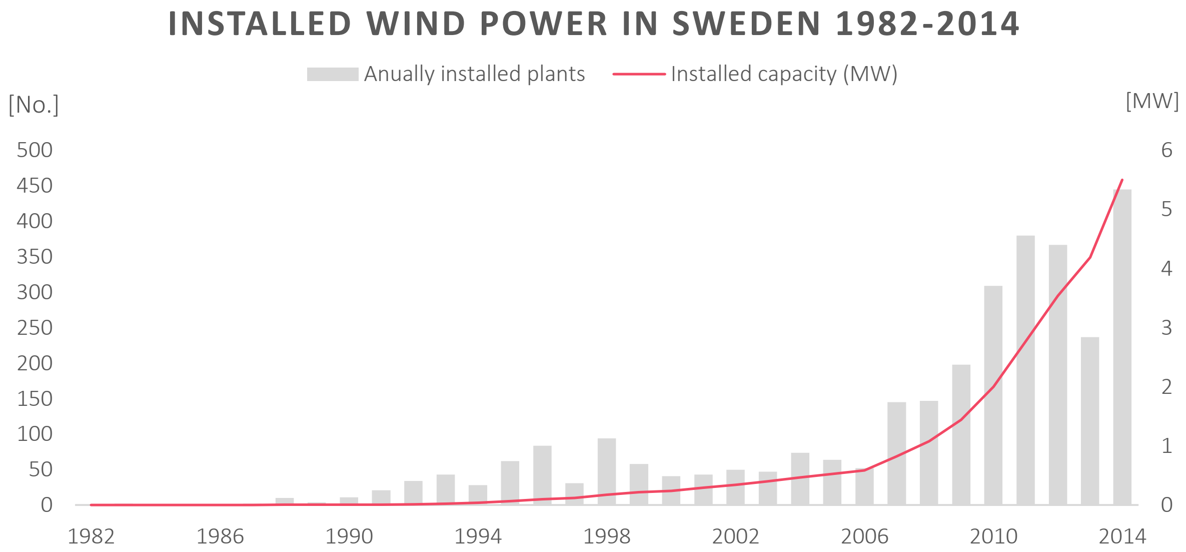


Figure 1: Installed wind power in Sweden 1982-2014, installed turbines and cumulative installed capacity. Based on data from the Swedish Energy Agency (1982-2013) and Swedish Wind Energy (2014) [2, 3]

The total electricity generation from wind energy in 2014 was 11.5 TWh. The national goal for Sweden is 30 TWh in 2020 [6], almost three times the current generation.

Offshore wind power is still relatively undeveloped in Sweden with a total of 212 MW installed power, equal to 2.6 % of the total share [7]. All currently installed wind power farms are listed in table 2. Yttre Stengrund is planned to be decommissioned in 2015, making it the first offshore wind farm to be decommissioned in the world after only 14 years of operation. It consists of wind turbines of an old model of which only a few was ever built, making spare parts expensive [8].

Table 2: Offshore wind power farms in Sweden as of 2014. [9]

WIND FARM	CAPACITY [MW]	TURBINES[1]	MODEL (MW)	OWNER	YEAR[2]
Lillgrund	110	48	Siemens SWT-2.3-93 (2.3)	Vattenfall	2008
Karehamn	48	16	Vestas V112 (3.0)	E.ON	2013
Vänern	30	19	WinWind Dynawind (3.0)	Kraft AB	2010
Utgrunden	11	7	Enercon Wind 70 (1.5)	Vattenfall	2006
Yttre Stengrund	10	5	NEG Micon (2.0)	Vattenfall	2001
Bockstigen	2.75	5	WinWorld (0.55)	Vattenfall	1998

[1] Number of installed turbines in the entire wind farm

[2] Year of commissioning

5. INVENTORY OF MATERIAL USE

A single wind power plant can weigh up to several hundred tonnes and the material used varies with capacity, design, manufacturer and location. Practically all the plants installed in Sweden uses a three-bladed design [10] with a few variations of generator types, and more than 97% is located onshore. The most common wind turbine model in Sweden is Vestas V90 with 412 turbines registered in VindStat, before Enercon E82 with 203 registered turbines [5]. The material composition of the most common wind turbine in Sweden, a Vestas V90, can be seen in figure 2.

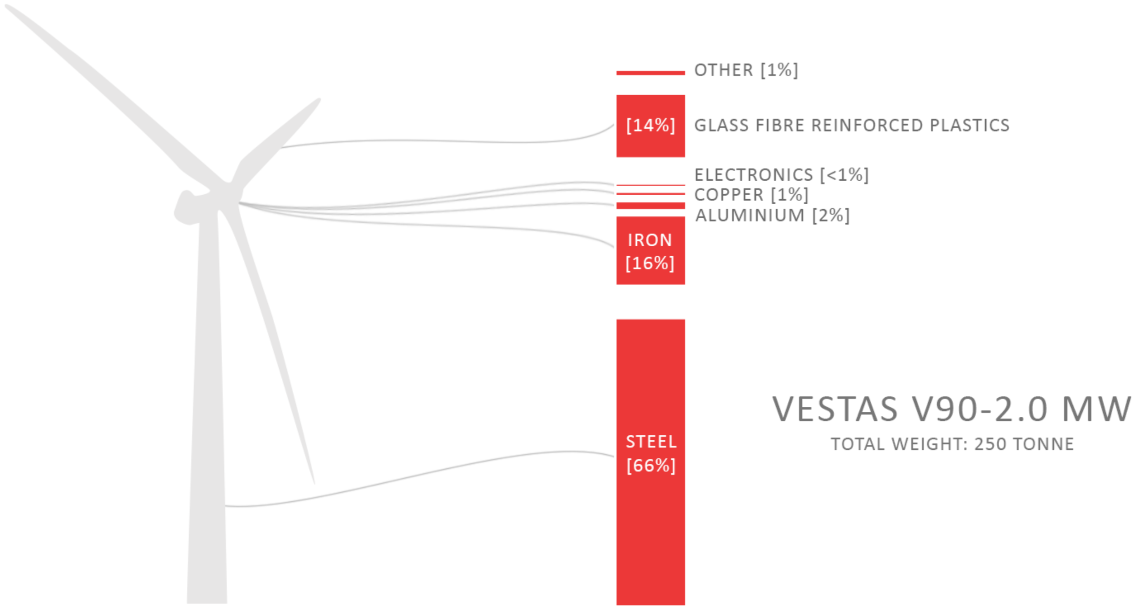


Figure 2: Material found in the most common wind turbine in Sweden, Vestas V90 2.0 MW [11]. The lines point to the part where most of each material is found.

This chapter presents descriptions of the different turbine parts and their material, while quantified data used for calculations is given in the results. The weight and material percentages are based on 13 different turbines from 8 different Life Cycle Assessments [12-18].

5.1 FOUNDATION

Unless the ground on the location is solid rock, in which case the tower may be anchored straight to the ground, a foundation stable enough to withstand the strong momentum caused by forces from wind and rotation of the blades is needed. At onshore locations a gravity foundation is most commonly used in the form of a large concrete disk buried in the soil with a steel construction in the centre for anchoring the tower [19]. As the intrinsic purpose of this construction is to use gravitational forces to compete with the momentum from the turbine it is always the heaviest part, between 60-90 % of total weight in onshore turbines. The material used is ranging between 3-6 % steel and the rest is concrete. The material found here is excluded in estimations (see explanation in chapter 1.6).

5.2 TOWER

To raise the *hub height* (distance from ground to rotor hub, the most common height measure of a wind turbine) from the ground both to reach higher wind speeds and allow larger rotor diameter a tower construction is used, most commonly a welded steel tube bolted to the foundation [10].

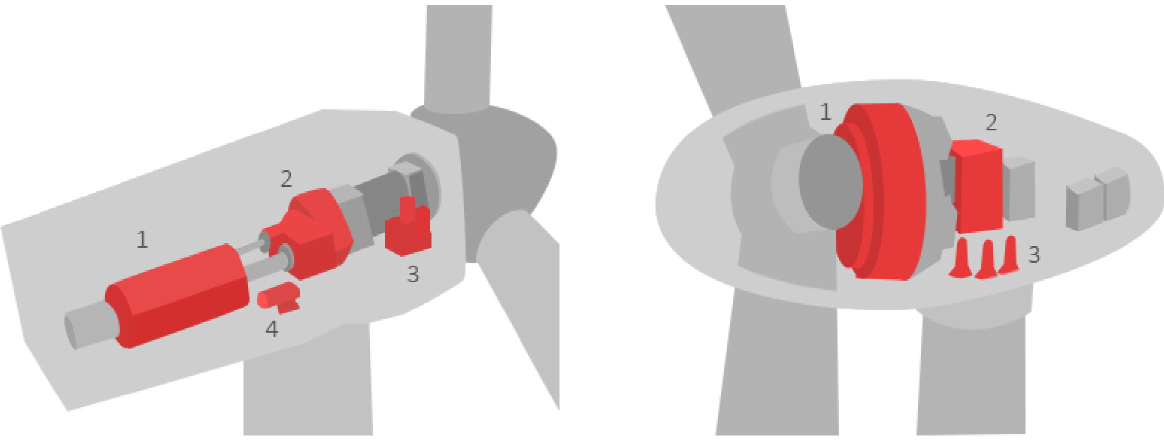
Excluding the foundation, the tower is the heaviest turbine part at about 60-70 % of the total weight. Material used are steel (95-100 %), aluminium (0-2 %), copper (0-1 %) and glass reinforced plastics (0-4 %)

5.3 NACELLE

Mounted on top of the tower is the nacelle, i.e. the part containing the mechanical parts needed to transform the rotational energy of the rotor blades into electricity. The housing cover is generally made out of *glass reinforced plastics* (GRP) and its structure is supported by a metal frame. The specific components found inside the nacelle depends on the manufacturer and the design. The two leading companies on the Swedish wind turbine market are Vestas and Enercon [5].

Vestas main design is using a doubly fed induction generator (DFIG), which runs on fixed speed with a gear box that convert the slow rotation of the blades into higher speeds [20]. The Enercon concept on the other hand is using a gearless design with a direct drive synchronous generator (DDSG), which runs on variable speed and is directly connected to the rotation from the blades [21]. Figure 3 shows a slightly simplified cross section of two common examples of the different designs. The DDSG design does not require a gear box, but instead a larger generator is required. The equipment is mounted to a single cast frame, called the main carrier, to ensure stable mechanical behaviour. Both designs use a yaw system which keeps the rotor directed towards the wind direction.

VESTAS | DOUBLY FED INDUCTION GENERATOR **ENERCON** | DIRECT-DRIVE SYNCH. GENERATOR



1. ASYNCHRONOUS GENERATOR
2. GEAR BOX
3. ROTOR LOCK SYSTEM
4. YAW SYSTEM

1. SYNCHRONOUS GENERATOR
2. MAIN CARRIER
3. YAW SYSTEM

Figure 3: Cross section of two different nacelle designs, DFIG and DDSG, highlighting certain components. Modelled after Vestas V90 [22] and Enercon E82 [21].

The major materials found in the nacelle are steel, copper, aluminium, iron, GRP (for the cover) and smaller amounts of electronics and lubricants. The DDSG generator is generally heavier and contains larger amounts of copper [23].

In recent years a generator design using permanent magnets instead of electromagnets have become more popular to reduce the generator weight, which means rare earth metals are present. The dangers and environmental hazards regarding these materials have been investigated at KTH [24]. Many of the larger manufacturer's newest models use permanent magnets, and since 2012 a few wind farms using these models have been installed in Sweden [25, 26]. These materials have not been included in estimations (see explanation in chapter 1.6)

5.4 ROTOR

The rotor is the part of the turbine that is designed to convert the kinetic wind energy in a certain circular area and convert it into rotational energy. In a horizontal axis wind power plant this is achieved when the wind hits the blades in an angle that generates lift. It is the same principle used in an aeroplane wing only that instead of using the lifting force to cancel out gravitational forces it is used to rotate the blades [27]. The most efficient aerodynamic design is achieved at certain thickness along the length of the blade. At the same time the rotor blades need to be durable and retain its shape while enduring strong forces, which means the material used has to be durable, stiff and light weight [28].

The most commonly used material in turbine blades is GRP (based on polyester or epoxy) since it has all the properties mentioned above at the same time as it is relatively cheap. A steel or aluminium construction would be strong enough but at the same time very heavy. *Carbon reinforced plastics* (CRP) is an alternative to GRP that is even stronger and hence can be built at even lower weights, but is more expensive [29]. As the rotor blade diameter increases, CRP could become increasingly common since lower weight means less stress on the rest of the construction [30]. The most commonly found blade materials in observed life cycle assessments are GRP (80-95 %), CRP (0-10 %), plastics (0-15 %), steel (2-9 %) and aluminum (0-1 %) [13]. A cross section of a typical wind turbine rotor blade can be seen in figure 4.

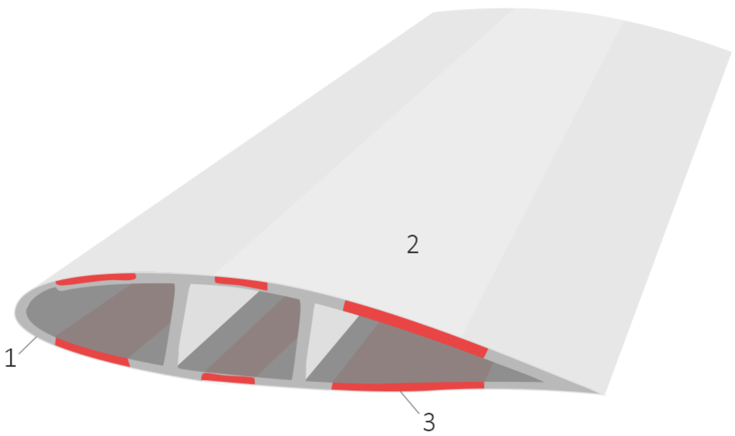


Figure 4: Cross section of a typical wind turbine rotor blade, constructed mainly with composite material and plastics [31].

The hub is also included as part of the rotor in this study. It is the structure that provides a coupling between the rotor blades and the main shaft that is in turn connected to the generator/gear box. It is generally made out of cast iron (sometimes along with some low-alloy steels) and is either covered with GRP [16] or built inside the nacelle cover [32].

6. WIND TURBINE LIFE TIME

A wind power plant (like most technology) is exposed to two forms of aging. Loss of performance as a result of physical wear and tear and relative aging compared to the technology on the market that is constantly evolving. Sooner or later every plant will either be taken down since it is no longer worth repairing or simply be replaced with newer more efficient technology. The period from commission to decommission is called the technical lifetime.

In Sweden there is a third motivation for replacing older plants; the electricity certificate system. It is a form of subsidies which grants the owner one certificate per MWh generated electricity the first 15 years of operation. It is decided to be valid until 2035, meaning turbines installed after 2020 receives fewer years. The certificate is sold on an open market to electricity users that are obligated to purchase a certain amount each year, and these sales generally account for about a third of the total income from a plant. [33] Replacing the turbine with a new one will grant another 15 years of certificates, moving a reused turbine to a new location will however not get renewed certificates. [34, 35]

6.1 TURBINE LIFE TIME

Dolan and Heath [4] has reviewed available life cycle assessments and compiled a table of methods and assumptions used. 20 years is by far the most common life time used for all types of wind power plants. Furthermore, Staffell and Green [36] has studied the performance of aging wind power plants and found that the trend of decline is consistent for different turbine generations, meaning newer turbines age in a similar rate as old ones. It will therefore be assumed that the average lifetime is the same regardless of when the plant was installed.

As the wind power technology is still relatively young, few countries have markets that have been well developed for more than 20 years, and hence there is not yet much empirical data on turbine life time. In table 3 the development of wind energy use in 1984-1994 is listed for the ten countries with the highest wind energy use in 1994 according to BPs statistical review from 2015 [1]. The development over these years is presented to show why some markets have more decommissioned turbines to examine than others.

Table 3: Wind energy use per country in GWh between 1984 and 1994. The countries listed are the top 10 users in 1994, also listed in that order.

COUNTRY [GWH]	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994
USA	7	6	4	4	1	2133	2817	2981	2917	3036	3482
DENMARK	34	52	127	176	295	433	616	748	925	1045	1148
GERMANY	0	0	1	2	8	26	71	100	275	600	909
CHINA	0	0	0	0	0	0	2	9	131	212	384
U.K.	0	0	0	0	0	9	9	9	33	217	344
NETHERLANDS	0	0	1	2	16	23	56	88	147	174	238
INDIA	0	0	0	0	0	0	30	113	88	95	191
SPAIN	0	0	0	0	0	13	14	15	103	116	175
SWEDEN	5	6	6	6	5	5	6	13	31	52	75
CANADA	0	1	1	1	1	1	2	2	3	31	56

USA had the fastest growing early market, however no continuous data over turbine decommissioning has been found. Denmark was an early adopter to the technology and now has the largest share of wind power in its electricity mix (see table 3), while Germany started to develop their wind power market around the same time as Sweden but at a much higher rate. The large quantity of installed plants gives a larger sample for evaluating the expected life time. The installed and decommissioned number of plants in Denmark, Germany and Sweden can be seen in figure 5 [32, 38-42]. The prognosis seen is assuming that every plant is decommissioned 20 years after its installation date, i.e. the estimated number of decommissioned plants in 2014 is the same as the number of installed plants in 1994.

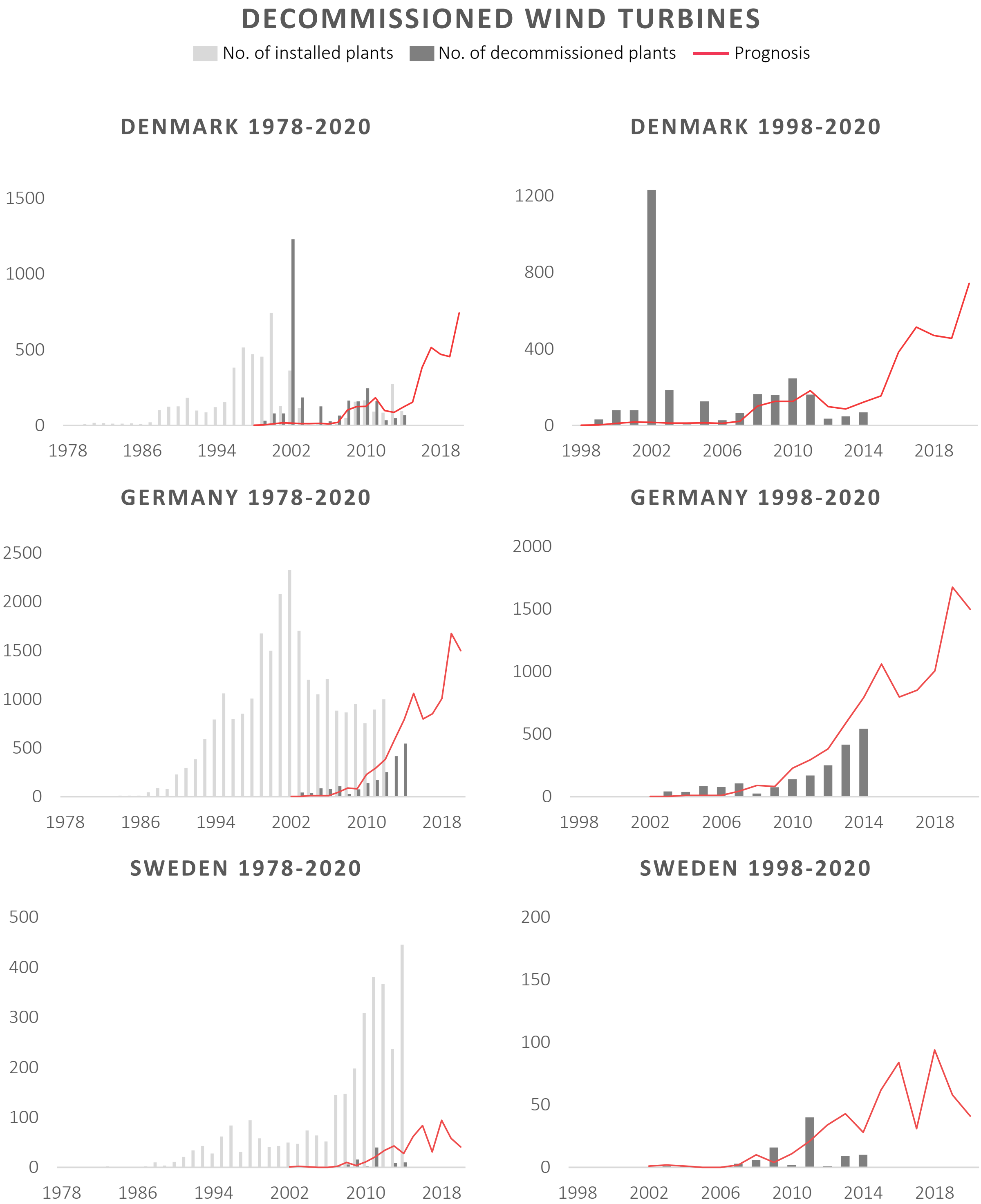


Figure 5: Installed and decommissioned wind turbines in Denmark, Germany and Sweden compared to estimated number of decomissionings assuming an average of 20 year life time (based on [32, 38-42]). Note the difference in magnitude between charts, I.E. they should not be used for comparison between countries.

Apart from the peak in 2002, a result of a repowering programme running between 2001 and 2003 [43], the real scenario follows the predicted trend relatively well in Denmark. In Germany the number of decommissioning is growing in the expected pattern, even though the development is one or two years later than the prognosis. The data for Sweden so far is scarce, and attempting to find a pattern from such a small sample could be misleading. The first larger decommissioning projects does however appear at the estimated time (around 20 years after market development starts) and magnitude.

6.2 PART REPLACEMENT

The calculated turbine life time is representing the number of years a plant is in operation, which isn't necessarily the same as the life time for individual parts. Some may be repaired or exchanged during this period.

A common issue with wind power plants using a geared generator design is failure of the gear box. A report by Elforsk [44] concludes that the average lifetime is 8 – 10 years, meaning the gear box typically has to be replaced or extensively repaired at least once during the plants lifetime. The rotor blades has to endure strong forces and harsh conditions and therefore needs to be regularly serviced. If there are cracks or damages, the blade has to be repaired or replaced to prevent decreasing efficiency or in worst case catastrophic accidents. [45] The third main component that has a relatively high risk to fail in all wind power plants is the generator. It contains both moving parts and electrical components that can malfunction for many various reasons, for example continuous wear and tear or faulty wiring. [46]

Two empirical studies on different databases from Germany [47] and USA [48] each present average replacement rate for these components which can be used as a frame of reference for how the life time of parts on the Swedish market may turn out. They are both presented in table 4 along with the average between the two.

Table 4: Average component replacement per year and wind turbine, based on empirical data from Germany and USA. [47, 48]

	GEAR BOX	**GENERATOR**	**ROTOR BLADES**
USA 2001 - 2009	5.0%	3.5%	2.0%
GERMANY 1989 - 2006	1.2%	2.2%	2.4%

7. END-OF-LIFE TREATMENT

When a turbine has reached the end of its productive life time, its remaining parts needs to be removed from the location either to make room for new turbines or just to restore the area to its former state. In Sweden it is always the owner and operator of the turbine or farm that has the first and primary responsibility to ensure that the restoration is handled properly, according to section 2 and 10 of chapter 10 in the Environmental Code [49]. If a liable person cannot be found the responsibility is first shifted to the owner of the grounds and secondly to society. The degree of restoration (e.g. how much of the foundation has to be removed) is however not specified and is regulated in each individual case by the county government [50].

7.1 WASTE TREATMENT PRIORITY

The material from disposed components and decommissioned wind turbines should be treated according to the waste hierarchy presented in the European Waste Framework Directive [51] in order to keep the negative environmental impact as low as possible. The directive proposes the following order of priority:

a. Prevent/reduce waste (e.g. by using components with better life time)

b. Re-use the parts as they are or with preparation

c. Recycle the material

d. Recover the energy in the material (e.g. by incineration)

e. Dispose of the material (e.g. by landfill)

A flow chart over the decommissioning process when following the order shown above, as described by an American study [52], can be seen in figure 6. At end-of-life, turbines parts are reused (sometimes after remanufacturing) whenever possible and in otherwise disposed of according to the waste hierarchy presented above.

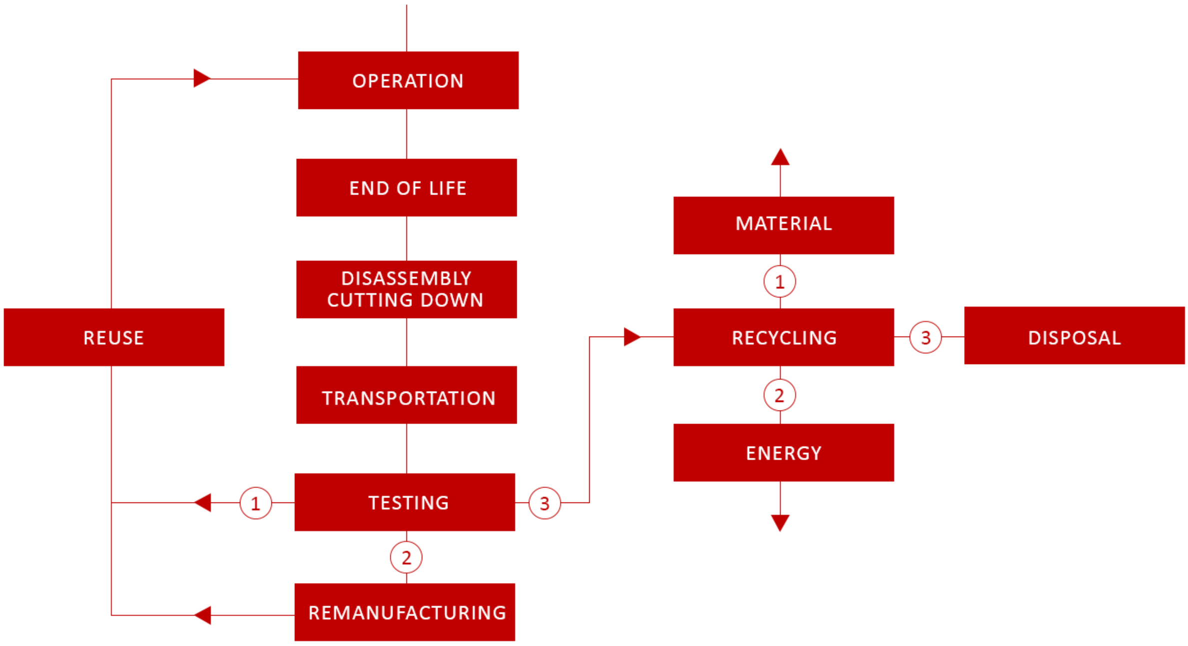


Figure 6: Flow chart describing the proper logistics for wind power decommissioning. The entire turbine or parts should be reused if possible. Unusable parts should have its material recycled or the energy in the material recovered. The last resort is to dispose of the material to landfill or similar [52]. The numbers in the chart represents order of priority in each step.

7.2 RE-USE

The preferred route is that either the whole plant or parts of it is sold for second hand use on another location. However, a report carried out by the Swedish Energy Agency and several other Swedish wind power associations [53] concluded that there is no regular second hand market in place, and that the technical advancements are so rapid that it is difficult to find use for old parts in new projects. Rotor blades are exposed to heavy wear and tear during their life time, and are as a result generally not suitable for reuse unless the plant is replaced before the end of its technical lifetime [54]. Many of the smaller plants from the few early repowering projects that has so far been carried out, however, has been sold off to farms and other small scale use.

7.3 RECYCLING, RECOVERY AND DISPOSAL

Parts that are not reused for practical or economic reasons should if possible be recycled. The average recyclability for an entire wind turbine (excluding the foundation) is calculated to be around 80 %, where most of the non-recycled material is found in the rotor blades [54].

METAL

Steel, copper, aluminium and copper is sold as scrap for recycling. The Swedish steel industry recycles around 1.5 million tonne steel and iron waste annually and exports around 1.0-1.3 million to countries with larger production. The recyclability is around 90 % and the recycled product is as good as new [55]. Around 60 000 tonne aluminium and 65 000 tonne copper is recycled annually in Sweden. Similar to steel and iron, recycling does not really degrade the material and the recyclability is high; 95 % for aluminium from the building- and transport sector and similar levels for copper [55].

BLADE MATERIAL

Plastics and organic material may be incinerated in a CHP plant or similar to recover the energy as heat and electricity [50]. Composite material on the other hand have proven challenging to recycle. As of 2014, the following methods of treatment have been identified:

Mechanical recycling (Grinding)

The blades are cut into smaller pieces that are then further crushed, shredded and milled down until the resulting material can be divided into fibres and resins and the copper elements can be sifted out. The process is very labour intensive and damages the fibres. The recycled material cannot therefore replace new production and is generally used as a filler in artificial wood, cement or asphalt [54, 52].

Currently the only industrial scale recycling of blade material is performed by Zagons Logistik in Melbeck, Germany. They use the mechanical recycling approach and produce a material that works well as a filler in cement production. This material is then sent off to Holcims cement plant Lägerdorf for further processing into a fully functional product. In 2012 the company reprocessed about 400-500 tonnes of material per month, i.e. 5 000-6 000 tonnes per year [56].

Incineration

After being cut down to reasonable size, the composite material is mixed with municipal waste and is then burned to produce useful heat. Since glass fibre is considered incombustible it is mostly polymers and carbon fibre (if present) that creates calorific value. The ash content is very high and has to be dealt with (landfilled) after incineration [57, 54]. High combustion temperatures are required for incineration of composite material, and as not many incinerators can handle this long transport distances may occur. The environmental protection agency in Sweden suggests it is environmentally motivated to transport blades 300-500 km to avoid landfill [50].

Pyrolysis

Composites are heated up to between 450-700 °C under anaerobic conditions causing the polymeric resin to be converted into gas, leaving the fibres intact and recoverable unlike when the material is grinded. The produced gas can then be burnt in CHP plants or similar, and the fibres can be processed and used as new raw material. A collaboration project between University of Borås and Swedish recycling companies attempted to recover the glass fibres with microwave pyrolysis, resulting in a loss of strength compared to virgin material, although with relatively small difference [58]. However this is not a fully developed method that is available large scale and is therefore still very expensive [52, 57].

Landfill

The cheapest option is landfill, but since the organic content in rotor blades is around 30 % [54], this is banned in many countries and the last resort in European countries according to the waste hierarchy. In Sweden it is prohibited to send any organic or combustible waste to landfill [59].

ELECTRONICS

Cables and electronic equipment are delivered to a recycling company that separates them into metals (for recycling), plastics (for energy recovery) and toxic materials (disposal) [50, 60]. In 2014, around 79 000 tonnes of electronic waste (excluding lighting, white goods and batteries) was collected and processed. [61]

8. CALCULATIONS

Several different calculation methods have been used to ensure that as much of the actual installed wind power is included in the estimations. The following chapter explains the process from collected data to predicted results. It is divided into the following four main steps, performed in descending order:

A) MATERIAL AMOUNTS IN SPECIFIC MODELS

Specific data on material amounts for the most common turbine-models in the VindStat data has been collected and applied for each of these turbines.

B) MATERIAL AMOUNTS BASED ON ROTOR DIAMETER

The remaining turbines in the VindStat data has been given a calculated amount of each material based on rotor diameter and manufacturer.

C) SCALING UP

Since the VindStat data doesn't cover all installed turbines, the combined weight estimated through previous steps is scaled up to represent the actual number of wind turbines in Sweden.

D) MATERIAL AMOUNTS FROM REPLACED COMPONENTS

The amount of waste material generated from replaced parts has been estimated through modelling a possible future development and analyzing statistics to assume a reasonable amount of replaced parts each year.

The fraction of the total estimated weight that is derived from each step varies every year, but a graphical representation of the parts that make up the final value is shown in figure 7:

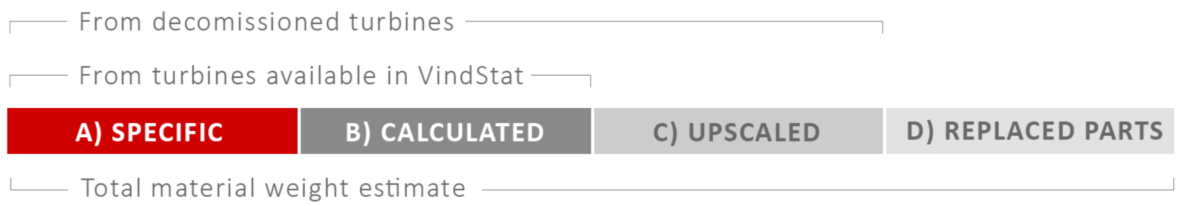


Figure 7: A graphical representation of the four steps used to estimate the total material use in all Swedish wind turbines each year. Specific turbine weights and estimated weights are scaled up to represent the total weight of decommissioned turbines each year, and finally the weight from replaced parts is added.

For each material a minimum, maximum and average weight estimation is presented. The following chapters describes each step in detail.

8.1 MATERIAL AMOUNTS IN SPECIFIC MODELS

Roughly 75 % of all the installed power in Sweden is constructed by two companies; Vestas and Enercon. [5] The material used in their turbines has therefore been closely examined to reduce the need of weight estimations. Material data over popular Vestas and Enercon plants collected from various life cycle assessments is presented in table 5. Together they cover 934 (54 % of total 1737) turbines in the VindStat data base [11-16].

Table 5: Material amount for specific turbines common in Sweden collected from various life cycle assessments

MODEL	HEIGHT [METERS]	STEEL [TONNES]	IRON OR CAST IRON [TONNES]	ALUMINIUM [TONNES]	COPPER [TONNES]	BLADE MATERIAL[1] [TONNES]	ELECTRONICS [TONNES]
ENERCON							
E40	44	59	9.3	0.2	2.7	1.7	0.0
E44	55	72	10	0.2	2.8	7.0	0.0
E66	98	247	21	0.2	9.3	18	0.1
E70	100	359	46	6.9	10	23	0.1
E82	107	246	73	1.3	11	29	0.2
E112	120	642	100	0.9	44	68	0.6
VESTAS							
V52	50	76	11	1.2	1.2	8.0	0.1
V66	67	168	26	2.9	3.0	19	0.3
V80	78	236	21	1.7	2.8	25	0.3
V82	78	186	29	3.1	2.9	30	0.3
V90	80	204	40	4.2	1.7	37	0.4
V112	84	245	66	3.4	4.9	49	1.0

[1] A combination of plastics GRP, CRP and core materials. More information in chapter 5.4

These weights have then been applied to each turbine in excel by checking the maker and rotor diameter. If, for example, the maker is Enercon and the diameter 70 m the model is assumed to be E70 and copper amount in the plant is assumed to be 10 tonne.

TOWER HEIGHT COMPENSATION

As shown in table 5 above, precise data is only available for specific hub heights. A taller turbine will need more building material in the tower construction. The relationship between tower height and weight (in cases where the rotor diameter remains the same) has been examined by comparing different versions of a 3 MW wind turbine presented by Elforsk. [62] The weight of the tower for different hub heights can be seen in figure 8.

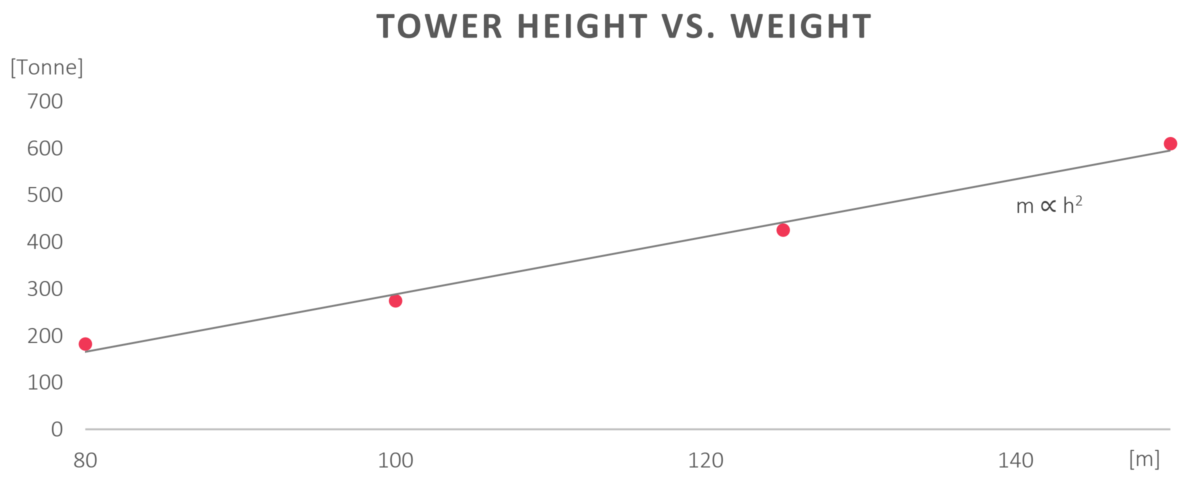


Figure 8: Hub height vs. tower mass. Tower mass increase proportional to hub height squared. The sample values in the chart are based on data in a 3 MW turbine [62]

A correlation between the two parameters has been observed, where the tower weight is proportional to the hub height squared. The tower weight is almost 100 % steel (see chapter 5.2). The steel amount found in the tower is therefore recalculated according to equation 1.

$$m_{steel,tower} = m_{steel,tower,d} \cdot \left(\frac{h}{h_d}\right)^2 \quad \text{(Eq. 1)}$$

Where:

$m_{steel,tower}$	=	Recalculated steel mass found in the tower [kg]
$m_{steel,tower,d}$	=	Available data on steel mass in the tower for specific model [kg]
h	=	Actual hub height for the turbine [m]
h_d	=	Hub height specified in the available data [m]

In certain cases only the total amount of steel in the entire turbine is specified and not the fraction of which that is found in the tower. In observed turbines [13-15, 17, 18] the fraction of all steel found in the tower structure averages 85 % with ranges between 80-90 % in DFIG turbines, and average 60 % with ranges between 55-75 % in DDSG turbines. The same is assumed to be true for the turbines with unspecified steel fraction in the tower and total steel amount is therefore recalculated according to equation 2:

$$m_{steel,sp} = x_s \cdot m_{s,d} \cdot \left(\frac{h}{h_d}\right)^2 + (1 - x_s) \cdot m_{s,d} \quad \text{(Eq. 2)}$$

Where:

$m_{s,specific}$	=	Total amount of steel in the turbine [kg]
$m_{s,d}$	=	Available data on steel mass in the tower for specific model [kg]
x_s	=	Average fraction of total steel found in tower for the turbine design.
h	=	Actual hub height for the turbine [m]
h_d	=	Hub height specified in the available data [m]

The rest of the turbine mass is assumed to remain the same regardless of hub height as neither the rotor blade diameter or generator size changes.

EXAMPLE

The average steel amount in an Enercon turbine with an 82 diameter rotor diameter and a hub height of 80 m is, since the amount for E82 with 100m hub height specified in table 5 is 246 tonne, calculated according to equation 2:

$$m_{steel,sp,min} = 0.75 \cdot 246 \cdot \left(\frac{80}{107}\right)^2 + (1 - 0.75) \cdot 246 = 164.6\ tonne$$

$$m_{steel,sp,max} = 0.55 \cdot 246 \cdot \left(\frac{80}{107}\right)^2 + (1 - 0.55) \cdot 246 = 186.3\ tonne$$

$$m_{steel,sp,average} = 0.6 \cdot 246 \cdot \left(\frac{80}{107}\right)^2 + (1 - 0.6) \cdot 246 = 180.9\ tonne$$

The same equation is then used for both minimum and maximum fraction of steel found in the DDSG tower to produce a deviation interval.

8.2 MATERIAL AMOUNTS BASED ON ROTOR DIAMETER

There are 803 turbines (46 % of total 1737) in the data base for which no specific material weight data has been found. The only known properties for these turbines are the ones stated in the statistics; manufacturer, hub height, rotor diameter and rated power. The following steps have been used in an attempt to produce as accurate estimations as possible based on these parameters:

A) First of all the total weight of each major turbine part, the tower, nacelle and rotor (including the rotor hub), have been estimated based on rotor diameter.

B) The typical material breakdown (percentage of each material) for each specific part has then been analysed statistically and used to separate the part into different materials.

C) Material from each part is then categorised and summed up to arrive at the total amount of each material for the turbine.

A graphical example of the weight estimation process can be seen in figure 9.

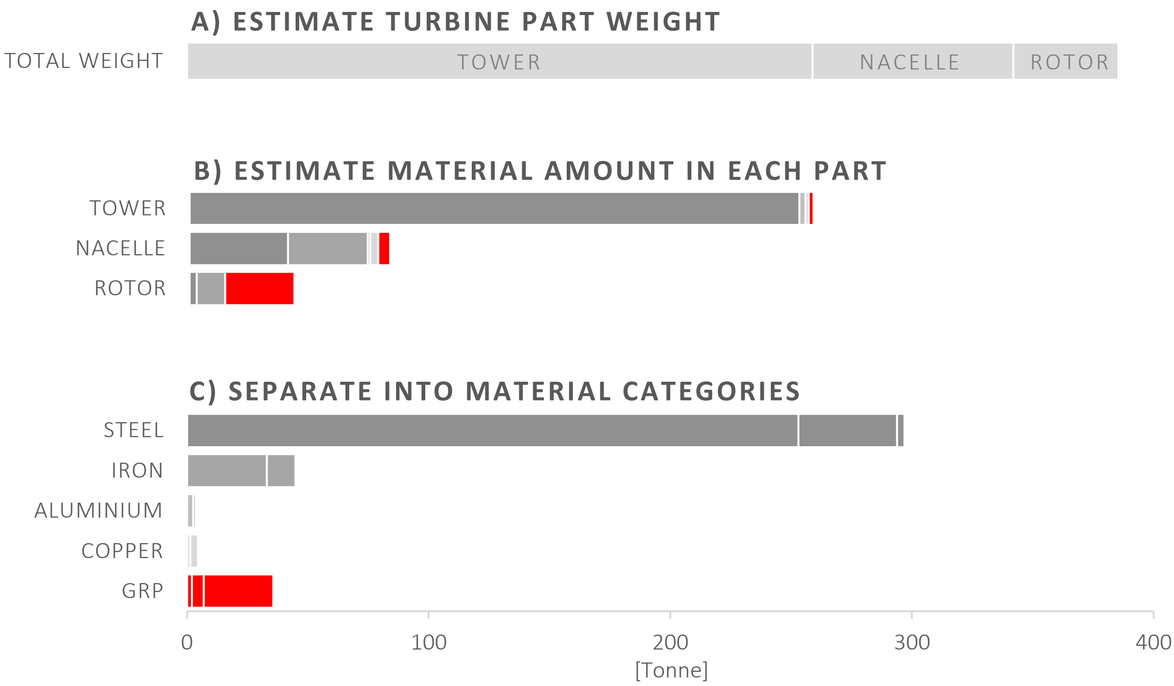


Figure 9: The weight estimation process for turbine models without available data over material weights. The example is based on a DFIG turbine with 80 m rotor diameter.

PART WEIGHT

An empirical study published in Environmental science and technology [63] analyses 12 different turbines and presents a logarithmic function for weight estimation based on rotor diameter, along with different size and scaling factors for each turbine part, which can be seen in equation 3:

$$\log y = \log a + b \log x \qquad \text{(Eq. 3)}$$

Where:

y	=	Estimated mass of turbine part [kg]
x	=	Rotor diameter [m]
log a	=	Intercept value
b	=	Scaling factor

Solving for y and renaming variables (y=m and x=d) gives equation 4:

$$m_{part} = 10^{a} \cdot d^{b} \qquad \text{(Eq. 4)}$$

Where:

m_{part}	=	Estimated mass of turbine part [kg]
a	=	Intercept factor
b	=	Scaling factor
d	=	Rotor diameter [m]

The study also presents the standard error (a measure of how much the calculated values deviates from the real values) of the observed turbines compared to the scaling formula for each turbine part. The standard error a well as scaling and intercept values used in this study is presented in table 6.

Table 6: Intercept- and scaling factors used in equation 4 to calculate the weight of different turbine parts. The standard error is presented to show the precision of each calculation.

TURBINE PART	INTERCEPT FACTOR(A)	SCALING FACTOR(B)	STANDARD ERROR
ROTOR	0.3	2.22	0.165
TOWER[1]	1.7	1.90	0.088
NACELLE (DFIG)	0.6	2.19	0.147
NACELLE (DDSG)[2]	0.2	2.58	0.147

[1] Scaling factor has been slightly increased (from 1.82 to 1.9) to better correlate with observed turbines.
[2] These values are not taken from the mentioned study, but extrapolated based on turbines observed in this report. See explanation below figure 10.

Figure 10 show graphic representations of each formula along with the standard error presented in the report. [63] Also plotted in the charts for comparison is the mass from turbines observed in this report [13-15, 64-66]. The plotted turbines varies between charts as not all data are available for each turbine.

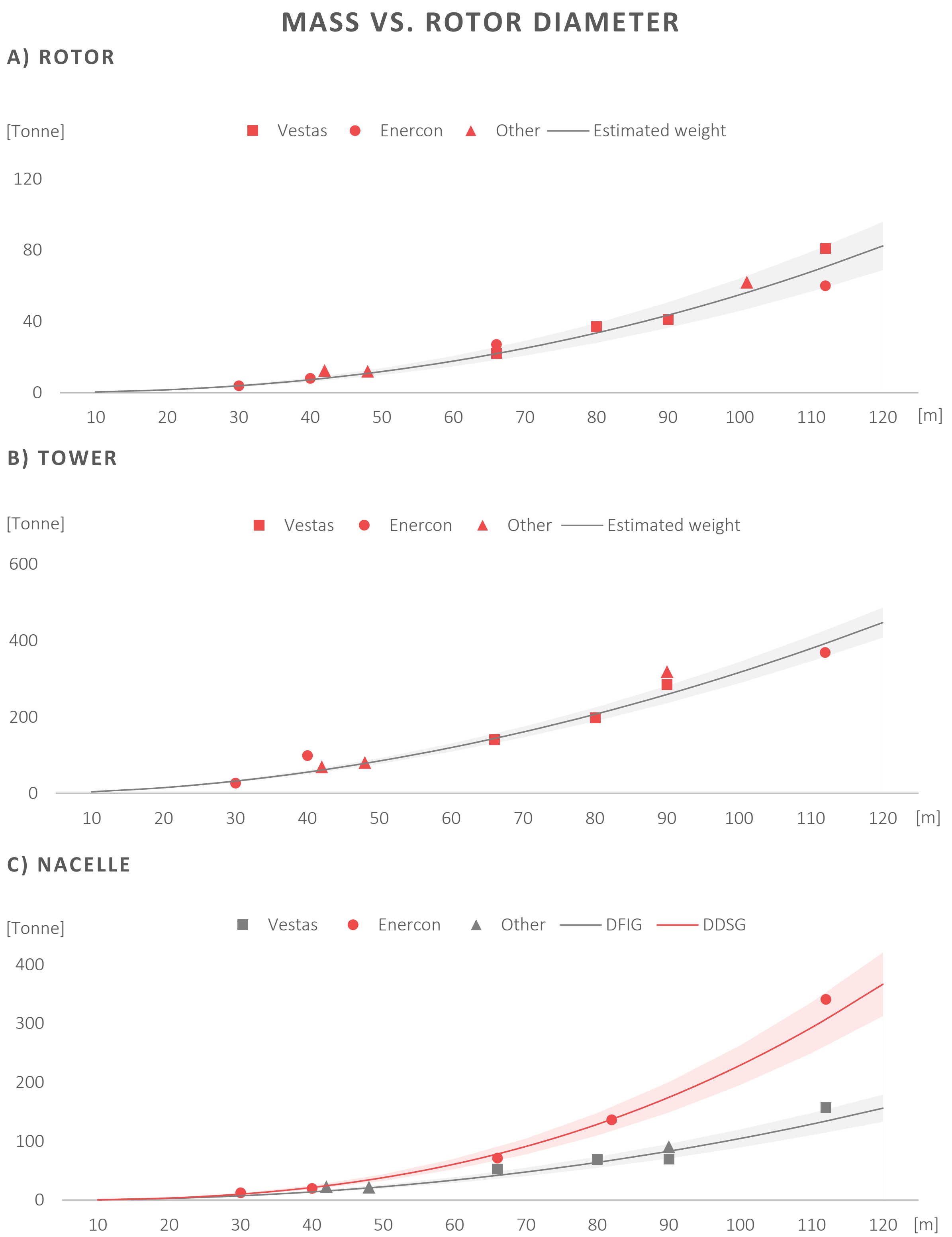


Figure 10: Estimated weight of certain turbine parts as a function of rotor diameter according to equation 1, along with actual mass in real turbines observed in this report. Two categories are presented for nacelle weight; Geared- and direct drive generator design. Lighter areas represent the standard error.

The plotted curve for nacelle weight shows definite correlation with data for Vestas and other DFIG turbines, but Enercon turbines nacelle weight grows at a faster rate with increasing diameter. Separate scaling factors for DDSG turbines has therefore been extrapolated as can be seen in figure 10c and table 6. Both tower and rotor weight in observed turbines seem to correlate well with the calculated weights.

MATERIAL AMOUNTS PER PART

As the mass of each turbine part has been estimated according to the method described above, the breakdown of material in each part is needed to convert this weight into material amounts. Eight turbines [11-16] (four of each generator design) have been examined to find the typical fractions of steel, iron, aluminium, copper, blade material and electronics for each defined part. The resulting values are shown in table 7.

Table 7: Material fraction per turbine part shown as average and lowest and highest percentages present in the data.

DFIG		**HUB AND ROTOR**			**TOWER**			**NACELLE**	
	MIN.	**AVG.**	MAX.	MIN.	**AVG.**	MAX.	MIN	**AVG.**	MAX.
STEEL	0%	**7%**	14%	96%	**98%**	100%	41%	**49%**	54%
IRON	13%	**27%**	41%	0%	**0%**	0%	36%	**40%**	47%
ALUMINIUM	0%	**0%**	0%	0%	**1%**	2%	0%	**1%**	3%
COPPER	0%	**0%**	0%	0%	**0%**	1%	2%	**4%**	8%
BLADE MATERIAL	58%	**66%**	87%	0%	**1%**	2%	5%	**6%**	8%
ELECTRONICS	0%	**0%**	0%	0%	**0%**	0%	0.60%	**0.60%**	0.60%

DDSG		**HUB AND ROTOR**			**TOWER**			**NACELLE**	
	MIN.	**AVG.**	MAX.	MIN.	**AVG.**	MAX.	MIN	**AVG.**	MAX.
STEEL	0%	**5%**	10%	95%	**98%**	100%	39%	**48%**	56%
IRON	0%	**0%**	0%	0%	**0%**	0%	30%	**40%**	53%
ALUMINIUM	0%	**0%**	0%	0%	**0%**	2%	1%	**1%**	1%
COPPER	0%	**0%**	0%	0%	**0%**	1%	7%	**10%**	13%
BLADE MATERIAL	89%	**94%**	100%	0%	**1%**	5%	0%	**2%**	5%
ELECTRONICS	0%	**0%**	0%	0%	**0%**	0%	0.10%	**0.13%**	0.17%

Equation 5 is used to calculate the amount of each material found in the entire turbine based on the fractions found in table 7:

$$m_{material,cc} = x_{m,r} \cdot m_{rotor} + x_{m,t} \cdot m_{tower} + x_{m,n} \cdot m_{nacelle} \qquad \text{(Eq. 5)}$$

Where:

$x_{m,r}$ = Material fraction of rotor

$x_{m,t}$ = Material fraction of tower

$x_{m,n}$ = Material fraction of nacelle

EXAMPLE

To estimate the amount of steel in a 1.8 MW Vestas wind turbine with 100 m rotor diameter, the tower, nacelle and rotor weight is first estimated according to equation 6:

$$m_{tower} = 10^{1.7} \cdot 100^{1.9} = 316\,000\ kg$$

$$m_{nacelle} = 10^{0.64} \cdot 100^{2.19} = 105\,000\ kg$$

$$m_{rotor} = 10^{0.3} \cdot 100^{2.22} = 55\,000\ kg$$

The mass of each part is then multiplied with the minimum, maximum and average fraction of steel in that part, found in table 7:

$$m_{steel,cc,min} = 0.96 \cdot 316 + 0.41 \cdot 105 + 0 \cdot 55 = 347\ tonne$$

$$m_{steel,cc,max} = 1 \cdot 316 + 0.54 \cdot 105 + 0.14 \cdot 55 = 381\ tonne$$

$$m_{steel,cc,average} = 0.98 \cdot 316 + 0.49 \cdot 105 + 0.07 \cdot 55 = 364\ tonne$$

8.3 SCALING UP

The estimations are based on the annual report presented by VindStat and financed by the Swedish Energy Agency. [5] Since this registry is not mandatory, not all the installed wind turbines in Sweden are included. A comparison between the actual installed power [2, 3] and the amount registered with VindStat each year can be seen in figure 11a. There is a significant delay before owners report their plants, resulting in a gap between the VindStat data base and the actual installed turbines up to about 93 % in 2014. As can be seen in figure 11b however, the mean power of the installed plants each year are almost the same for both data bases, indicating that the turbines that are found in VindStat should be a decent representation of the types of plants installed that year.

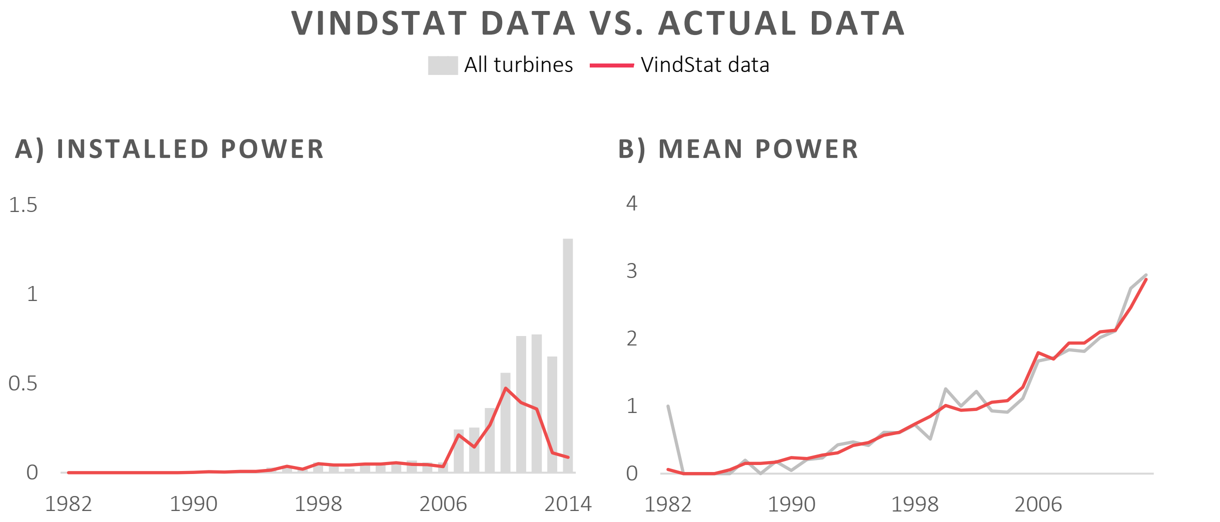


Figure 11: VindStat data vs. actual data. The installed power and mean power per turbine each year for the VindStat data base is compared to the complete data presented by the Swedish Energy Agency and Svensk Vindenergi. [2, 5, 3]

To cover the gaps in available data, the difference between all turbines and the ones available in VindStat have been used to scale up the calculated waste amounts according to equation 6:

$$m_{material,ins,year} = \frac{(m_{material,sp,year} + m_{material,cc,year})}{x_{coverage}} \qquad \text{(Eq. 6)}$$

Where:

$m_{material,ins,year}$	=	The total amount of a specific material in installed turbines a specific year [kg]
$m_{material,sp,year}$	=	Material mass derived from specific turbine data [kg]
$m_{material,cc,year}$	=	Material mass derived from rotor diameter based calculations [kg]
$x_{coverage}$	=	VindStat coverage for that year [%]

The data for the first 10 years (1982-1992) is very inconsistent and derives from few data points, and the compensation will therefore only be applied from 1992 and onwards.

EXAMPLE

For 2010 only 79 % of the total number of turbines is reported to VindStat. The estimated minimum amount of steel derived from specific turbine data is 53565 tonne and from diameter based weight estimations 7758 tonne. The minimum total amount of steel in installed plants that year is therefore calculated according to equation 6:

$$m_{steel,ins,min} = \frac{(53565 + 7758)}{0.79} = 72457\ tonne$$

8.4 MATERIAL AMOUNTS FROM REPLACED COMPONENTS

Average number of replaced faulty components per year is assumed to fall somewhere between the highest and lowest values in Germany and USA as presented in table 4. In other words 2.2 - 3.5 % (avg. 2.9 %) of all generators and 2.0 - 2.4 % (2.2 %) of all rotor blades in all turbines, as well as 1.2 - 5.0 % (3.1 %) of all gear boxes in DFIG turbines is assumed to be replaced with new components every year.

PREDICTED WIND POWER DEVELOPMENT

As the material flow from replaced components is constant and annual, and not delayed 20 years from installation date like material from decommissioned plants, an estimation of future wind power development in Sweden is needed to calculate the flow of replaced material.

Wind power is an intermittent energy source without full control over when energy can be generated, and therefore there is always a need for regulating power (energy sources that can be regulated on command) to keep electricity generation at consumer levels. How much wind power the Swedish energy system can handle is a debated issue [67], however it is likely that at some point the system will be saturated. A study from KTH [68] shows that 30 TWh wind power should not have dramatic effects on the need for regulating power.

As no detailed plan of the coming development has been found, the national goal of 2020 (30 TWh of annually generated electricity) is assumed to be the maximum capacity Sweden will reach. To convert this number from generated energy into installed power, the capacity factor (CF) at which this electricity is generated has to be known. The CF describes the actual output as part of maximum possible output over a period of time [29] (a year in this case), and is calculated according to equation 7:

$$cf = \frac{E}{365 \cdot 24 \cdot P} \qquad \text{(Eq. 7)}$$

Where:

E = Generated energy in a year [Wh]

P = Total installed power that year [W]

CF in the entire Swedish wind power sector has been calculated according to equation 7 for 1982-2014, and the result is presented in figure 12.

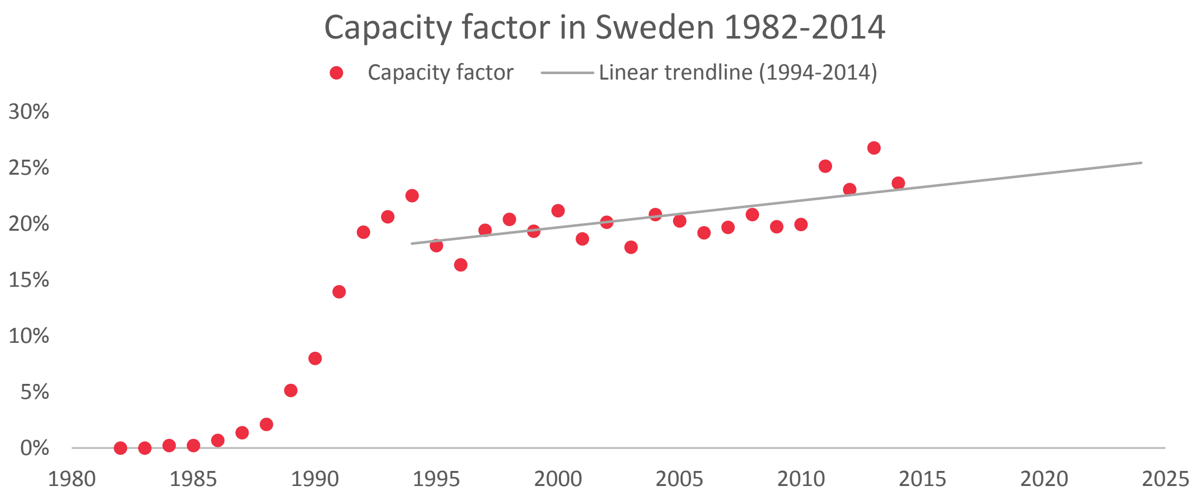


Figure 12: Capacity factor in Sweden 1982-2014. The amount of generated electricity from wind power per year devided with the maximum possible output if all turbines run at full power for the entire year. The trendline is based on data in 1994-2014

A trendline has been added based on data over latest 20 years (as the technology seem to have stabilized somewhat in this period), which is described in equation 8:

$$y = 0.0024x - 4.61 \qquad \text{(Eq. 8)}$$

Where:

y = Capacity factor [%]

x = Year

This gives a capacity factor around 24 % in 2020. As a result the goal of 30 TWh translates into installed capacity at around:

$$P = \frac{30 \cdot 10^{12}}{365 \cdot 24 \cdot 0.24} = 14\,269 \cdot 10^{6} = 14.3\ GW$$

Assuming this is the installed capacity Sweden will eventually stabilize at, the development up until that point needs to be estimated. A study at Uppsala University [69] proposes an equation for a logistic growth curve for wind power capacity that fit historical growth patterns for similar energy technologies, as shown in equation 9:

$$P(t) = \frac{A}{1 + e^{-k(t-t_0)}} \qquad \text{(Eq. 9)}$$

Where:

P = Installed capacity

A = The saturation level or future maximum installed capacity

k = Steepness factor for the growth curve

t_0 = The point in time with the highest growth rate

The saturation level, *A*, is in this case set to 14.3 GW and *t* is set as 0 in 1982 By using the least squares method in excel [70] the curve has been fitted to the historic data of installed power in 1982-2014, [2, 3] giving the suggested values of k = 0.317 and t_0 = 33.6. The resulting curve along with historic values is shown in figure 13:

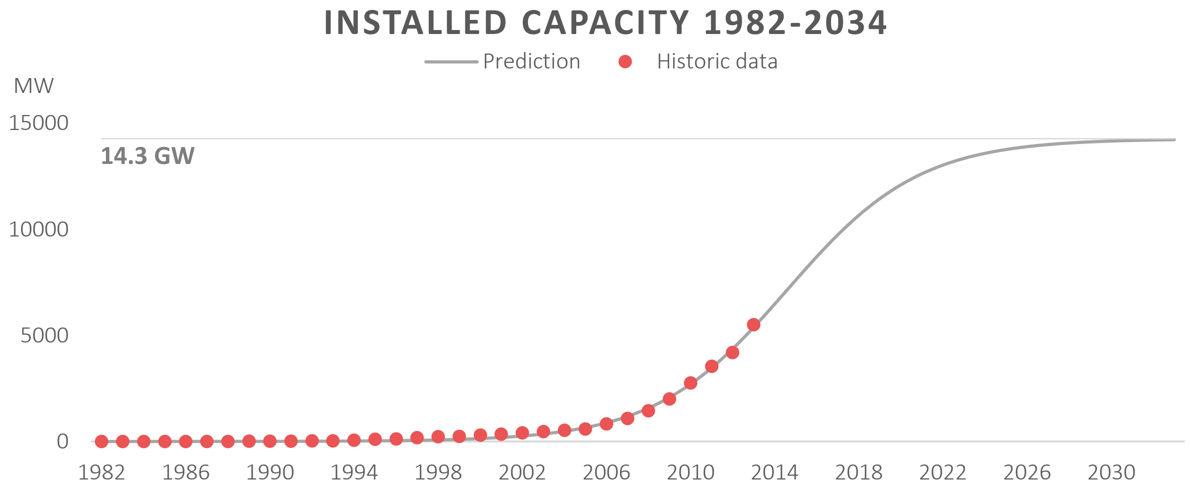


Figure 13: Installed capacity 1982-2034. Historic data over installed capacity (red dots) from 1982-2014, and the predicted development from equation 9 (grey line) in 2014-2034.

In this suggested growth rate the goal is not reached until after 2030, however around 11.5 GW is installed in 2020 which is more than twice the capacity of 2014.

COMPONENT WEIGHT ESTIMATIONS

The generator and gear box is part of the turbine nacelle, and the rotor blades are part of the rotor. The percentage of the nacelle weight deriving from the generator and the gear box as well as the percentage of the rotor weight deriving from rotor blades have then been estimated by using the values presented in three different LCA's [14, 17, 18] and assuming the percentages are representative for all turbines. Material fractions in these different components have also been taken from these studies, and both are presented in table 8:

Table 8: Weight and material percentages for larger commonly replaced components; Generator, gear box and rotor blades.

COMPONENT/MATERIAL	MIN.	**AVG.**	MAX.
GENERATOR:			
Percentage of nacelle weight	16%	**30%**	44%
Steel	68%	**79%**	90%
Copper	10%	**21%**	32%
GEAR BOX:			
Percentage of nacelle weight	14%	**22%**	31%
Steel	50%	**75%**	100%
Iron	0%	**25%**	50%
ROTOR BLADES:			
Percentage of rotor weight	58%	**71%**	84%
Blade material	91%	**95%**	100%
Steel	0%	**3%**	9%
Aluminium	0%	**0.30%**	1%

As both rotor diameter and nacelle size is dependent on turbine capacity, a proportionality between total weight and total installed capacity has been identified, described by the following equation 10:

$$m_{part,year,est} = a \cdot P^b \quad \text{(Eq. 10)}$$

Where:

$m_{part,tot,est}$	=	Estimated total weight of all nacelles or rotors in one year
a	=	Scaling factor
b	=	Growth factor
P	=	Total installed power that year (as estimated in equation 9)

Equation 3 has been used to estimate the total weight of all installed nacelles as well as all installed rotors each year 1992-2010 (the period with best coverage in VindStat). By using the least squares method in excel the curve has been fitted to the estimated values. The factors produced by this process is presented in table 9 and the curve, along with the values calculated with equation 3, is shown in figure 14:

Table 9: Scaling and growth factors to estimate total nacelle and rotor weight based on total installed power. The variables are then put into equation 10.

FACTOR	**A**	**B**
NACELLE	92.5	0.88
ROTOR	60.4	0.83

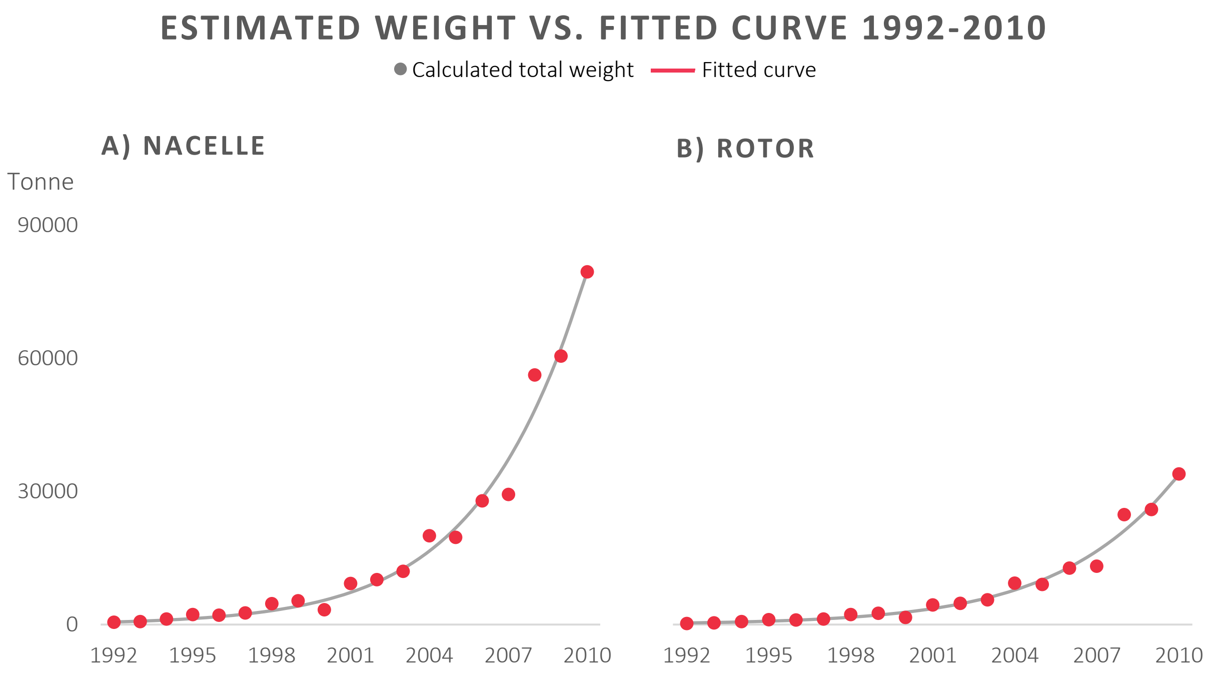


Figure 14: Estimated weight vs. fitted curve 1992-2010. The total nacelle and rotor weight per year has been estimated with equation 3, and an equation describing the nacelle and rotor weight as exponentially proportional to installed power has been fitted to match these values.

Combining equation 9 and equation 10 gives an estimate of total nacelle and rotor weight in installed turbines per year from 1982 and onward:

$$m_{nacelle,year} = 92.5 \cdot \left(\frac{14\ 300}{1 + e^{-0.317(t-33.6)}}\right)^{0.88}$$

$$m_{rotor,year} = 60.4 \cdot \left(\frac{14\ 300}{1 + e^{-0.317(t-33.6)}}\right)^{0.83}$$

The material flow from replaced components has then been calculated by combining the total weight of installed nacelle and rotors with the parameters in table 9 in equation 11:

$$m_{material,rc} = r \cdot x_c \cdot m_{part,tot} \cdot x_{m,c} \qquad \text{(Eq. 11)}$$

Where:

r	=	Components replacement rate [% per year]
x_c	=	Components weight fraction of nacelle or rotor
m_{part}	=	Total weight of all installed nacelle or rotors [kg]
$x_{m,c}$	=	Material fraction of component weight

EXAMPLE

The total weight of all installed nacelles in 2020 is calculated:

$$m_{nacelle,2020} = 92.5 \cdot \left(\frac{14\ 300}{1 + e^{-0.317((2020-1982)-33.6)}}\right)^{0.88} = 345\ 306\ tonne$$

The total amount of steel from replaced components in 2020 is then:

$$m_{steel,rc,2020,min} = 0.022 \cdot 345\ 306 \cdot 0.16 \cdot 0.68 + 0.012 \cdot 345\ 306 \cdot 0.14 \cdot 0.5 = 1117\ tonne$$

$$m_{steel,rc,2020,max} = 0.035 \cdot 345\ 306 \cdot 0.44 \cdot 0.90 + 0.050 \cdot 345\ 306 \cdot 0.31 \cdot 1.00 = 10138\ tonne$$

$$m_{steel,rc,2020,average} = 0.029 \cdot 345\ 306 \cdot 0.30 \cdot 0.79 + 0.031 \cdot 345\ 306 \cdot 0.22 \cdot 0.75 = 4140\ tonne$$

8.5 TOTAL MATERIAL AMOUNT PER YEAR

An average of 20 years life time is assumed for all installed turbines, and waste material from decommissioning is generated 20 years after installation. The total amount of waste material for a specific year is calculated according to equation 12:

$$m_{material,year} = m_{material,ins,(year-20)} + m_{material,rc,year} \quad \text{(Eq. 12)}$$

Where:

$m_{material,year}$	=	Total amount of waste material in a specific year
$m_{material,ins,(year-20)}$	=	Total amount of installed material 20 years earlier
$m_{material,rc,year}$	=	Total amount of estimated material from replaced components that year

EXAMPLE

The total amount of steel in installed turbines in 2005 is estimated to a minimum of 7856 tonne, maximum of 8837 tonne and average of 8262 tonne. Estimated steel from replaced components in 2025 is minimum 1374 tonne, maximum 12311 tonne and average 5049 tonne. Total amount of steel waste from wind power in 2025 is therefore calculated according to equation 12:

$$m_{steel,2025,min} = 7856 + 1374 = 9\ 230\ tonne$$

$$m_{steel,2025,max} = 8837 + 12311 = 21\ 148\ \text{tonne}$$

$$m_{steel,2025,average} = 8262 + 5049 = 13\ 311\ \text{tonne}$$

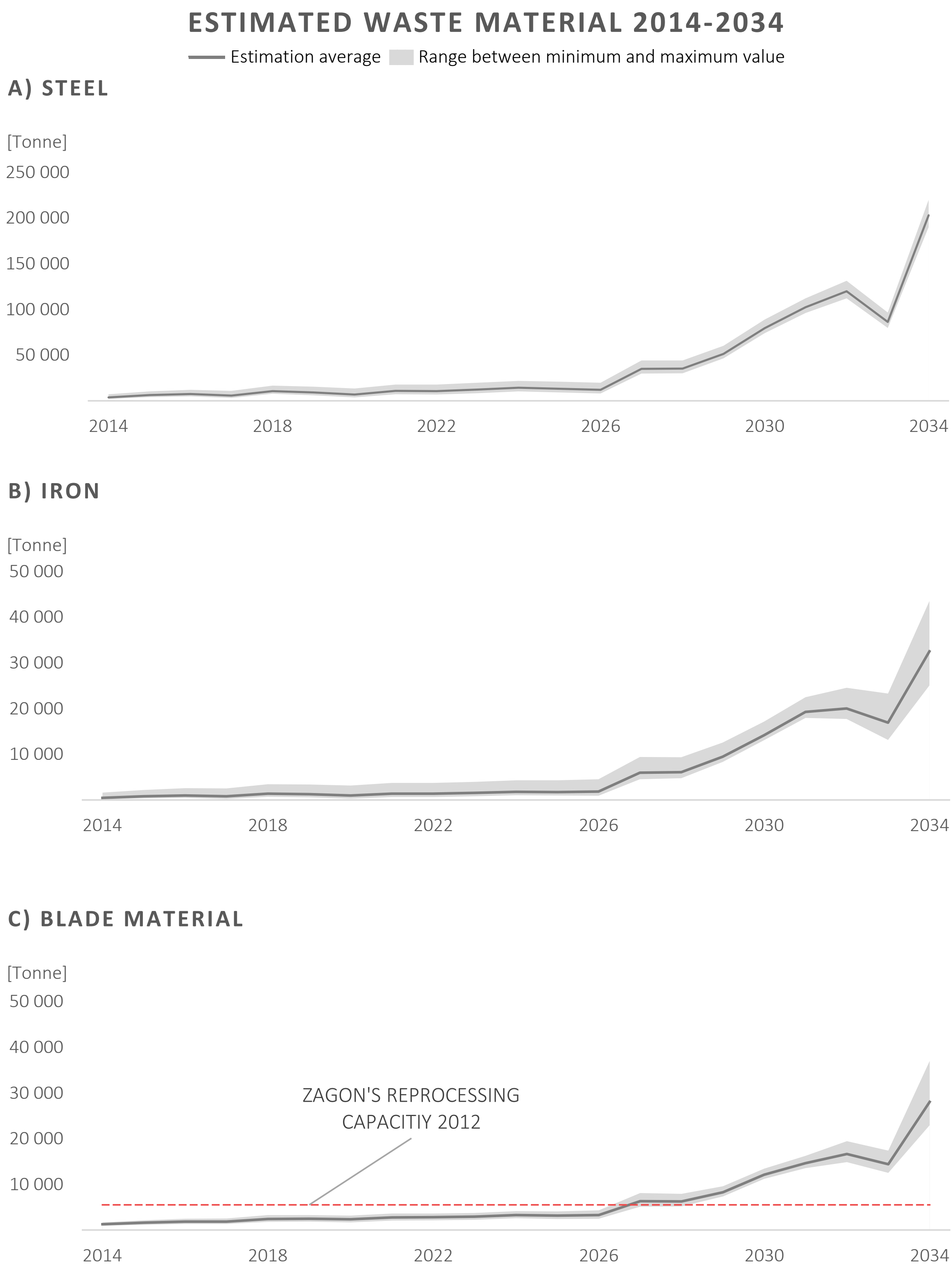
9. RESULTS

9.1 MATERIAL CATEGORISATION

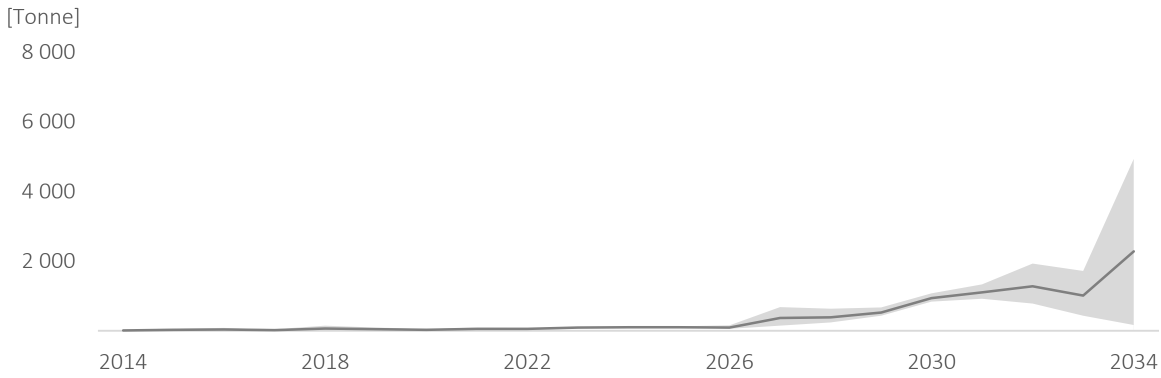
Metals are categorised into *steel, iron, copper* and *aluminium* since these are the ones most commonly present. All plastics and composite materials are summed up as *blade material* (although it is not only found in rotor blades). The reasoning behind this is that these materials are often either presented as GRP [13] or separated as polymers, resins and fibres [11] in the given data, either way making it difficult to separate plastics and composites. Furthermore, these materials are often built into each other and it is therefore assumed they have to be treated by the same company. The final category is *electronics* which includes cables and electronic equipment found in the nacelle.

9.2 ESTIMATED WASTE MATERIAL FROM DECOMMISSIONED TURBINES

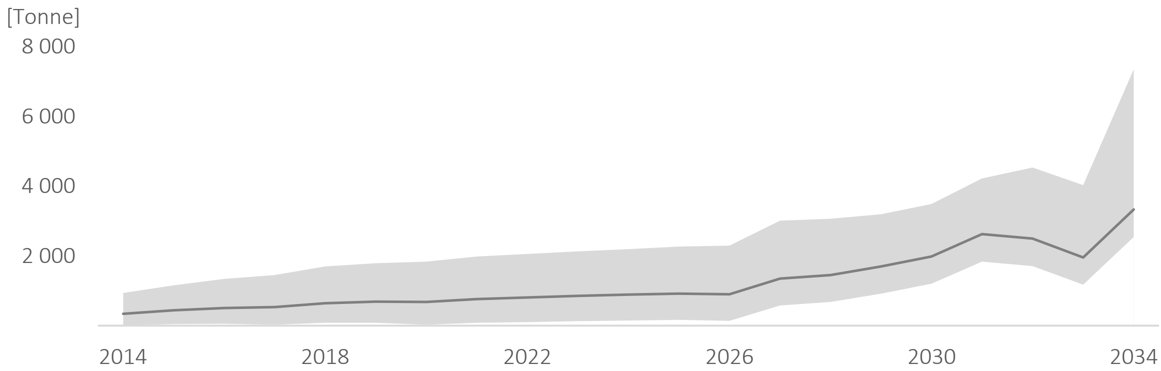
The estimated annual waste amount from the Swedish wind power industry for each material category is presented in figure 15.



D) ALUMINIUM



E) COPPER



F) ELECTRONICS

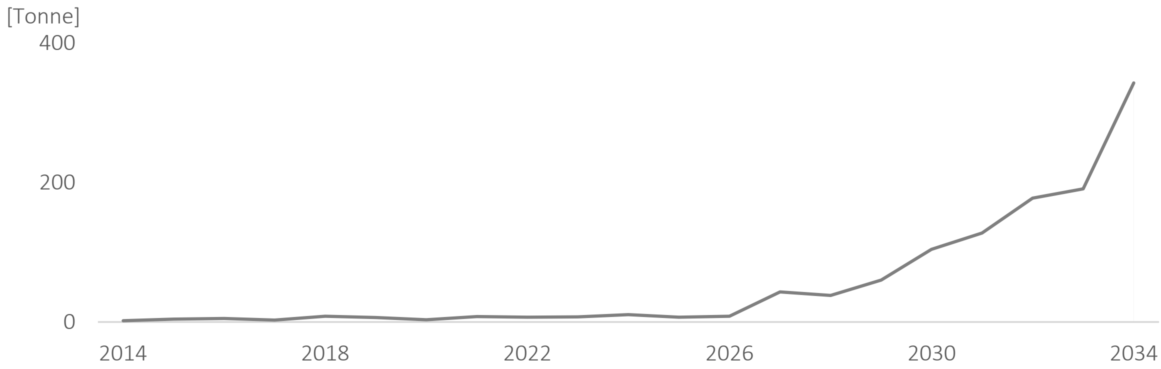


Figure 15: Estimated steel, iron, blade material, copper, aluminum and electronic waste from the Swedish wind power industry in 2014-2034, based on the calculations described above.

Total amount of generated waste is estimated to increase almost linear with an average of 12 % per year between 2014 and 2026, and then increase more rapidly at an average of 41 % per year between 2026 and 2034. The amount of blade material in wind power waste is expected to surpass the current reprocessing capacity of Zagons Logistik in 2026-2027. Further comparisons with waste handling capacities in 2014 have been made for all categories and presented in table 10.

Table 10: Recycled amount of material in Sweden 2014 compared to estimated waste from wind power plants in 2024 and 2034.

MATERIAL [TONNE]	RECYCLED 2014	ESTIMATED WASTE 2024	PERCENTAGE OF 2014 TOTAL	ESTIMATED WASTE 2034	PERCENTAGE OF 2014 TOTAL
STEEL & IRON	1 500 000	16 009	**1%**	236 656	**16%**
ALUMINIUM	60 000	116	**0%**	2 290	**4%**
COPPER	65 000	891	**1%**	3 333	**5%**
BLADE MATERIAL[1]	6 000	3 274	**55%**	28 060	**468%**
ELECTRONICS	79 000	11	**0.01%**	343	**0.4%**

[1] Zagon Logistiks reprocessing capacity is used as reference value, not the recycled amount of blade material in Sweden 2014.

Steel and iron waste from wind power is estimated to reach about 10-20 percent of the current recycled amounts in Sweden within two decades. Aluminum and copper is not as prominently used, and based on these estimations will only reach around 4-5 % of the current recycled amounts, and the amount of electronics waste will likely reach less than 1 % of the total recycled amount. Blade material is mostly made out of composites which is rarely recycled today, and the annually waste amounts produced is likely to surpass those of the only reprocessing industry's capacity quickly.

9.3 SECOND HAND SCENARIOS

The waste estimations presented above does not take second hand use of parts or turbines into consideration. As very little information exist concerning a second hand market in Sweden, three different scenarios have been produced to examine how actual generated waste may differ from the estimated amounts.

SCENARIO A

50 % of all decommissioned turbines and their parts are sold for second hand use in Sweden. They have 15 years renewed life time and are therefore fully decommissioned not until 35 years after installation.

SCENARIO B

50 % of all decommissioned turbines are sold for second hand use abroad. They are therefore never seen as fully decommissioned as the waste material is generated outside Sweden.

SCENARIO C

All small turbines (< 1 MW) are sold for second hand use, 50 % of all medium sized (larger than 1 MW and smaller than 3 MW) turbines are sold for second hand use and 75 % of all large turbines (> 3 MW) are sold for second hand use. The re-used turbines are never seen as decommissioned (i.e sent abroad) in this scenario.

The results from the three scenarios are shown in figure 16 below. The grey area shows the total estimated decommissioned capacity each year without any reuse of turbines, i.e. the value used for weight estimations, while the red lines represent the different scenarios and shows the decommissioned capacity each year with second hand markets in place.

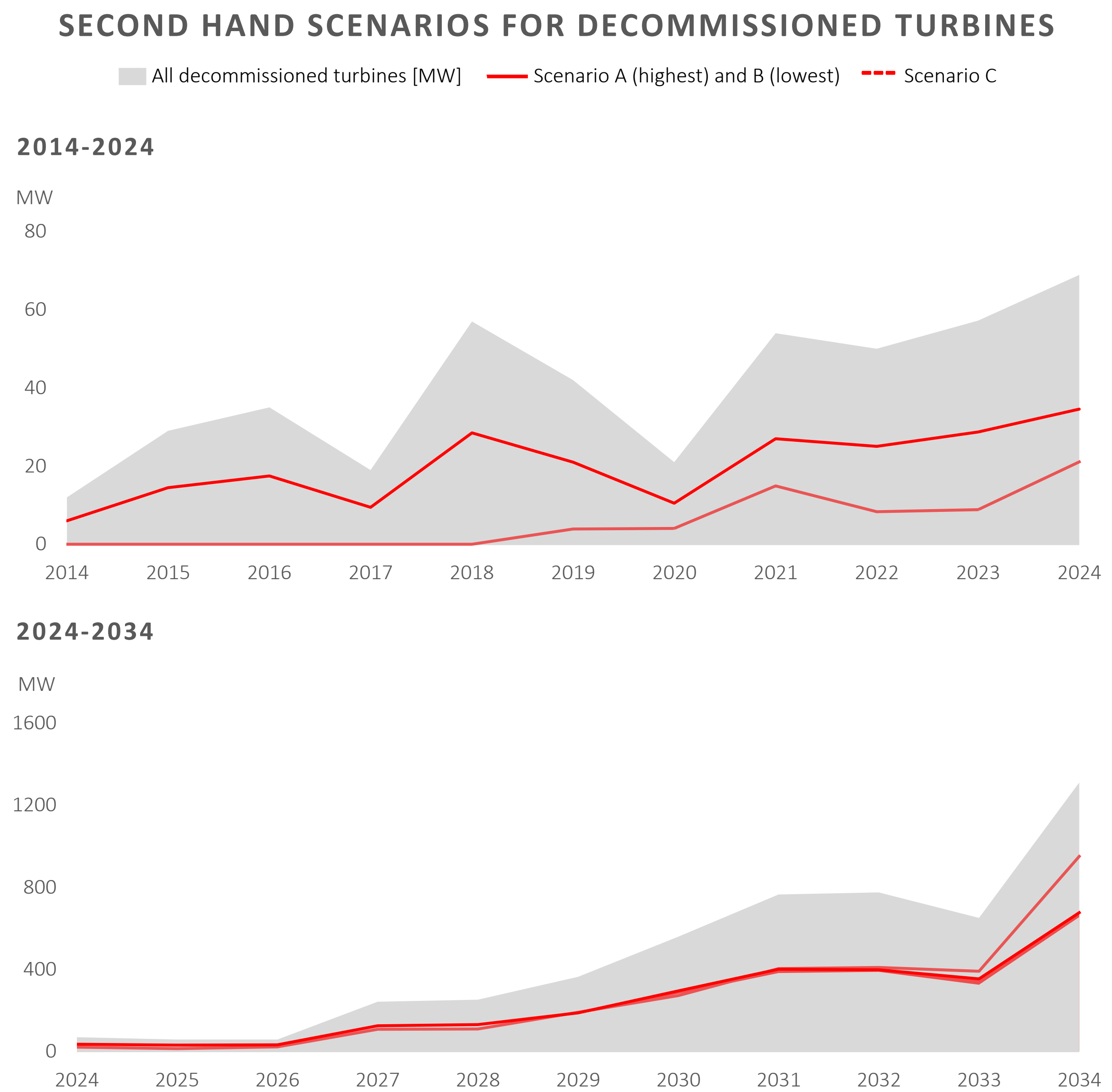


Figure 16: Total amount of decommissioned power turning into waste each year in three different scenarios. Scenario A and B are almost identical, and the difference between the two are therefore represented by a red area.

Both scenario A and B would result in almost precisely 50 % amount of waste produced in the next 20 years compared to the reference scenario. Scenario C would result in much less waste than predicted amounts in 2014-2024, but get closer to 75 % of predicted amounts in the decade after that as more and more large turbines are decommissioned.

10. DISCUSSION AND FURTHER WORK

The sudden increase in estimated annual waste material growth seen from 2026 and onward is due to the accelerated installation of turbines in Sweden around 2006. As shown when comparing the assumed average life time of 20 years with empiric data in figure 6 however, the predicted decommissionings could likely be offset one or two years in either direction. Since the material is not immediately hazardous, short term storing should however not be a large problem. This along with the fact that some decommissioning can most likely be postponed if necessary, the specific material amount each year is probably less interesting than the overall growth pattern and general weight magnitudes. These seem to be relatively on point, at least when comparing to the small data samples available.

Even though generated steel and iron scrap is estimated to reach large magnitudes relative to the current total recycling values, these materials are perhaps not the most problematic ones since the recycling industry for the metals found in wind turbines is very well developed and the increase in annual waste amounts is expected to happen gradually over the next 20 years. Electronic waste could be slightly more critical as quantities of toxic material may be present, however the annual amount of electronic waste is estimated to be very low compared to the annual recycled amount even in 20 years. Further studies on the possible issues with toxic material from electronic components in wind turbines is encouraged as this is not covered in this study.

The amount of blade material waste generated annually is estimated to surpass that of Zagon Logistik's yearly reprocessing capacity [56] somewhere around 2028. Even if they had the needed capacity (completely disregarding their own need to process waste), their location (Melbeck) is further than 500 km from most Swedish wind farms, which is the furthest environmentally defendable distance to avoid landfill according to the environmental protection agency [50]. Another similar large scale reprocessing industry is therefore needed, preferably somewhere in decent range of most large wind farms. This could be an opportunity to launch a full sized pyrolysis recycling industry, using similar methods tested in the project with University of Borås, to receive a more versatile end product.

As a way to reduce composite waste in the more distant future, if no adequate method of fully recycling these is developed, another material with better recyclability could perhaps be used instead. Sandvik has developed a form of steel, duplex stainless steel [71], with a very high tensile strength (see comparison with composite material in table 11) which allows for a lighter construction weight than regular steel. Swedish Steel Yachts (SSY) uses the material to build ultra-light steel boats [72] by replacing the more commonly used glass fiber hull.

Table 11: Typical tensile strengths for composites (glass and carbon) and for SAF 2507, one of the high strength stainless steels from Sandvik.

MATERIAL	TENSILE STRENGTH [MPA]	DENSITY [G/CM^3]
GRP [73, 74]	678	1.8
CRP [73, 74]	923	1.6
SAF 2507 [71]	800-1000	7.8

According to Håkan Rosén [75], senior engineer at SSY, a rotor blade constructed mostly out of SAF 2507 could likely weigh about the same as one made of CRP and cost the same, or slightly more, than a GRP blade. Another benefit he mentions is that the mirror polished surface they use might be something to look at regarding problems with buildup of ice. If rotor blades out of this material where developed successfully, it would be a fully recyclable alternative to the more problematic GRP blades. Although, the several times higher density (see table 11) means that a steel blade would either have to be much thinner to have the same weight as composite blades. Further research is encouraged no full comparison between different material (besides density and tensile strength) have been performed.

A well-functioning second hand market for both components, parts and whole turbines could be one solution to lowering waste amounts without lowering the installed capacity of wind power. Early decommissioned small turbines have so far been sold mainly to customers inside the country, and the amount of waste generated from these is therefore delayed for as long as the turbines are kept in operation. Second hand scenario A and B in this study show that reusing turbines is a way to lower the waste amounts in the coming decades, even if they are reused in Sweden with lower life time than new turbines.

As electricity certificates are only given the first 15 years of operation and not renewed when the turbine is moved for second hand use [35], they may be a hindrance for a second hand market to develop, especially when it comes to larger turbines. Reused turbines could be seen as a riskier investment to begin with, and the loss of electricity certificates may push investors towards new turbines. If this is the case and mainly smaller turbines are reused while larger are decommissioned, the waste amounts would be reduced mostly in the next decade or so and then increase more rapidly. This could potentially be a problem as the industry would be less experienced with handling the waste than if there is a more steady flow of both small and large turbines.

Another aspect that is difficult to predict is how the market would react to the large amounts of turbines that would be decommissioned at the same time. It could potentially drop the prices so low that there is more scrap value in the material. The future development of second hand markets has been one of the biggest factors of uncertainty in this study, and further studies on this subject is encouraged.

The estimated amount of material from replaced components is more unreliable than estimations based on installed turbines, mainly due to the uncertainty of future wind power development. It is impossible to predict exactly what capacity will be reached before the market is saturated, and the rate of installations may be different from the suggested development. The prognosis made here is based on previous development and national production goals proposed by the government. Low electricity prices, public opposition and other factors may of course lead to a slower development rate than what is suggested. Furthermore, the number of replaced parts in the Swedish market and for newer turbines might not be within the same interval as the historic data for Germany and USA used in this study, and the material in the components will likely change in future turbines.

Copper is mainly found in the generator [23], a component that is expected to be replaced in some turbines, and therefore the annual waste copper weight is largely based on replaced components leading to very uncertain predictions. This is also reflected in the resulting chart, as the range between minimum and maximum values is wide. Another uncertain parameter in the calculations is the steel weight compensation based on height differences, as the recalculation equation is based on a small sample size. As most heights of turbines in VindStat are relatively close to the observed turbines the difference in total weight even if this method is flawed would however be minor.

The issue with rare earth metals in new models using permanent magnets, which are hazardous to produce and complicated to recycle according to the mentioned KTH research [24] has not been addressed in this study since the technology is relatively new and the future development hard to predict. A proper investigation into the waste amounts of these materials is recommended to make sure it can be properly handled. Another major material that has been completely left out of the study is concrete, which is found in very large amounts in the turbine foundation. Either a method to calculate the foundation weights based on location or an empirical study is needed to estimate the concrete amounts, as well as research on how often the material is simply left on location instead of removed.

The longer each turbine (as well as its parts and components) is in operation, the lower the amounts of waste will be in the near future. As most of the turbines that will be decommissioned during the two coming decades are already installed, using different material and more durable components is not a solution for the short term problems. Having a second hand market as a "buffer", extending turbine life time and keeping a lot of the material in use for another cycle, is however one way to postpone some of the generated waste until possibly a better waste handling is in place.

11. CONCLUSIONS

The material commonly present in wind turbines, and by extension in generated waste, is steel, iron, aluminium, copper, electronic components and blade material such as glass- or carbon reinforced plastics and PVC. The annual waste amounts from wind power in Sweden by 2034 is estimated to reach 237 600 tonne *steel and iron* (16 % of currently recycled amounts), 2 300 tonne *aluminium* (4 %), 3 300 tonne *copper* (5 %) and 343 tonne *electronics (<1 %)*. *Blade material* waste generated annually is estimated to be 28 100 tonne in 2034, more than four times the capacity of the only full scale reprocessing industry for these materials in operation today. The amount of annual waste for all material is estimated to increase linear at around 12 % per year until around 2026, and then several times faster during the decade after that due to a quick acceleration in installed turbines around 2006.

As all major types of metal present in wind turbines are already recycled on a large scale, they are assumed to be less problematic than the most commonly used blade materials since no industrial scale recycling alternative is currently available for these. Development of such an industry locally is important to be able to handle these materials in a sustainable way. Switching to a more easily recyclable material could be part of a long term solution, and Sandviks high strength steel is proposed as a possible alternative for further research.

All waste estimations are based on the assumption that no turbines or parts are reused after decommissioning, which is unlikely. Three different development scenarios show that a well-functioning second hand market could be an efficient way to reduce the amount of wind power waste in the short term, although more extensive research is needed to draw any actual conclusions.

In any case it is very likely that the annual amounts of waste from wind turbines will grow substantially during the coming decades compared to 2014. This increase should be manageable given appropriate measures are taken to ensure all materials are taken care of. Failure to do so could lead to build up- or landfilling of material that should be treated in a more sustainable way, thus increasing the negative environmental impact of the wind turbine life cycle.

12. REFERENCES

[1] BP, "Statistical Review of World Energy," June 2015. [Online]. Available: http://www.bp.com/content/dam/bp/excel/Energy-Economics/statistical-review-2015/bp-statistical-review-of-world-energy-2015-workbook.xlsx. [Accessed 07 July 2015].

[2] Energimyndigheten, "Vindkraftstatistik 2014 - Tabeller," Febuary 2015. [Online]. Available: https://www.energimyndigheten.se/Global/Press/Pressmeddelanden/Vindkraftstatistik%202014.pdf. [Accessed 07 July 2015].

[3] Svensk Vindenergi, "Vindkraftstatistik och prognos: Kvartal 4 2014," 13 Febuary 2015. [Online]. Available: http://www.vindkraftsbranschen.se/wp-content/uploads/2015/02/Statistik-vindkraft-kvartal-4-2014-20150213.pdf. [Accessed 07 July 2015].

[4] S. L. Dolan and G. A. Heath, "Life Cycle Greenhouse Gas Emissions of Utility-Scale Wind Power," *Journal of Industrial Ecology,* vol. 16, no. 1, 2012.

[5] VindStat, "Driftuppföljning av Vindkraftverk: Årsrapport 2014," Energimyndigheten, Stockholm, 2014.

[6] Regeringen, "Proposition 2008/09:163: En sammanhållen klimat- och energipolitik," Regeringskansliet, Stockholm, 2009.

[7] European Wind Energy Association, "The European offshore wind industry - key trends and statistics 2014," EWEA, 2015.

[8] A. Nilsson, "Vindpark till havs rivs: Sydöstran," 18 September 2014. [Online]. Available: http://www.sydostran.se/blekinge/vindkraftpark-till-havs-rivs/. [Accessed 10 May 2015].

[9] 4C Offshore, "Offshore wind farms in Sweden: 4C Offshore," 2014. [Online]. Available: http://www.4coffshore.com/windfarms/windfarms.aspx?windfarmid=SE08. [Accessed 09 May 2015].

[10] S. Engström, "Elforsk rapport 10:49: Nytt och trendigt inom vindkraften," Elforsk, Stockholm, 2010.

[11] P. Garrett and K. Ronde, "Life Cycle Assessment of Electricity Production from a V90-2.0 MW Gridstreamer Wind Plant," Vestas Wind Systems A/S, Randers, 2011.

[12] L. Eymann, M. Stucki, A. Fürholz and A. König, "Ökobilanzierung von Schweizer Windenergie," Bundesamt für Energie BFE, Bern, 2015.

[13] T. Zimmermann and S. Gößling-Reisemann, "Influence of site specific parameters on environmental performance of wind energy converters," *Energy Procedia ,* vol. 20, pp. 402-413, 2012.

[14] M. Gueder, "Energetische Bewertung von Windkraftanlagen," Fachhochschule Würzburg-Schweinfurt, Schweinfurt, 2004.

[15] Vestas, “Life cycle assessment of electricity produced from onshore sited wind power plants based on Vestas V82-1.65 MW turbines,” Vestas Wind Systems A/S, Randers, 2006.

[16] N. D'Souza, E. Gbegbaje-Das and P. Shonfield, “Life Cycle Assessment of Electricity Production from a V112 Turbine Wind Plant,” PE North West Europe ApS, Copenhagen, 2011.

[17] E. Martinez, F. Sanz, S. Pellegrini, E. Jimenez and J. Blanco, “Life cycle assessment of a multi-megawatt wind turbine,” *Renewable Energy,* no. 34, pp. 667-673, 2009.

[18] C. Ghenai, “Life Cycle Analysis of Wind Turbine,” InTech, Florida, 2012.

[19] A. Helander, ”Grundläggning av vindkraftverk: Värmeflödesanalys i vindkraftverks ingjutningsgods och simulering av tjäldjup med TEMP/W,” Luleå University of Technology, Luleå, 2009.

[20] Vestas Wind Systems A/S, “2 MW Product Brochure,” October 2014. [Online]. Available: http://nozebra.ipapercms.dk/Vestas/Communication/Productbrochure/2MWbrochure/2MWProductBrochure/. [Accessed 07 July 2015].

[21] Enercon GmbH, “ENERCOn Wind energy converters: Product overview,” July 2010. [Online]. Available: http://www.enercon.de/p/downloads/EN_Productoverview_0710.pdf. [Accessed 07 July 2015].

[22] Vestas Wind Systems A/S, “V90-1.8 MW; V90-2.0 MW; Technical Specifications,” October 2008. [Online]. Available: http://www.vestas.com/files%2Ffiler%2Fen%2Fbrochures%2Fproductbrochurev901_8_2_0_uk.pdf. [Accessed 07 July 2015].

[23] H. Polinder, F. F. van der Pijl, G.-J. de Vilder and P. Tavner, “Comparison of Direct-Drive and Geared Generator Concepts for Wind Turbines,” *IEEE Transactions on Energy Conversion,* vol. 21, no. 3, pp. 725 - 733, 2006.

[24] C. Abrahamsson, ”Miljöpåverkan, hälsopåverkan och LCC för direktdrivna kontra växellådsdrivna vindkraftverk med avseende på deras innehåll av jordartsmetaller,” Kungliga Tekniska Högskolan, Stockholm, 2014.

[25] Arise, “Jädraås Vindkraftpark: Arise,” Arise AB, 2014. [Online]. Available: http://www.arise.se/sv/jadraas-vindkraftpark. [Accessed 31 May 2015].

[26] D. Valiollahi, “Siemens levererar 12 vindkraftverk till Vattenfalls vindpark Högabjär-Kärsås: mynewsdesk,” 04 December 2014. [Online]. Available: http://www.mynewsdesk.com/se/siemens_ab/pressreleases/siemens-levererar-12-vindkraftverk-till-vattenfalls-vindpark-hoegabjaer-kaersaas-1094266. [Accessed 31 May 205].

[27] Gurit, “Wind Energy Handbook: Wind Turbine Blade Aerodynamics,” 2012. [Online]. Available: http://www.gurit.com/files/documents/2aerodynamicspdf.pdf. [Accessed 07 July 2015].

[28] S. K. Babu, S. N. Raju, S. M. Reddy and N. D. Rao, “The Material Selection for Typical Wind Turbine Blades Usding a MADM Approach & Analysis of Blades,” MCDM, Chania, 2006.

[29] T. Wizelius, Vindkraft i teori och praktik 2:a upplagan, Studentlitteratur, 2007.

[30] K. Wood, “Wind turbine blades: Glass vs. carbon fiber : Productionmachining,” 31 May 2012. [Online]. Available: http://www.productionmachining.com/articles/wind-turbine-blades-glass-vs-carbon-fiber. [Accessed 06 June 2015].

[31] H. Albers, S. Greiner, H. Seifert and U. Kühne, “Recycling of Wind Turbine Rotor Blades,” Hochschule Bremen: Institut für Umwelt und Biotechni, Bremen, 2009.

[32] R. L. Arantegui, “JRC wind status report,” European Commission, Petten, 2012.

[33] Eoulus Vind AB, “Vill du investera i vindkraft?,” 2011. [Online]. Available: http://www.eolusvind.com/LinkClick.aspx?fileticket=CJ7zmKPPvf8=. [Accessed 07 July 2015].

[34] Energimyndigheten, “Tilldelningsperiod för anläggningar: Energimyndigheten,” 29 April 2015. [Online]. Available: https://www.energimyndigheten.se/Foretag/Elcertifikat/Elproducent/Utfasning-av-anlaggningar/. [Accessed 22 May 2015].

[35] Energimyndigheten, “Begagnade vindkraftverk och tilldelning av elcertifikat: Energimyndigheten,” 29 April 2015. [Online]. Available: https://www.energimyndigheten.se/Foretag/Elcertifikat/Elproducent/Begagnade-vindkraftverk-och-tilldelning-av-elcertifikat/. [Accessed 22 May 2015].

[36] I. Staffell and G. Richard, “How does wind farm performance decline with age?,” *Elsevier: Renewable Energy,* vol. 66, p. 775–786, 2014.

[37] Energistyrelsen, “Master data register for wind turbines at end of March 2015,” Energistyrelsen, Copenhagen, 2015.

[38] A. Keuper, “Wind Energy Use in Germany - Status 31.12.1993,” DEWI magazin, 1994.

[39] German Wind Energy Association, “Wind Industry in Germany 2014,” Bundesverband WindEnergie, Berlin, 2014.

[40] German Wind Energy Association, “Number of wind turbines in Germany: BWE,” 31 December 2012. [Online]. Available: https://www.wind-energie.de/en/infocenter/statistiken/deutschland/number-wind-turbines-germany. [Accessed 22 May 2015].

[41] Deutsche WindGuard, “Status of Land-Based Wind Energy Developement in Germany,” Deutsche WindGuard, Varel, 2012-2014.

[42] E. Bruns and D. Ohlhorst, “Wind Power Generation in Germany - a transdisciplinary view on the innovation biography,” *The Journal of Transdisciplinary Environmental Studies,* vol. 10, no. 1, pp. 46-67, 2011.

[43] J. Lawson, “Renewable Energy World: Repowering gives new life to old sites,” 2013. [Online]. Available: http://www.renewableenergyworld.com/rea/news/article/2013/06/repowering-gives-new-life-to-old-wind-sites?cmpid=rss. [Accessed 1 May 2015].

[44] A. Horste and I. El-Thalji, “Växellådshaverier på landbaserade vindkraftverk,” Elforsk, Stockholm, 2011.

[45] E. Viberg and A. Rasouli, “Underhållet i en vindkraftpark,” Kungliga Tekniska Högskolan, Stockholm, 2014.

[46] Elforsk, “Analys av havererade asynkrongeneratorer,” Energimyndigheten, Stockholm, 2002.

[47] E. Echavirria, B. Hahn, G. van Bussel and T. Tomiyama, “Reliability of Wind Turbine Technology Through Time,” *The Journal of Solar Energy Engineering,* vol. 130, no. 3, 2008.

[48] S. Sheng, “Report on Wind Turbine Subsystem Reliability – A Survey of Various Databases,” NREL, 2013.

[49] The Swedish Government, “The Swedish Environmental Code (Ds 2000:61),” Ministry of the Environment and Energy, Stockholm, 2000.

[50] L. Aldén, “Nedmontering av vindkraftverk och efterbehandling av platsen,” Energimyndigheten, Visby, 2013.

[51] EU, “Directive 2008/98/EC on waste: European Commission,” 03 Mars 2015. [Online]. Available: http://ec.europa.eu/environment/waste/framework/. [Accessed 22 April 2015].

[52] K. Ortegon, L. F. Nies and J. W. Sutherland, “Preparing for end of service life of wind turbines,” *Elsevier: Journal of Cleaner Production,* vol. 39, pp. 191-199, 2012.

[53] Svensk Vindenergi, “Vindkraftverk - kartläggningar av aktiviteter och kostnader vid nedmontering, återställande av plats och återvinning.,” Svensk Vindenergi, Stockholm, 2009.

[54] R. Cherrington, V. Goodship, J. Meredith, B. Wood, S. Coles, A. Vuillaume, A. Feito-Boirac, F. Spee and K. Kirwan, “Producer Responsibility: Defining the Incentive for Recycling Composite Wind Turbine Blades in Europe,” *Energy Policy,* vol. 47, pp. 13-21, 2012.

[55] SGU, “Uppdrag att göra en kartläggning och analys av utvinnings- och återvinningspotential för Svenska metall- och mineraltillgångar,” Sveriges Geologiska Undersökning, Uppsala, 2014.

[56] E. Gill, “The complexities of recycling begin to bite: Wind power monthly,” 2012. [Online]. Available: http://www.windpowermonthly.com/article/1124486/complexities-recycling-begin-bite. [Accessed 30 November 2014].

[57] EWEA, “Research note outline on recycling wind turbines blades,” The European Wind Energy Association, Brussels, 2012.

[58] Stena Metall, “Recycling of waste glass fiber reinforced plastic with microwave pyrolysis,” LIFE +, 2012.

[59] Avfall Sverige, “Svensk avfallshantering 2015,” 2015. [Online]. Available: http://www.avfallsverige.se/fileadmin/uploads/Statistikfiler/sah_2015.pdf. [Accessed 07 July 2015].

[60] Ragnsells, ”Elektronik - Diverse små enheter,” 2011. [Online]. Available:

http://www.ragnsells.se/sv/Miljokunskap/Kallsorteringsguide/Elektronik--diverse-sma-enheter/. [Använd 30 June 2015].

[61] El-kretsen, ”Insamlade och behandlade mängder 2014,” 17 Febuary 2015. [Online]. Available: http://www.el-kretsen.se/sitespecific/elkretsen/files/insamlingsstatistik_2014.pdf. [Använd 07 July 2015].

[62] Elforsk, “Tall towers for large wind turbines,” Energimyndigheten, Stockholm, 2010.

[63] M. Caduff, M. Huijbregts, H.-J. Althaus, A. Koehler and S. Hellweg, “Wind Power Electricity: The Bigger the Turbine, The Greener the Electricity?,” *Environmental Science & Technology,* vol. 46, no. 3, p. 4725–4733, 2012.

[64] Wiind Turbine Models, “Turbines: Wind Turbine Models,” 2011-2015. [Online]. Available: http://en.wind-turbine-models.com/turbines. [Accessed May 2015].

[65] The Wind Power, “SWT-2.3-101: The Wind Power,” November 2014. [Online]. Available: http://www.thewindpower.net/turbine_en_551_siemens_swt-2.3-101.php. [Accessed 19 May 2015].

[66] K. Lindvig, “The installation and servicing of offshore wind farms,” European Forum for Renewable Energy Sources, 2010.

[67] M. G. Axelsson, “Tål elnätet mer vindkraft?: Forskning och framsteg,” 07 August 2012. [Online]. Available: http://fof.se/tidning/2012/7/tal-elnatet-mer-vindkraft. [Accessed 23 June 2015].

[68] L. Söder, ”På väg mot en elförsörjning baserad på enbart förnybar el i Sverige: En studie om behovet av elkraft,” Kungliga Tekniska Högskolan, Stockholm, 2013.

[69] S. Davidsson, L. Grandell, H. Wachtmeister and M. Höök, “Growth curves and sustained commissioning modelling of energy: Investigating resource constraints for wind energy,” *Energy Policy,* vol. 73, p. 767–776, 2014.

[70] W. Lee, “Curve Fitting in Microsoft Excel,” [Online]. Available: http://www.cpp.edu/~seskandari/documents/Curve_Fitting_William_Lee.pdf. [Accessed 07 July 2015].

[71] Sandvik, Sandvik duplex stainless steels, Sandviken: Sandvikens tryckeri, 2009.

[72] Swedish Steel Yachts , “Manufacturing: SSY,” [Online]. Available: http://www.ssy.se/pro/manufacturing/. [Accessed 09 June 2015].

[73] J. Pandey, S. Gulia, M. Ramachandran and K. Kalita, “Comparison of jute fiber over glass fiber and carbon fiber reinforced plastic,” *International Open Journal for Engineering Research,* vol. 1, no. 1, pp. 26-30, 2015.

[74] U.S. Department of Energy: Office of Energy Efficiency and Renewable Energy, “Request for Information: Fiber Reinforced Polymer Composite Manufacturing,” U.S. Department of Energy, Washington, 2013.

[75] H. Rosén, Interviewee, *Using duplex stainless steel in wind turbine rotor blades.* [Interview]. 08 June 2015.