An analysis of the challenges and opportunities of End-Of-Life management of wind turbine blades in Denmark.

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Abstract

Denmark faces a challenge of treating wind turbine blades at their end of life. Currently they have largely been landfilled, but this results in no recovery of energy or materials of the blades. Given the high price of blade material, together with the trend of blades getting more expensive, this seems suboptimal.

This thesis investigates the degree of the problem, that is, the amount of blade material that needs to be treated in Denmark in the future. Furthermore, it is sought to develop a Geographic information system-model that can minimize the cost of EoL treatment of wind turbine blades.

Rarely is transport accounted for on anything but a general level. This thesis seeks to minimize the overall costs of EoL treatment by including the individual freight costs of the given turbine's blades. The main inputs of the model are the future blade material inflow, the location of current and future turbines, the location of EoL-sites and the costs and benefits related to each EoL technology per ton of blade material.

Based on the assumptions and data of this thesis, it was possible to develop a mass flow model that predicts the outflow of blade material by year in the period 2020-2050. Furthermore, it was possible to develop a Geographic information system-model that minimizes the cost of EoL treatment for current and future Danish wind turbines.

The direct costs of EoL treatment were yielded, together with the indirect costs which account for the recovered value of blade material and energy.

The optimal EoL option in terms of cost depended on the specific turbine.

Abstract in Danish

Danmark står over for problemet at behandle vindmøllevinger efter endt levetid. Indtil nu har den mest anvendte løsning bestået af deponering i landfills, eventuelt med afbrænding inden.

Grundet den høje produktionspris for vindmøllervinger, samt den forventede stigning i materialeprisen virker dette ikke til at være optimalt.

Derfor undersøges der I dette speciale hvor meget vingeaffald det forventes at der skal behandles i Danmark i fremtiden. Herudover ønskes det at udvikle en geografisk informationssystemsmodel, der automatisk kan minimere prisen for behandling ved end levetid.

Sjældent tages der forbehold for transportomkostninger på anden vis end med antagede gennemsnitsværdier. For dette speciale ønskes det at minimere nedlæggelsesomkostningerne ved at tage forbehold for hver individuelle turbines transportomkostninger. Den vigtigste modeldata er fremtidigt vingemateriale vingematerialeindstrømning, nutidige og fremtidige vindturbiners lokation, lokationen på EoL-steder samt omkostningerne og fordelene for hver EoL teknologi.

Udfra de gjorte antagelser og den benyttede data var det muligt at udvikle en "Mass flow" model, som projekterede den forventede fremtidige udstrømning af vingemateriale på årsbasis, i perioded 2020-2050.

Herudover blev en geografisk informationssystemsmodel udviklet, som kan minimere nedlæggelsesomkostningerne for nutidige of fremtidige vindturbiner i Danmark.

De direkte omkostninger ved nedlæggelse blev udregnet, såvel som de indirekte omkostninger, som tager forbehold for den potentielt genvundne værdi i form af genvundet materiale og energi.

Den optimale EoL løsning ifht. omkostninger afhang af den specifikke turbine.

Summary

Denmark is expected to increase its wind turbine (WT) capacity up until 2050. This, combined with the fact that a large portion of Denmark's electricity is already produced by WT, means that large quantities of wind turbine blades (WTB) need to be decommissioned over the course of the coming decades.

This is problematic, given the great difficulty associated to managing Wind turbine blades (WTB) at their end-of-life (EoL), given their material composition. Currently, European WTB are largely landfilled or incinerated, which produces waste that is then landfilled.

Because WTB degrade negligibly when landfilled, and because they are very energy intensive and expensive to produce, it is sought to find better EoL options.

The need to find better EoL options is supported by the material trend of WTB, which entails higher proportions of carbon fiber reinforced polymers being used for the blades. These fibers are a magnitude more expensive and energy intensive to produce than the generically used glass fiber reinforced polymers, which increases the inventive to recover them.

The EoL technologies investigated during this paper were many, but only a few were deemed relevant at this point in their development. These were:

- Prevention
- Reuse
- Repurposing
- Mechanical grinding
- Cement kiln co-processing
- Pyrolysis
- Fluidised bed
- Solvolysis
- High Voltage Pulse Fragmentation

The EoL technologies were investigated for 3 WTB types:

- Glass fiber reinforced polymer blades (GFRP)
- Hybrid fiber reinforced polymer blades (HFRP)
- Carbon fiber reinforced polymer blades (CFRP)

For each blade type, the direct and net energy consumption, GHG emissions and costs were derived for their EoL treatment on a per ton basis.

Hereafter, the expected WT installations of the future were estimated for the following energy scenarios, in a Mass Flow model.

- AF19
- Wind, Biomass, Bio+, Hydrogen, Fossil (All by the DEA)
- IDA

The installations account for the variability in outflow for each energy scenarios, which means the future outflows of WTB in tons was projected as well.

From here, the blade weight of each currently registered WT in Denmark, and the blade weight of future installations made in the period 2020-2050 were derived through an empirical regression, together with inflow projections of wind capacity.

The placement of all registered wind turbines was obtained through the DEA's Master Data Register. Future onshore WT were assumed to be placed in the same areas as current onshore turbines, whilst the placement of future offshore wind turbines was derived by accounting for required capacity by energy scenario, and LCOE of offshore area.

The above data and assumptions are sufficient to calculate the theoretical costs of decommissioning current and future Danish WTB. However, a large portion of the costs of decommissioning blades stems from transport, which needs to be accounted for.

To account for transport, the placement and blade weight data was coupled with a **G**eographic **I**nformation **S**ystem-model. The developed GIS-model accounts for marine and land transport. The vehicle for land transport depends on the size of the wind blade.

The GIS-model optimizes the decommissioning in terms of one of the following: Energy consumption, GHG emissions or cost. For this thesis, it has been used to optimize the costs associated to decommissioning. This optimization accounts for the costs of transport, which depends on the driven route between the given turbine and EoL site.

Ultimately, the lowest direct and lowest net costs are derived for decommissioning the following WTblade categories:

- Currently installed onshore & offshore turbine blades.
- Future onshore & offshore turbine blades for each of the investigated energy scenarios.

These costs are shown in the figure below.

Net cost of cheapest decomissioning scenario [mio.DKK]										
Net cost with EOL benefits [mio.DKK]						Cost without EOL benefits [mio.DKK]				
Scenario	Onshore	Offshore	Future onshore	Future offshore	Total	Onshore	Offshore	Future onshore	Future offshore	Total
AF19	-60.72	-62.89	-124.55	-235.2	-483.36	37.90	111.48	62.35	447.80	659.53
Wind	-60.72	-62.89	-42.78	-383.54	-549.93	37.90	111.48	21.42	739.90	910.70
Biomass	-60.72	-62.89	-42.78	-153.4	-319.79	37.90	111.48	21.42	259.90	430.70
Bio+	-60.72	-62.89	-42.78	-78.01	-244.40	37.90	111.48	21.42	135.64	306.44
Hydrogen	-60.72	-62.89	-42.78	-463.0	-629.39	37.90	111.48	21.42	966.81	1137.61
Fossil	-60.72	-62.89	-42.78	-153.0	-319.39	37.90	111.48	21.42	259.87	430.67
IDA	-60.72	-62.89	-68.93	-383.0	-575.54	37.90	111.48	34.51	739.87	923.76

AF19, which is the most recently produced energy scenario has an expected total decommissioning cost of 659.53 million DKK, which is around 112 DKK per Danish citizen.

The sensitivity of these results was investigated for the lifetime assumptions of the turbines in the mass flow model, and a potential blade replacement of 20 % after 15 years of blade operation.

The cost results were not overly sensitive to changes in the assumed lifetimes, at least not for the lifetime investigated lifetime interval.

Blade replacement, however, had a significant impact on the costs, depending on the energy scenario.

Summary in Danish

Det forventes at Danmark vil forøge sin vindturbinekapacitet op til 2050. Dette, kombineret med det at der allerede er en stor installeret vindturbinekapacitet i Danmark betyder at store mængder vindmøllervinger skal nedlægges i løbet af de kommende årtier.

Dette er problematisk, da det er besværligt at genanvende vindturbinevinger ved aftjent levetid. Dette skyldes deres unikke materialekomposition. Status quo er at vindmøllevinger hovedsagligt transporteres til deponering, muligvis med afbrændning inden.

Fordi vindturbineblade kun nedbrydes negligerbart i deponering, og fordi de er energikrævende og dyre at producere, ønskes det at finde bedre EoL ruter. I forlængelse af dette er målet for dette projekt for det første at projektere mængden af WTB materiale som kræver EoL behandling I fremtiden. For det andet ønskes det at udvikle en GIS-model som kan optimere EoL omkostningerne for danske WTB.

Behovet for at finde bedre EoL ruter støttes af den materialle udvikling der foregår for vindturbineblade, som udgøres af større mængder af carbon fiber i kompositmaterialet. Carbon fiber baserede vinger er en størrelsesorden dyrere og mere energikrævende at producere end glasfiber baserede vinger, hvilket øger encitamentet for genvindelse.

Mange EoL teknologier blev undersøgt i forbindelse med dette speciale, men kun få blev set som relevante ifht. Deres nuværende udviklingsstadie. Disse var:

- Forebyggelse
- Genbrug
- Genanvendelse
- Mekanisk nedbrydning
- Cement ovn co-processering
- Pyrolyse
- Fluidiseret overflade
- Solvolyse
- Højspændings pulsframentation

Disse EoL teknologier blev undersøgt i relation til 3 vindmøllervingetyper:

- Glasfiber baserede vinger
- Hybrid fiber baserede vinger
- Carbon fiber baserede vinger

For hver bladtype blev de indirekte og indirekte energiomkostninger, CO2-ækvivalentudledninger og omkostninger simuleret på en ”per ton” basis.

Herefter blev den forventede installation af vindmøllervinger projiceret for følgende energiscenarier i den såkaldte ’Mass flow model’:

- AF19
- Ving, Biomasse, Bio+, Hydrogen, Fossil (alle produceret af energistyrelsen)
- IDA

De projicerede installationer for disse energiscenarier tager forbehold for variabiliteten i udstrømningen af vinmøllevinger, dvs. nedlæggelsen af vinger, hvilket er baggrunden for også at have projiceret den overordnede nedlæggelse af vindmøllervinger i fremtiden.

Herfra estimeredes vægten af hvert blad for alle registrerede vindturbiner i Danmark, samt vægten af de vinger som forventes installeret i perioden 2020-2050, vha. en empirisk regression samt en indstrømmelsesprofil.

Placeringen af registrerede vindmøller kom fra Stamdataregistret. For fremtidige landvindturbiner blev det antaget at de placeres der hvor nuværende landvindturbiner er placeret. For havvindturbiner blev det antaget at fremtidige installationer ville ske hvor den relaterede LCOE er lavest, med forbehold for den forventede isntallerede kapacitet ift. de givne energiscenarier.

Det ovennævnte er nok til at udregne den forventede teoretiske omkostning af vingenedlæggelse for nutidige vindturbiner såvel som fremtidige vindturbiner. Disse ville dog ikke inkludere de transportmæssige omkostninger, som er vigtige at tage forbehold for.

For at tage forbehold for de transportmæssige omkostninger er placeringsdata for nutudige og fremtidige vindturbiner fødet ind i en **G**eografisk **I**nformations**S**ystem-model. Den udviklede GIS-model optimerer nedlæggelsen af vindturbinervinger ifht. de følgende; Energiforbrug, GHG-emissioner eller omkostninger. I dette speciale er GIS-modellen brugt til at optimere Ifht. omkostninger. Denne optimering tager forbehold for transportomkostningerne som afhænger af transportruten mellem vindturbinen og det givne EoL steds placering.

Slutteligt oudregnes de laveste direkte og indirekte netto-omkostninger for følgende turbinekategorier:

- Installerede land- og havvindturbiner
- Fremtidige land- og havvindturbiner for hvert energiscenarie

Omkostningerne fra GIS-modellen ses nedenfor.

Net cost of cheapest decomissioning scenario [mio.DKK]										
Net cost with EOL benefits [mio.DKK]						Cost without EOL benefits [mio.DKK]				
Scenario	**Onshore**	**Offshore**	**Future onshore**	**Future offshore**	**Total**	**Onshore**	**Offshore**	**Future onshore**	**Future offshore**	**Total**
AF19	-60.72	-62.89	-124.55	-235.2	-483.36	37.90	111.48	62.35	447.80	659.53
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IDA	-60.72	-62.89	-68.93	-383.0	-575.54	37.90	111.48	34.51	739.87	923.76

AF19, som er det senest producerede energiscenarie har en forventet total nedlæggelsesomkostning på 659.53 millioner DKK, hvilket svarer til omtrent 112 DKK per danske statsborger.

Sensitiviteten af disse resultater blev undersøgt i forhold til møllernes antagede levetid samt en potentiel vingeudskiftning på 20 % efter 15 års operation.

Omkostningerne var ikke særligt sensitive til ændringer i de antagede levetider, i hvert fald ikke for det undersøgte levetidsinterval.

Vingeudskiftning derimod havde en stor indflydelse på de forventede totale nedlæggelsesomkostninger, for visse scenarier.

Preface & Acknowledgements

This master's thesis corresponds to a workload of 30 ECTS points and follows the ENTEK education committee's recommendations on technical guidelines for theses.

It was conducted in the period of February 1st-2020 to June 2nd-2020, by Oliver Dalip Singh Grewal at the faculty of Energy Technology Engineering (ENTEK), university of Southern Denmark (SDU).

The supervisor of this thesis was Professor Gang Liu, and the co-supervisor was Ph.D. student Kasper Dalgas Rasmussen.

I would like to thank both for their expert supervision, guidance, and discussions. I would additionally like to thank Srinivasa R. Bhuvan Gummidi for his inputs.

Lastly, I would like to thank Clemens Raffler, the developer of one of the used GIS-algorithms, who helped me with the GIS-part of this thesis.

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List of Abbreviations & Acronyms

CF	Carbon fiber
CFRP	Carbon fiber reinforced polymer
DEA	Danish Energy Agency (Energistyrelsen)
EoL	End-of-Life
ETRS89	European Terrestrial Reference System 1989
GF	Glass fiber
GFRP	Glass fiber reinforced polymer
GHG	Greenhouse Gas
GIS	Geographic Information System
HF	Hybrid fiber
HFRP	Hybrid fiber reinforced polymer
LCOE	Levelized cost of energy
TRL	Technology Readiness Level
UTM 32N	Universal Transverse Mercator Zone 32N
WT	Wind turbine(s)
WTB	Wind Turbine Blade(s)

1 Introduction

The Danish government has ambitions of making Denmark entirely independent of coal, oil and gas by 2050 [1]. This requires large investments in sustainable energy technologies, an important one of which is wind turbines [2]. To increase the installed MWe capacity of wind turbines in Denmark, the government has passed legislation to entice both private persons and municipalities to invest in onshore wind turbines [3]. Additionally, large offshore areas have been reserved for preliminary investigations of wind farms as well as later installation, with the goal of installing 800 MW between 2018 and 2030 [4]–[6]. However, the predicted increase in installed wind turbine (WT) material is accompanied by the problem of effectively managing their parts at their EoL. Most WT parts are easily recycled, but the structural requirements to the blades mean that they are made, mostly, from composite material, which is infamously hard to manage at its EoL [7]. Additionally, the blades are the part of a WT with the highest uncertainty of handling together with the highest importance in terms of environmental impacts related to its EoL management [8]. So far, composite material has mainly been dealt with through incineration followed by landfill, or direct landfill.

However, due to the nature of composite material, it does not degrade [9]. Therefore, EoL options are being developed to, not only save landfilling area, but also to extract the value vested in the materials, which is especially important for composites made from expensive fibers.

To effectively optimize the EoL management options in a holistic way, the transport aspect of the blades must be accounted for, since this aspect may overshadow the benefits of certain EoL management options. The transport expenses are especially important for offshore turbines, which need to be transported by large vessels and dismantled by offshore cranes, but even the onshore turbines have considerable costs associated to their transport, since the form of the blades means that large trucks need to be used, even if the weight of the blade is considerably lower than the maximum payload of the truck [10]. This makes it worthwhile to develop a detailed cost model for the transport part of wind turbine blades' EoL.

1.1 Reading guide

The background for this thesis is expressed in the section 'Problem statement'. In here, the problem that this thesis seeks to solve is described. Furthermore, this section will discuss the scope investigated, as well as the delimitations of this thesis.

Hereafter, the general 'Background' of the thesis will be described, which will be expanded on in the relevant sections.

From here, the generic structure of a wind turbine blade is investigated in 'WTB blueprint & Material', together with an investigation of the background of using composite material for WTB.

After having laid out the background for using composite materials, the general hierarchy of EoL types are described in the section 'EoL management '. In the same section, EoL options deemed relevant are briefly discussed and investigated in a 'Comparative analysis'.

The data and assumptions made in this thesis are then described in the section 'Data & Assumptions'. These discussed assumptions apply for both the 'Mass flow model' and the 'GIS-model'.

In the section 'Mass flow model', the method behind the mass flow model is expanded on, relevant parameters are discussed, the model is sought to be validated, and the inflows & outflows are produced.

The next section: 'GIS-model', expands on the methodology of the GIS-model. Furthermore, this section contains data and assumptions that only apply to this model.

The GIS-model is followed by the 'Results' section, which contains the ultimate direct and indirect costs of decommissioning the investigated blade types of Denmark.

The results are followed by 'Sensitivity analyses' on the results of the GIS-model.

The work of the thesis is concluded with a 'Discussion' and 'Conclusion' on the work performed. Lastly, the Bibliography and Appendices are provided. Note that certain appendices are in excel format.

Specifics on how the two models were derived on a micro-level can be acquired from the attached excel appendices. Each excel file contains a reading guide in their first sheet, which discusses the purpose of the file as well as the workings of each of its sheets. This is elaborated on in Appendix I.

2 Problem statement

It has been politically decided that Denmark will transition into a completely renewable energy sector up until 2050 [11]. In reference to this transition, Denmark is projected to have its capacity of wind turbines increase. At some point, the given turbine will need to be decommissioned. Since the blades of the turbine are quite energy and emission intensive to produce, together with expensive, it would be worthwhile to recycle them at their decommission, instead of simply landfilling them or incinerating them [12], [13]. Many EoL treatments exist, but due to the variability in materials used to construct WTB, no single optimal EoL exists for all WTB.

This means that the optimal EoL technology should be determined by accounting for the specifics of the blade. Additionally, the transported distance has a cost related to it. This cost should be accounted for when determining which EoL treatment is optimal for the given turbine.

Hence, the goal of this project is twofold.

1. It is aimed to project the amount of blade material that will need EoL treatment by year.
2. It is sought to develop a GIS-model which can minimize the EoL costs of Danish wind turbine blades by optimizing the transport aspect. Furthermore, the portion of the total decommissioning cost stemming from transport will be derived.

The total weight of WTB that need to be decommissioned is derived from the following energy scenarios' projected WT installations, using a mass flow model.

- AF19 [14]
- Wind, Biomass, Bio+, Hydrogen & Fossil [15]
- IDA [16]

This is accompanied by a GIS-model which is specific to whether the given turbine is placed onshore or offshore, both in terms of required transport and the estimated weight and material composition of the given blade. Additionally, the period for which installed turbines have their decommissioning optimized by the model is 2020-2050, since the used energy scenarios are only projected up until 2050, and since 2050 is a highlighted year of the Danish energy sector's sustainability transition.

2.1 Problem Scope & Delimitation

Information on wind turbines is mostly closed source, meaning specific data on specific blades is very difficult to obtain. This is a problem due to variability of materials used and the material distributions [9]. To accommodate this problem, specific blade models were used to derive the energy consumption, GHG emissions and costs of various EoL options. This means that some of the assumptions of e.g. the blade material used for a specific turbine may be inaccurate. The closed source nature of information on WTB also means that an empirical regression was used to determine the weight of the blades of each turbine. This empirical regression has a fixed hub to rotor weight ratio, which is assumed to be a fair delimitation.

The fact that the model should be able to determine which EoL treatment is optimal requires that at least one of each investigated EoL treatment type is found. It was found that certain companies do not want to disclose exactly which EoL treatment is used, and that fewer than one of each treatment types were found in Europe at a commercial level. Therefore, EoL sites were produced and placed around Denmark, to prove the functionality of the model.

The model calculates the EoL costs and optimizes the EoL based off the shortest transport distance. This distance does not account for pay roads or pay bridges. It does not optimize for the route that would cost the least in terms of fuel consumption and truck driver salary. Such optimizations are considered outside the scope of this thesis.

The rent cost of shipping and EoL treatment were not accounted for either. Instead, the expected operational costs were used here. This means the costs would likely be higher.

It is assumed that shearing does not occur until EoL treatment begins. The model should be able to optimize for which harbor is optimal accounting for the placement of shearing, which can reduce the transport costs. This is considered outside the scope of this thesis. In support of this decision, it should be noted that shearing reduces the degree to which fibers can be recovered in their full length. This means that shearing is likely only lucrative for EoL options that do not entail fiber recovery.

Lastly, it is assumed that all Danish harbors are fit for transporting large goods, such as WTB.

3 Background

This section explains the general background of this thesis. First, relevant EoL options are analyzed and discussed, and the energy consumption, GHG emissions and costs of the EoL options are derived.

Hereafter, the same variables for transport are derived. These variables are then used to calculate the "Distance of acceptance". The purpose of the "Distance of acceptance" is to determine which EoL sites should be used for each turbine, in terms of minimizing the combined cost of transport and EoL treatment.

3.1 WTB blueprint & Material Composition

Most WTB are made from composite material [17], [18]. In general, composite materials are any materials that are constituted by more than one material. To understand why composite material is used, it is required to understand the structure of a WTB and its structural requirements. The cross-sectional area is illustrated in Figure 1:

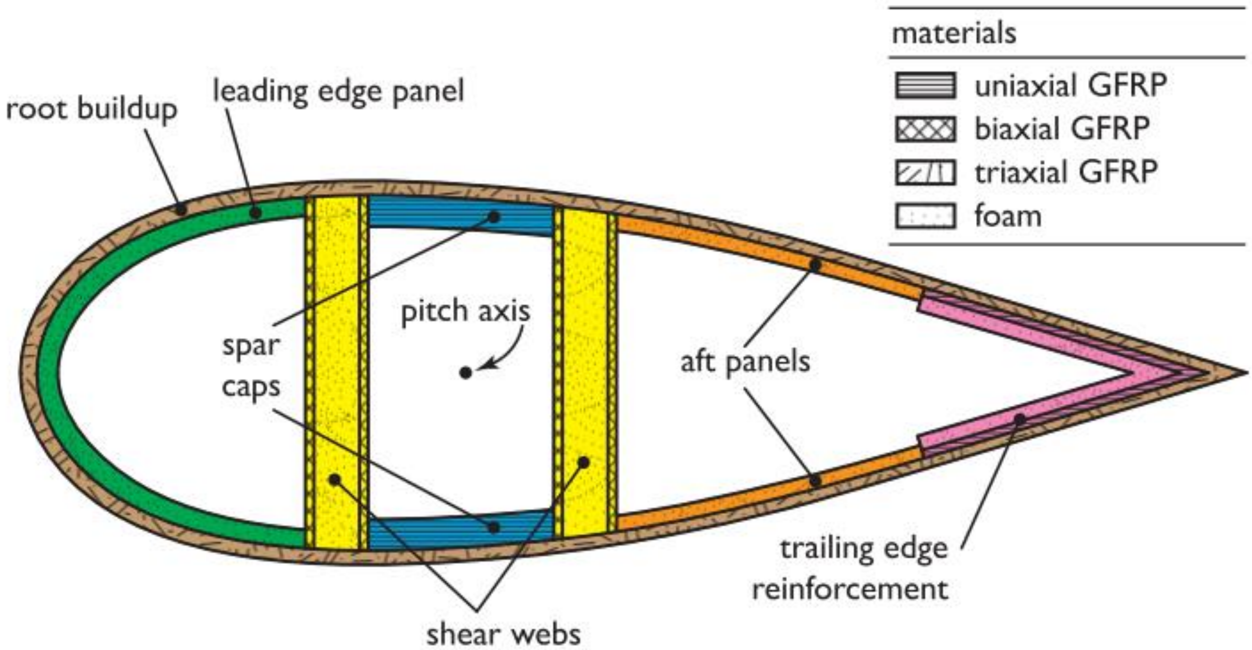

Figure 1- The cross-sectional structure of conventional WTB. Courtesy of Perry Roth-Johnson [19].

The cross section illustrates which material each part of the blade is made of, and as illustrated, quite a large portion is made from GFRP (Glass fiber reinforced polymer). The cross-section changes in relation to which part of the blade is looked at, but the above representation is still representative for a generic wind turbine blade. The importance of using strong materials with low density is elaborated on later.

3.1.1 Composite materials

In the case of WTB, the composite materials are a combination of fibers and resin, with a small amount of filler. The reason for using composite materials for wind turbines is the fact that composite materials has specifications in line with what is needed. This includes:

- Low density
- High mechanical strength
- Excellent corrosive and degradative resistance
- High fatigue resistance (especially important for long lifetimes)
- Tailorability of properties [20]

There are however changes in the importance of the relevant features of the materials. One such change is driven by the trend of increasing hub height and rotor diameter, as depicted in Figure 2:

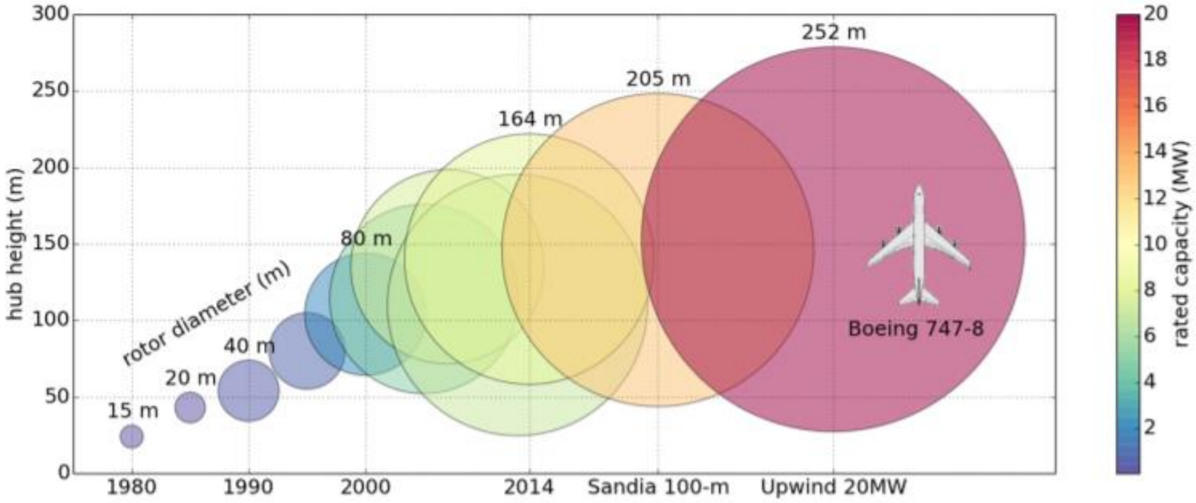

Figure 2- Trend for WT hub height, rotor diameter and MWe capacity. Courtesy of Perry Roth-Johnson [19].

This predicted size increase of WTB increases the requirements to the density of the blades as well as the stiffness. The density is important because the gravitational load increases with the size of the blades, and the importance of stiffness arises from the fact that longer blades need to be stiffer than their smaller counterparts, in order not to hit the tower [18] and to decrease flutter, which may slowly deteriorate the composite material leading to failure [21]. This is especially important for offshore turbines, which tend to be larger than their onshore counterparts.

At times, the nacelle and hub of a WT can be made from composite material as well, though they tend to be made of steel or other materials [22].

3.1.1.1 Fibers

There are a multitude of fibers that can be used, many of which are derivations of GF (Glass fiber) or CF (Carbon fiber). However, GF and CF are the most relevant ones, and rarely are other fibers seen in WTB [23]. Since CF is more stiff and lighter than glass fiber, it is expected that the above described trend of the size of turbines increasing will increase the proportion of turbine blades made from CF or at least, a HF (Hybrid fiber) containing CF [24].

3.1.1.2 Matrices

The matrix materials are unanimously resins, and are divided into 3 groups:

- Unsaturated polyesters
- Epoxies
- Vinyl esters

The resin is injected into the construction after the fiber layers and filler layers have been installed, so that it saturates them. It will then harden, finishing the composite material, after which the two halves of the blade are connected using adhesives [23].

It applies to all three of these groups that they are thermosetting, which means the resin cannot simply be reheated upon EoL and used elsewhere, without significant losses to its structural integrity [25].

An alternative to these resins is thermoplastics, which can be reheated and used anew with no decrease in strength. However, thermoplastics come with problems such as a high processing temperature, which may impact the integrity of the fibers. Additionally, it can be difficult to have thermoplastics impregnate the fibers evenly and fully. However, they have promising features such as low fabrication cost [24]. As of medio 2019, the use of thermoplastics was regarded to have a TRL of 6 (To understand the TRL scale, see Appendix A.

From this, it can be inferred that most wind turbines are made from thermoset resins, though that may change in the future [26]. Importantly, thermoplastics are unlikely to be used for blades larger than 5 meters for some time, due to its physical properties, and so, it should be regarded as a relevant technology only for small, onshore turbines for the coming years [7]. However, megawatt-scale thermoplastic resin blades are being studied, and depending on the future development of the technology, it may be used for larger blades in the future, though, assumedly, not for offshore turbines in the foreseeable future [27]. Lastly, thermoplastics can be manufactured into blades up to 6 times faster than is the case for thermosets [28].

The most relevant properties of the two matrices are shown in table 1:

Property	Thermosets	Thermoplastics
Production	Complex	Simple
Melt viscosity	Very low	High
Fiber impregnation	Easy	Difficult
Processing cycle	Long	Short to long
Processing temp./press.	Low to moderate	High
Production cost	High	Low
Mechanical properties	Fair to good	Fair to good (limited to smaller blades)
Solvent resistance	Excellent	Poor to good
Damage tolerance	Poor to excellent	Fair to good
Data base	Very large	Small
TRL	9	6
Potential for recycling	Low to moderate	High

Table 1-Relative properties of thermosets and thermoplastics as matrices [24].

A promising aspect of matrix materials is nanoengineered polymers and composites which have shown quite significant improvements in the lifetime, fatigue resistance, shear, weight, compressive strength, and fracture toughness. Unfortunately, this aspect is still under development, and large problems of practicality and economy still need to be solved before this technology is relevant. The nano-reinforcements can be made from various materials, which will all change the recyclability of the composite material, but this field has not been studied sufficiently [18].

3.1.1.3 Fillers

Fillers make up ~10 % of the total blade weight [29]. It is true for the general composition of WTB that the exact materials and material amounts are hard to ascertain. This is especially true for the filler portion of the blade which can be made from various materials, making exact calculations on EoL treatment specifications difficult. This problem has led even industry professionals to make general assumptions on the filler material. This is especially a problem in relation to the chemical EoL management types, since the filler material may influence the chemical reactions [9]. Specific examples of filler would be balsawood and plastic foam (PVC or PET foam) [17], [29], [30], [31].

3.1.1.4 Miscellaneous

The miscellaneous parts are necessary, but in terms of EoL impacts, they are not relevant since their percentual weight and impact are negligible.

A small portion of WTB is made from copper and steel, namely the lightning rod.

Furthermore, the coating of the blades is made from polyethylene (PE) or polyurethane (PUR). Other materials can be used for coating as well. The purpose of the coating is to decrease ultraviolet exposure, moisture absorption and temperature fluctuations, among others. These materials constitute a negligible portion of the blade and are therefore often left out of studies on wind turbine blade EoL treatment [9], [24], [31].

3.2 EoL management options

There is a wide variety of EoL management options for decommissioned WTB, and which specific option is optimal depends on the specific components of the wind turbine blade. For instance, treatment options with a higher fiber yield may not be worth the additional effort for GFRP, due to the fact that the GF price is about an order of magnitude lower, and an order of magnitude less environmentally impactful to produce [26]. Therefore, the EoL options should be compared on a per turbine basis.

3.2.1 Problems with currently used materials

As mentioned earlier, composite materials come with significant problems in terms of EoL management. The fact that the fibers and the matrix are so well connected in the composite material means separation can be difficult and expensive [32]. Additionally, effective solutions are mostly at developmental stages at this point in time [26].

The expected outflow of fiber glass from the Danish energy sector is expected to be between 2000 ton to 4500 ton annually up until 2050, depending on which energy plan is followed. For most projections, it is expected to increase annually. Additionally, the GF stock is expected to increase throughout this period according to most projections, which means the outflow after 2050 is expected to increase as well. This is all in spite of projections forecasting that the material intensity for GF will decrease by about 30 % in the period 2020-2050 [33].

The reason why this is a problem is that the relevant composite materials of this study are not easily broken down over time either, meaning that landfilling them should be regarded as a temporary solution, for which future solutions must be employed when they have been sufficiently developed. The problems related to EoL management of the used materials will be expanded on in ‘Hierarchy of EoL management’.

3.2.2 Hierarchy of EoL management

A general, hierarchical guideline of preference has been developed for waste, which includes the decommissioning of WTB. This hierarchy of waste is depicted in Figure 3:

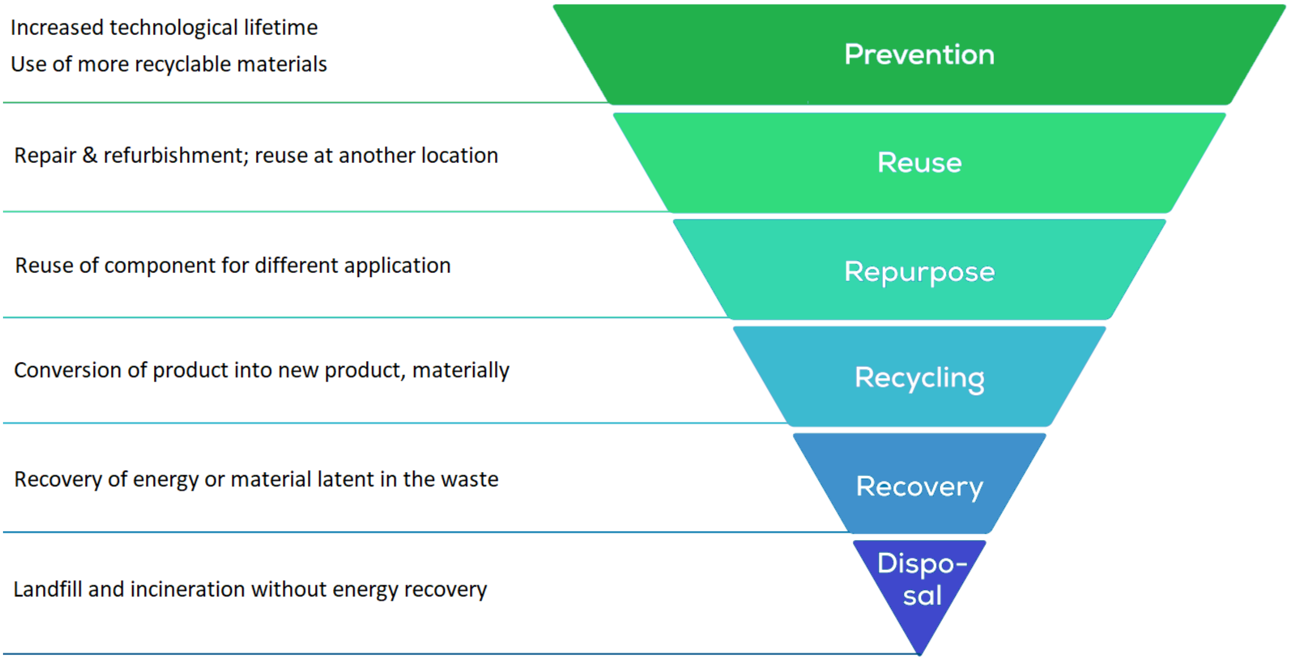

Figure 3- Waste treatment hierarchy [31].

The higher up the option is placed, the higher the preference. This figure is not an end-all guideline, but it roughly accounts for the relative environmental and economic costs associated with each option. The importance of the EoL management part of the energy system has led innovations relating to the above figure to be of medium to high priority [34].

3.2.2.1 Prevention

Most prioritized is prevention, which entails using alternative, sustainable materials to the currently used ones. As previously mentioned, this is not a likely thing to happen for WTB, though incremental changes may occur over time. It also includes reduction of the material intensity of the wind turbine, which is expected to decrease [33], [35]. Furthermore, increased lifetime of the composite material, new coatings, stronger structural designs, on-site repair, refurbishment etc. are included under prevention [26].

3.2.2.2 Reuse

Reuse is the second most preferred option. Currently, there is a market for selling decommissioned WTB to an extent. However, reusing blades comes with its problems. Firstly, the blade quality needs to be documented. Additionally, the blade will have to be properly disassembled from the turbine, transported, and reassembled. The option is valuable since it increases resource efficiency by extending the lifetime of the product. Even more preferable is performing minor repairs and installing the blade in its original place, to avoid the environmental impact and costs of long distance transport [9].

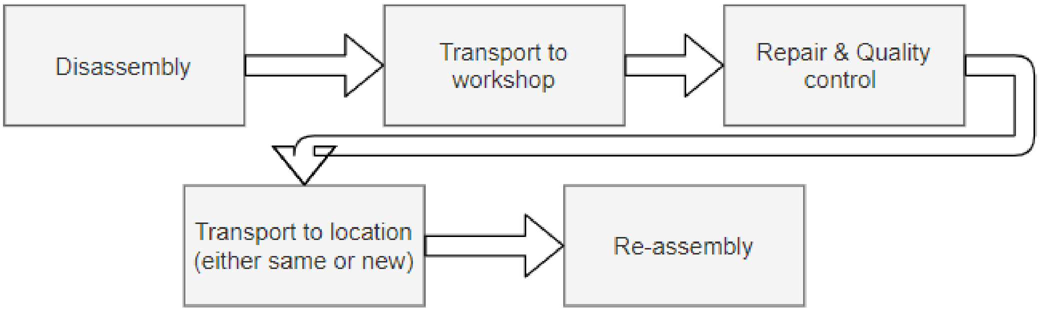

Figure 4- Process diagram for reuse of WTB.

3.2.2.3 Repurpose

Repurposing is generally quite close to simply being reuse, only differing by requiring certain intersections of the blade. Only rough intersections are made on the blade, after which it can be used for constructions such as: Bridges, furniture, public benches, playgrounds, bicycle sheds, etc. [36]. The sawing is mostly done with a wire saw or a circular saw depending on what the cut-up blade is purposed for. Repurposing and reusing the blades both have the effect of displacing the need for EoL management into the future which would still require some processes further down in the hierarchy of waste management after being decommissioned again [9], [37],[38]. Whilst the technological requirements are low, the market for this type of solutions is not exactly known. Hence, the future development of the market is not known.

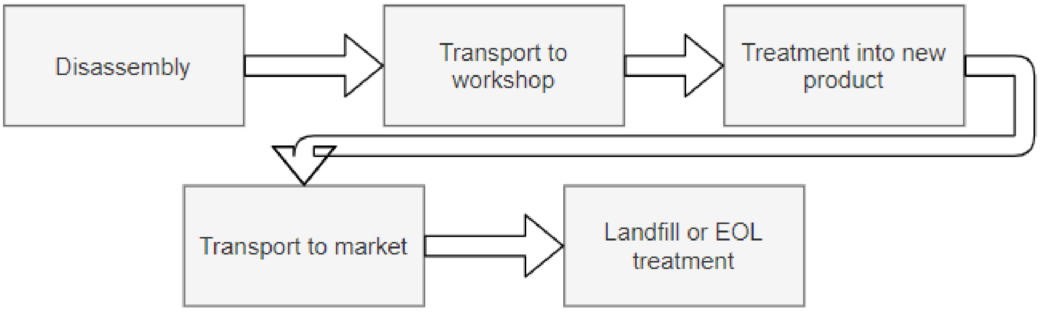

Figure 5- Process diagram for Repurposing of WTB

3.2.2.4 Recycling

Recycling often requires the same rough intersections as repurposing. After this initial cutting has been carried out, the resulting pieces are then cut into much smaller pieces using a jaw cutter. This process is dirty and requires sanitation and water fog to control the dust created [9]. Currently, the two most developmentally ready and relevant recycling options are:

Mechanical grinding, in which the composite material is ground into powder and separated into fiber rich powder and matrix rich powder. Up to about 40 % of the composite material will remain as waste, which is landfilled.

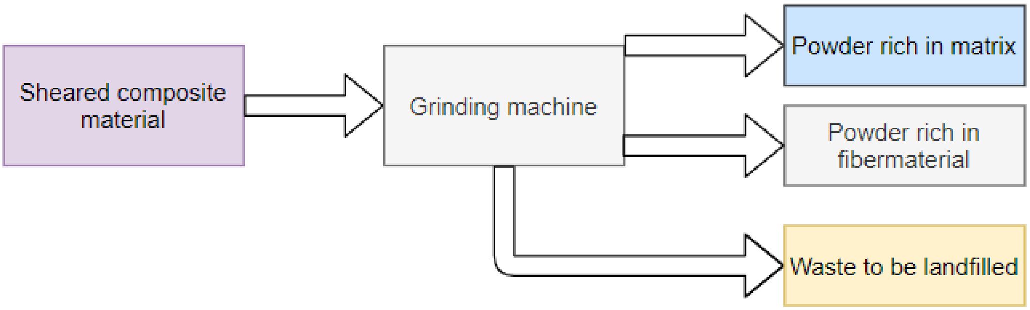

Figure 6- Process diagram for mechanical grinding

Importantly, the material is downcycled during mechanical grinding, and the fibers cannot be reused for WT applications after the grinding. Currently, this technology is more developed for GFRP (TRL: 9), and less so for CFRP (carbon fiber reinforced polymer) (TRL: 6/7) [9], [26].

Cement kiln co-processing, in which the composite material is used for clinker cement production. Not only is this option fully developed (TRL 9), but up to 75% of the raw materials for cement are substituted with composite material. Unlike mechanical grinding, this option leaves no waste. Additionally, the environmental impact of the cement industry is lowered [25], [26], [39].

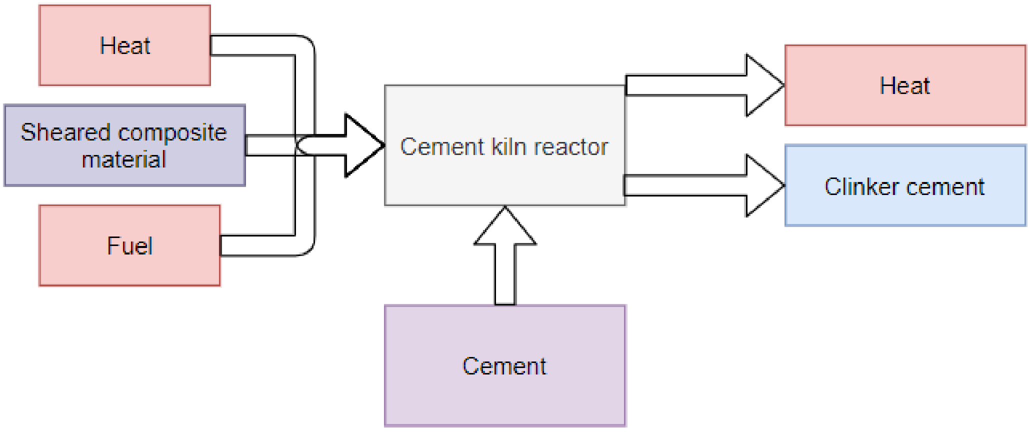

Figure 7- Process diagram for Cement Kiln co-processing

Whilst this process is energy intensive and does not allow reuse of fibers or matrix in other applications than cement clinker, it can, currently, process more composite material waste than is generated, which means countries that have restricted landfilling are likely to use this process until better ones have been further developed.

3.2.2.5 Recovery

Recovery is mainly done through one of four processes:

Pyrolysis, in which the blades are heated in an environment with no oxygen, to extract fibers and energy. Unfortunately, fibers are degenerated at high temperatures, so a trade-off occurs in which the operator maximizes the yield in terms of fiber strength and removal of binder. The fiber degradation mostly occurs between 300 °C degrees and 450 °C [40]. Pyrolysis requires a mechanical treatment of the blade to smaller pieces.

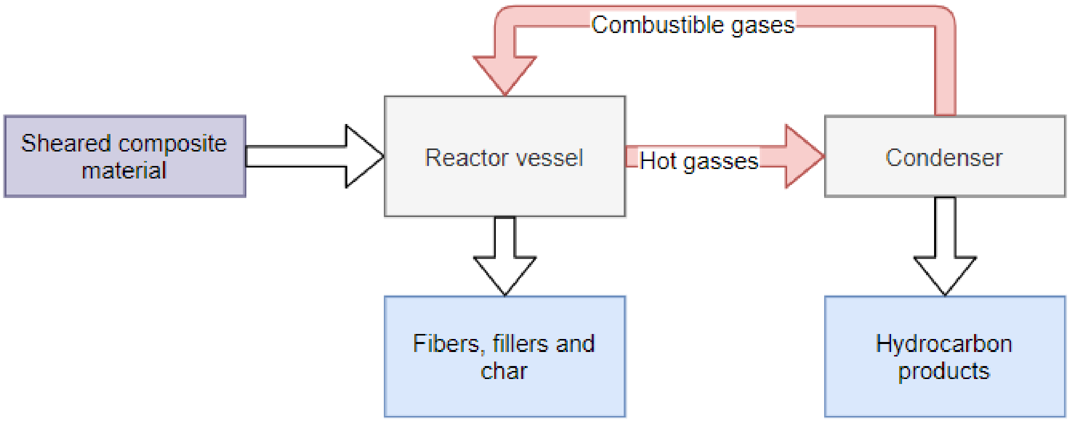

Figure 8- Process diagram for Pyrolysis.

The process has a TRL of 9, though a very similar process using microwaves is being developed that has a TRL of 4/5 [26].

Fluidised bed, which is also a thermal treatment option, pyrolyzes the polymer matrix on a layer of silica sand which is fluidized by a continuous stream of hot air high in oxygen. Hereafter, fibers, and other materials are carried further through the process, where the fibers are separated using a cyclone. This treatment option also requires cutting the blades into small pieces beforehand.

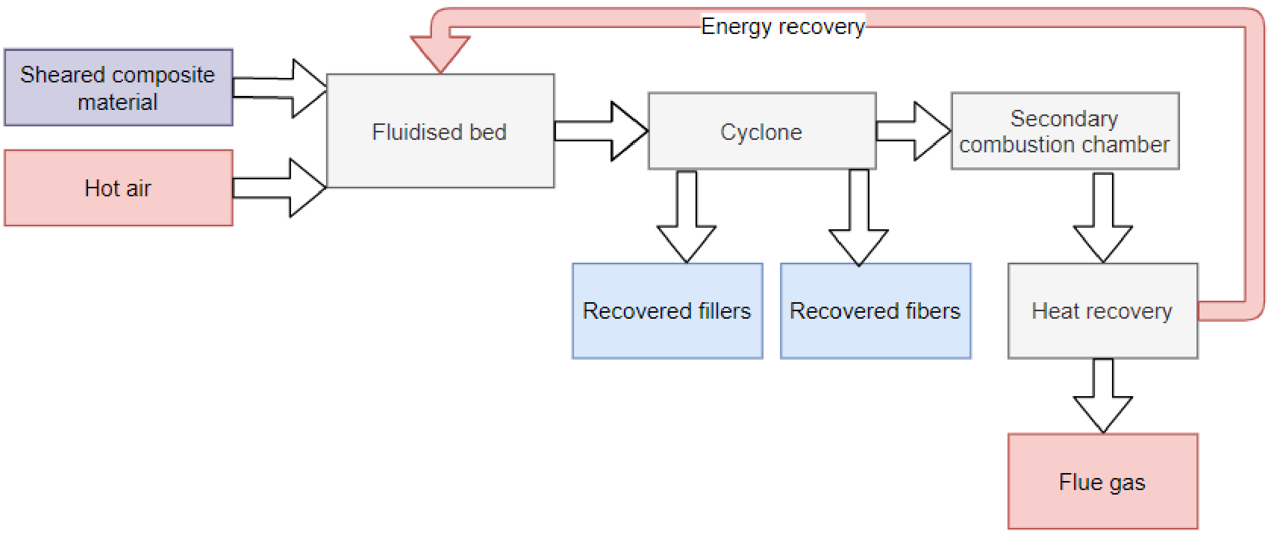

Figure 9- Process diagram for Fluidised bed (Gasification).

Fluidised bed's current TRL is at 5/6. Additionally, it is expected to not be economically viable for capacities below 10,000 tons per year [26].

Solvolysis, can either be done at near- and supercritical temperatures and pressures or at over near- and supercritical temperatures or pressures. Whilst the specific products of the treatment differ depending on which solvent is used, it is always the case that the fibers are separated from the resin.

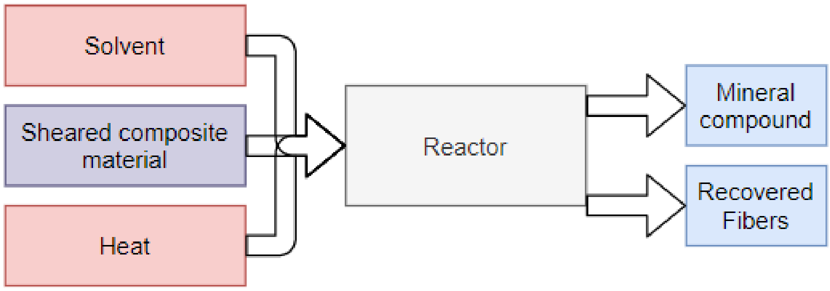

Figure 10- Process diagram for solvolysis.

Its current TRL is at 5/6. It is expected to be one of the more relevant processes for expensive fibers, since it recovers fibers with lower losses than the thermal methods [41]. However, the current level of development has a low throughput, a high energy intensiveness and large use of solvents (for which reuse of the solvents has not yet been explored).

High voltage pulse fragmentation, which separates different materials of the composite using electrical current at high voltage [13], [31].

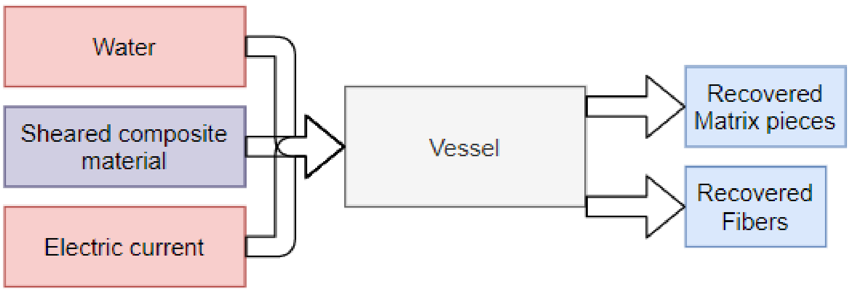

Figure 11- Process diagram for High voltage pulse fragmentation.

The current TRL of this process is 6. Whilst it is quite scalable, it does decrease the modulus of glass fibers [26].

3.2.2.6 Conversion

Conversion entails quite a bit of pretreatment, which is generally expensive and energy demanding. The process is a way to upcycle the blades by converting the composite material to valuable chemicals and materials. For instance, oil can be produced from the blades, and certain valuable chemicals can be generated such as oil [9]. Conversion is not in the waste management hierarchy since it is not relevant for all categories of waste. Currently, no conversion treatment technology is believed to be of relevance, either due to exceedingly high costs, or due to low TRL.

3.2.2.7 Disposal

Disposal is the simple option of transporting the blades to a location and simply depositing them there as landfill, without extracting any value from them. This option is slowly decreasing in likelihood because blades practically never degrade naturally, which has led many European countries to legislatively ban landfilling of WTB [42]. Additionally, it is expected that more countries will follow suit in restricting landfilling of composite materials [7], [30]. Whilst the environmental impact of proper landfilling is low, landfilling in this context should be regarded in the same way as reuse or repurposing should. Namely, it should be regarded as a temporary solution, for which the composite material can be processed at a time with better technological capabilities [9]. Generally, landfilling and incineration are the most used EoL options, which is expressed by the fact that the overwhelming majority of LCA's on the topic assume these EoL options for WTB [7], [43].

3.2.3 Comparative analysis

Whilst the hierarchy has been defined, the specific options for repurposing, recycling and recovery vary, both geographically and temporally. Additionally, which specific option is regarded as optimal will depend on which variable is used for the optimization (energy consumption, GHG emissions or cost) as well as the specific blade's size, material composition, structural specifications, and the specifications of the given EoL management option, data on which is not open to the public and is likely to change.

Therefore, the above described options are selected on a basis of what seems relevant according to current research. These may very well be substituted in the future by more economical or sustainable processes. However, the purpose of this thesis is not to list all possible options, but instead, list those that are currently relevant for Denmark, and to make a model for which it is possible to include future technologies when they are developmentally ready. The scope of this paper will therefore be limited to the options described above. The GIS model will enable its user to implement current data for a given EoL management process when one has such data.

A comparative table of the most relevant EoL technologies can be seen in Table 2, which highlights the strengths and weaknesses of the EoL options.

EoL Technologies			
Process	**TRL**	**Strengths**	**Weaknesses**
Reuse	9	Reduces stock flow costs, environmental impacts. Increases lifetime and can promote greenification of countries buying cheap used blades. Cheaper than producing new blades.	EOL treatment still needed at end of life.
Repurpose	9	Substitutes raw materials in other sectors. Cheap.	EOL treatment still needed at end of life.
Recycling			
Mechanical grinding	9/6	High throughput rates	Downcycling. High OPEX & CAPEX Up to 40 % waste
Cement kiln co-processing	9	High throuhgput. Can absorb all composite waste generated. Up to 75% substitution of raw material. Significant reduction in CO2 from cement industry.	Increased energy consumption in cement industry. Loss of (expensive) fibers.
Pyrolysis	9	Recovery of fibers. Scalable.	Fibers may retain residue from process. High degradation of glass fibers. Only economically viable for GFRP so far.
Fluidised bed	5/6	Recovery of fibers and fillers. High heat transfer efficiency.	High degradation of glassfibers. Requires high capacity to be economically viable.
Solvolysis	5/6	Recovery of resin and full length fibers.	Low throughput, high energy consumption, use of large amounts of solvent
HVPF	6	Highly scalable. Recovery of matrix and fibres.	Decreased quality of recovered glass fibers.

Table 2- EoL technologies. For TRLs with only one number, it applies to both GFRP & CFRP, except in the case of cement kiln co-processing which applies only to GFRP.

Whilst Table 2 serves as introductory information to the EoL options, the energy consumption, GHG emissions and cost associated to each EoL option have been derived for the purpose of developing the GIS-model.

The specific data on energy consumption have been derived from “Wind turbine blade end-of-life- options: An eco-audit comparison” [13]. They account for the lifetime impact of the turbine, the EoL impact, and the recycling benefit.

In turn, the recycling benefit accounts for processing losses, energy of retained fiber performance, recycled fiber rate, and many more aspects of the net impact of a blade. The study only considered energy consumption, and so, the net GHG emissions and net Cost of EoL were derived from the energy results yielded in this study. Note that the cost is derived from operational costs related to fuel consumption and salvaged value, and not actual cost prices.

The reasoning behind including the possibility of optimizing in terms of energy consumption and GHG emissions, and for even including these variables in the model is that potential subsidies or fees relating to the decommissioning would likely be placed on these variables. Accounting for such fees can be done directly when the energy consumption and GHG emissions are already yielded.

The following 3 subsections concern the variables: Energy consumption, GHG emissions & cost.

3.2.3.1.1 Energy consumption

The variables account for the energy consumption, GHG emissions and cost related to the production of the blade, which are shown in Table 3.

Energy cons. GHG emissions & Cost of blade production per ton of blade			
Blade fiber type	Glass fiber	Hybrid fiber	Carbon fiber
Energy Cons. [GJ/ton]	110	140	259
GHG emis. [tonCO2-eq./ton]	10	12	23
Cost [DKK/Ton]	79.225	456.287	833.349

Table 3- Energy, GHG emissions and cost intensity of producing 1 ton of wind turbine blade [12], [13].

This subsection and the following 2 subsections do not account for the value of products that are not directly related to the production of WTB, or costs of the EoL treatment type that are not related to energy, e.g. solvents. Therefore, the data below should not be regarded without account for the assumptions behind the calculations since the assumptions can change the yielded values.

First, the energy savings by EoL treatment were simulated for a GF blade, a hybrid GF and CF blade using CF for the spar caps, and a CF blade. The energy savings are presented relative to the energy required to produce a new blade [13], [39]. For cases in which raw materials of the blade are recovered, the resulting savings from not having to produce a new blade with virgin materials counts as an additional saving. This is the case for Figure 12, as well as for Figure 13 and Figure 14.

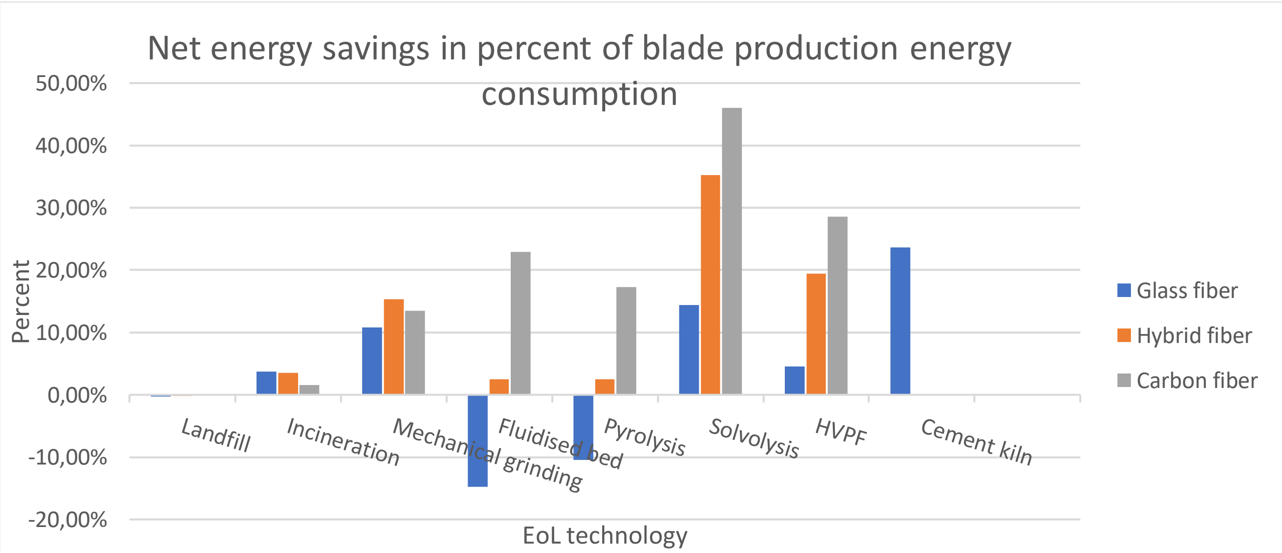

Figure 12- Percent of blade production energy consumption recovered through EoL treatment

The figure presents the net values, meaning the energy consumption of the EoL process has been accounted for. Negative values indicate a net expenditure, whilst positive values indicate net energy savings. Note how cement kiln co-processing is only an option for glass fiber. The cement kiln option's energy savings are, unlike the other treatment options, not related to any retention of the fibers for reuse, but rather a displacement of the energy needed to acquire the raw materials used for cement production, and the heating value of the composite, which decreases the fuel consumption during the production process [39].

It is clear how which EoL treatment type is optimal depends heavily on the type of blade. Additionally, larger net energy savings are experienced for the EoL of CF blades, for fiber recovering treatments, which is due to the much larger energy consumption related to its production.

Landfill energy recovery is negligibly small for all investigated blade types. However, the simulation does not consider the potential savings from temporally displacing the EoL treatment of the blade and treating it later, which would likely result in net positive energy savings.

3.2.3.1.2 GHG emissions

The percentage of the blades' production related GHG emissions negated through EoL treatment is presented in the figure below.

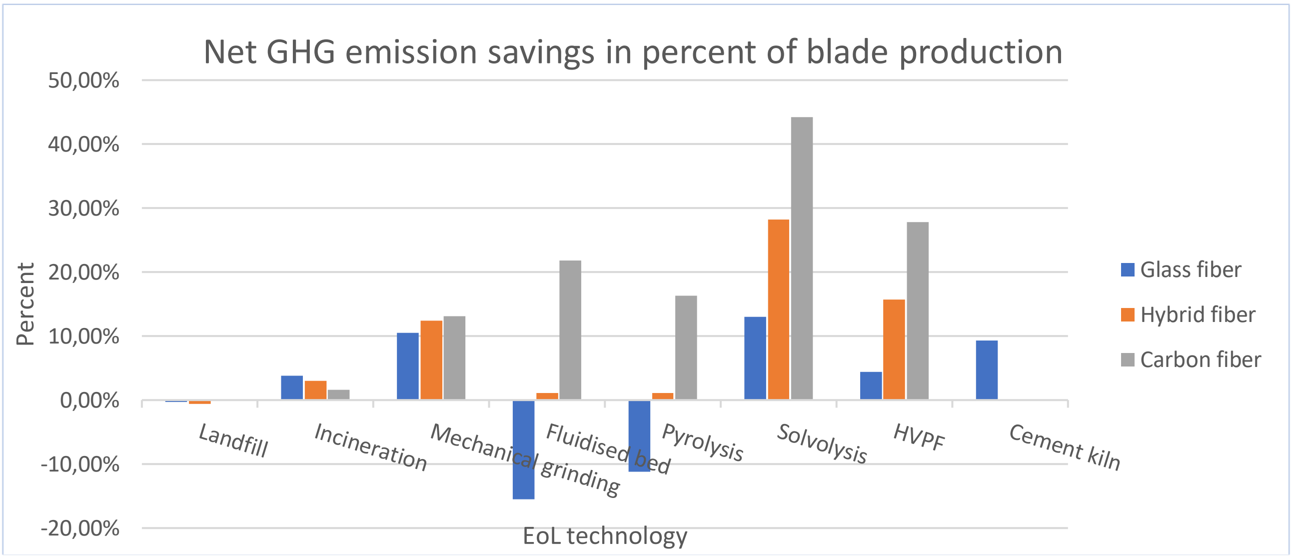

Figure 13- Percent of blade production related GHG emissions negated through EoL treatment

The GHG savings generally follow the same profile as the energy savings. Again, the largest savings are found in cases where expensive blades have their fibers recovered. From a sustainability point of view, the importance of dealing correctly with blades at their EoL is apparent. The values have been calculated by accounting for the efficiency of the various processes as well as the CO2 efficiency of the relevant fuels [13], [26], [44]–[47].

3.2.3.1.3 Cost

The cost savings in percent of the cost of the blade are presented below.

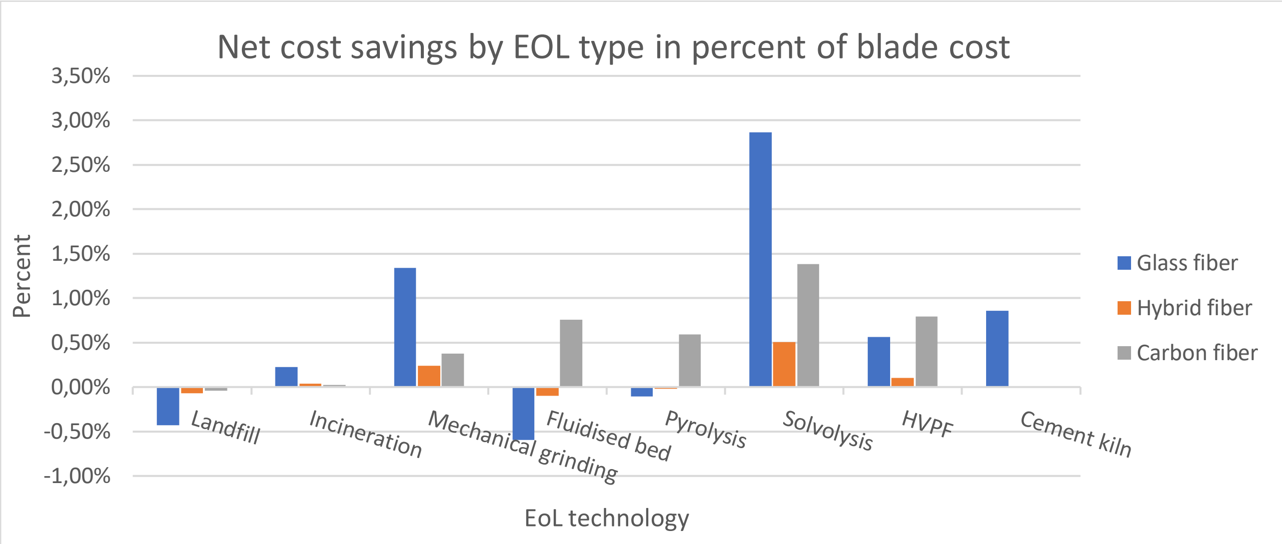

Figure 14- Percent of blade production cost negated through EoL treatment

Firstly, recall that the value of certain byproducts and the costs of catalyzers are not accounted for, meaning the extreme negation percentages of fiber recovering technologies are larger than they would be otherwise. Understand that the absolute savings are large for blades containing CF, since these are ~10 times as expensive as GF [48]. The cost was calculated by first finding a representative price for GF blades, and later scaling up the cost of the fiber portion to account for the higher price of CF. A limitation is that the cost is generally higher per ton of blade the smaller the blade is, which is not incorporated into the calculation [12], [49]–[54].

The relative savings acquired for GF tend to be higher, since the intrinsic value is so much lower for GF than CF.

The data on energy, GHG and cost support that landfill is not the best option. Of course, certain EoL technologies are currently not available, but cement kiln co-processing is, for which entire solutions can be bought, including freight to the kiln [55], [56]. This is even true for some of the recovery processes (pyrolysis or solvolysis); however, the relevant firm does not wish to disclose which technology specifically [57].

As mentioned earlier, landfill can still be worthwhile insofar as it offers temporal displacement, which could increase the savings related to EoL.

Lastly, note that the net energy consumption, net GHG emission and net cost is used in the GIS-model to determine which EoL type is optimal, accounting for the distance between the turbine and the EoL site.

Whilst having energy- GHG - and cost savings presented relative to the cost of the given WTB is worthwhile for the purpose of comparing, it is equally important to present such data in absolute values. This data is available in Appendix B. How this data was yielded can be seen in the excel appendix: EoL rank order. From this data, it can clearly be understood how EoL treatment of CF-based blades is much more impactful on a per ton basis.

4 Methodology

This section lays out the methodology behind the models together with the data and assumptions of the two models of this thesis.

4.1 Data & Assumptions

The purpose of this section is to outline the assumptions and data used for the mass flow model, and the GIS-model.

4.1.1 Material distribution

The material distribution of currently installed WTB is assumed to be as depicted in the table below

Polymer	Fiber	Filler
30%	60%	10%

Table 4- Material distribution of WTB.

The material distribution is prone to large variations, but the above values are typical for blades between 1 and 13 tons. This assumption is regarded as fair due to the high difficulty of acquiring turbine specific data [9].

4.1.2 Weight of blades

Whilst quite a bit of data on Danish WTB is available through the Master data register [58], the weight of the blades is not included. After extensive research, it has been found that such data is largely unavailable on a per turbine basis. A way of accommodating this lack of accessible data is using an empirical regression for the rotor weight [tons] and the rotor diameter [m] from [59], as seen below.

$$W_{Onshore} = 0.0051 * R^{2.01338} * 0.54$$

Equation 1- Blade weight W [tons] for onshore turbines, derived from the rotor diameter, R [m].

$$W_{Offshore} = 0.0035 * R^{2.1412} * 0.54$$

Equation 2-Blade weight W [tons] for offshore turbines, derived from the rotor diameter, R [m].

Since the rotor weight includes the weight of the hub, the weight proportion of the hub to the rotor has been accounted for by setting the blade weight to rotor weight proportion to be 54 % [60]. This was done even though smaller turbines are likely to have larger variance in their blade weight to rotor weight, due to the lower structural requirements caused by low structural tension from low weight and low gravitational force.

From this method, the blade weights have been calculated and are presented in Figure 15.

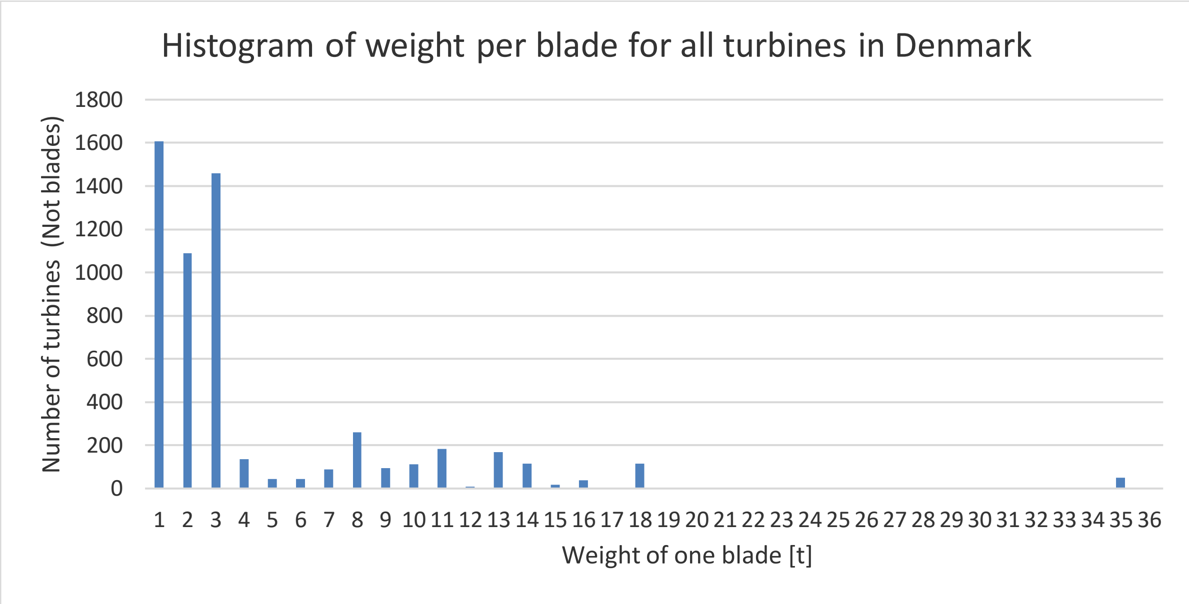

Figure 15- Number of turbines in Denmark by weight of an individual blade.

As the histogram depicts, relatively few turbines have blades that, individually, weigh more than 5 tons. The average capacity of installed offshore turbines is 3,05 MW whilst it is a mere 775 kW for onshore turbines, which means the right side of Figure 15 mostly consists of offshore turbines.

4.2 Mass flow model

This section concerns the data inputs of the mass flow model, the assumptions that were made, and the reasoning behind the model structure and data.

4.2.1 Energy scenarios

It is of interest to this thesis to project the future inflow of blades to estimate future energy cons. GHG emissions and costs associated to future turbines' decommissioning. The outflow is important insofar as it is used to correct the projected inflows by accounting for annual outflows. Additionally, it can potentially be used to assess the degree of the problem of decommissioning WTB in the future.

To project the future blade inflows the following 7 energy scenarios have been assessed:

- AF19 [11], [14].
- Wind, Biomass, Bio+, Hydrogen & Fossil [15].
- IDA [16].

The scenarios are clustered by their sources above.

The most recently produced scenario is AF19, which has been used to define the inflow distribution for the other scenarios, since such a distribution has not been defined for these. Since this inflow distribution is only defined up until 2040, the remaining 10 years of the investigated period have been projected linearly as the average inflow of 2020-2040. This seems to generally, be a fair assumption due to AF19's recency.

4.2.2 Lifetime

As mentioned earlier, there is a strong trend in increasing the size of wind turbines, and their blades, which is likely to increase the use of CF or HF in the composite material. Currently, this seems to be the main expected change in the material type used for the future turbines.

The size increase and general increase in the number of turbines is followed by an increase in total material use. For glass fiber, close to a threefold increase in GF stock used in the wind sector is predicted in the period 2020-2050 [33]. Whilst no sources predicting the use of matrix materials have been found, it is believed that this material stock will follow the stock of GF somewhat proportionally up until 2050.

The latest data on the lifetime of Danish turbines is depicted in Figure 16.

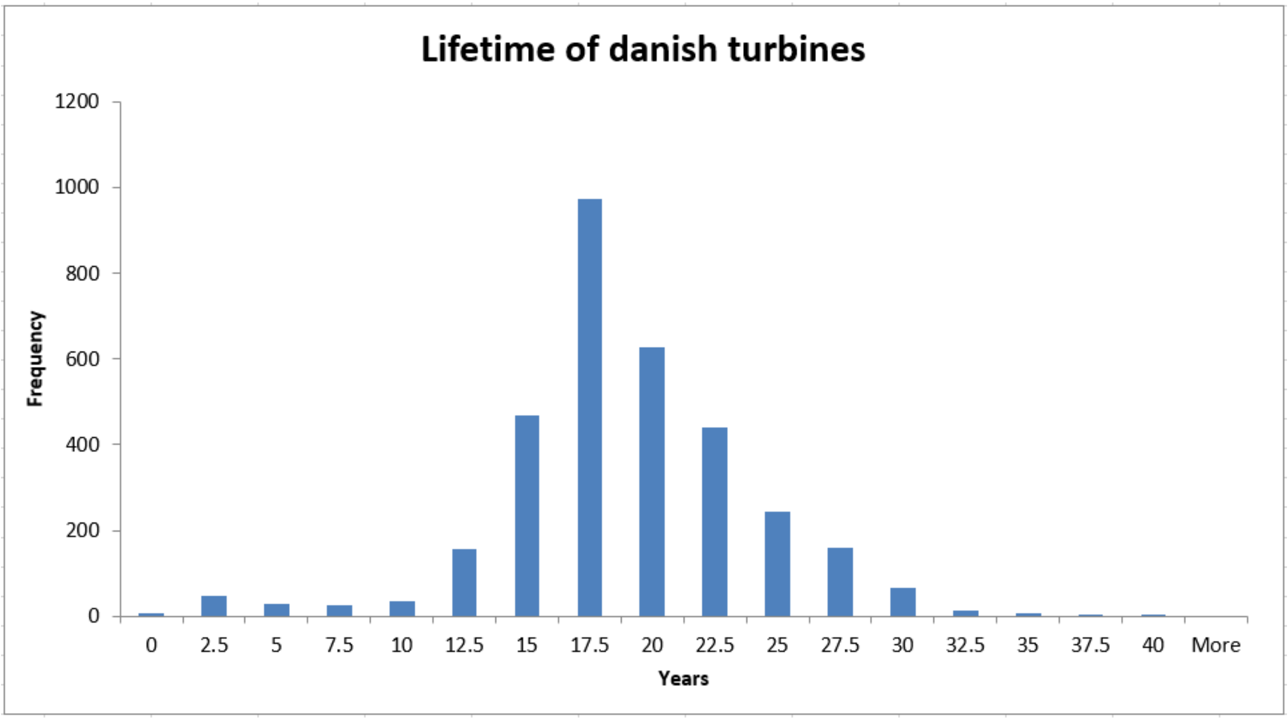

Figure 16- Lifetime distribution of Danish wind turbines. The data is derived from the Master Data Register.

The average lifetime is, for the most recent data, 17,75 years, which is a slight increase. This number is expected to increase, as the market for reuse is developed, though no source projecting the increase has been found, though a lifetime for future Danish offshore wind farms of 30 years is used in LCOE calculations [58],[61]. It should be noted that the lifetimes of 17,75 have been calculated from decommissioned Danish turbines, meaning they are likely already obsolete for turbines currently in operation. The average lifetime calculated from already decommissioned turbines is not representative of offshore turbines, since only few of those have been decommissioned at this point, due to their late introduction into the energy sector. Whilst the lifetime is often set to be 20 years for onshore turbines in the literature, it seems more appropriate to use historically representative data for this category of turbines. However, for future turbines, as well as already installed offshore turbines, a more specific lifetime should be used.

To project the future blade weight outflow, a Weibull distribution will be used, which will account for the various lifetimes of the different turbine categories [35]. The average lifetimes of the turbine groups are as follows:

- 17.75 years for already installed onshore turbines.
- 22 years for onshore turbines installed in the future.
- 25 years for already installed offshore and nearshore turbines.
- 28 years for offshore and nearshore turbines installed in the future.

Whilst many Danish turbines are part of pilot projects, which would skew the average lifetime, it has still been chosen to use historic lifetime data for the already installed onshore turbines [59]. The higher lifetime for future turbines is derived from the fact that they are designed for higher lifetimes, and due to future developments in refurbishment and blade design. The value of 28 years is about the average of the interval used by Energinet for future offshore turbines [11].

To acquire a sense of the impact of changes in average lifetime, AF19's outflow will also be projected for different average lifetimes in the sensitivity analysis.

4.2.3 Expected WTB capacities

The blade inflows [tons] of each energy scenario was calculated using the expected installed capacities in highlighted years. For the case of AF19, the expected installed capacities were undefined for 2050. Therefore, the offshore capacity of 2050 was assumed to be equal to the average of the other cases, whilst the onshore capacity was equal to AF19's onshore capacity in 2035. The reason it is equal is to accommodate the onshore capacity of AF19 being quite unlike the other cases.

The table below shows the expected installed capacities.

	2020		2035		2050	
Scenarios	**Offshore MWe**	**Onshore MWe**	**Offshore MWe**	**Onshore MWe**	**Offshore MWe**	**Onshore MWe**
Wind	1700.8	4400	5000	3500	14000	3500
Biomass	1700.8	4400	3500	3500	5000	3500
Bio+	1700.8	4400	2100	3500	2500	3500
Hydrogen	1700.8	4400	6000	3500	17500	3500
Fossil	1700.8	4400	2150	3500	5000	3500
IDA	1700.8	4400	5887	3875	14000	5000
AF19	1700.8	4400	6490	5362	9667	5362

Table 5- Installed capacity by year for the investigated energy scenarios. Red numbers denote above mentioned estimations [14], [15] [16].

Note how all scenarios share the same onshore and offshore capacity for 2020, since this is current data from the Master Data Register.

The inflow in blade weight has been calculated under the assumption that all future onshore turbines have a capacity of 3.5 MW, whilst future offshore & nearshore turbines have a capacity of 8 MW. This is in line with the most recent average annual capacities derived from the Master Data Register, shown in Figure 23 and Figure 25, as well as the assumptions used in other studies [61].

Since the different energy scenarios have different expected capacities for the highlighted years, their respective outflows will differ. This, in turn, will impact the inflow required to reach the expected capacity. This will be accounted for, for each energy scenario individually.

4.2.4 Step process of inflow & outflow projections

The step process of projecting the future annual blade outflow in tons is depicted in Figure 17.

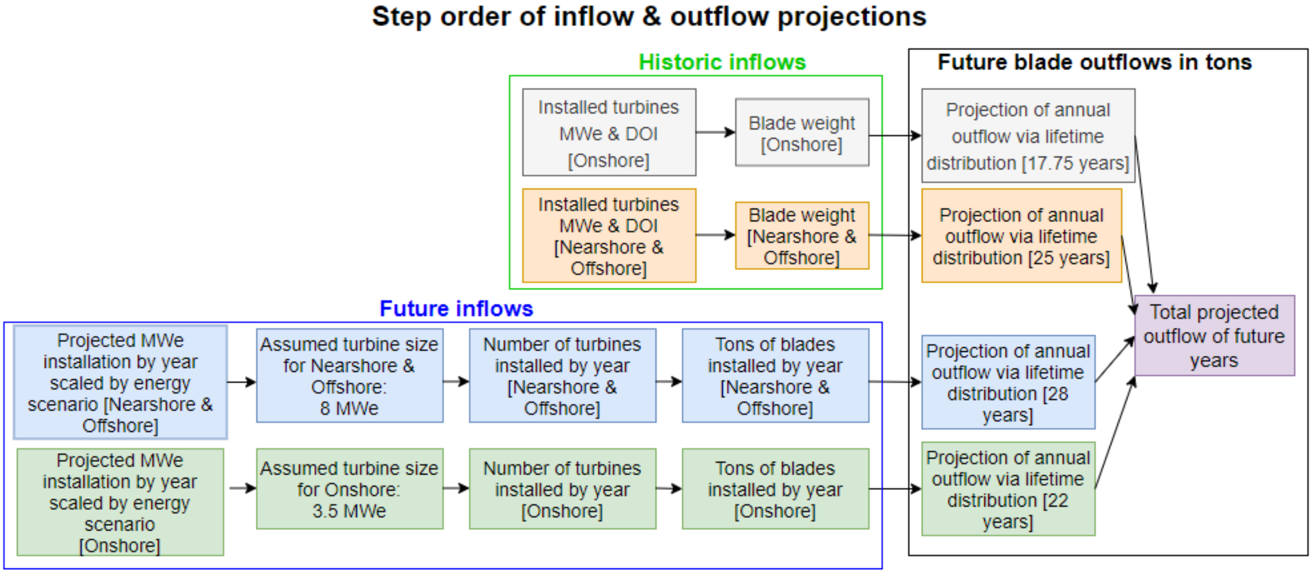

Figure 17- Step order of inflow & outflow projections. DOI denotes Date of Installation. Grey: installed onshore, Orange: Installed off- & nearshore, Blue: Future off- & nearshore, Green: Future onshore.

The step processes of the 4 previously discussed WT categories are color coded. Note how installed turbines have a significantly shorter step process, since their capacities, and thereby their total blade weight, have already been defined. Note that the future inflows have been projected for all previously discussed energy scenarios, which results in multiple outflow profiles.

4.2.5 Model validation

The validation of the model was carried out after results had been simulated. Figure 18 depicts projected outflows between 1995 and 2020 using the model and historic data. It should be noted that a few turbines had wrong decommission dates in the Master Data Register and were hence excluded.

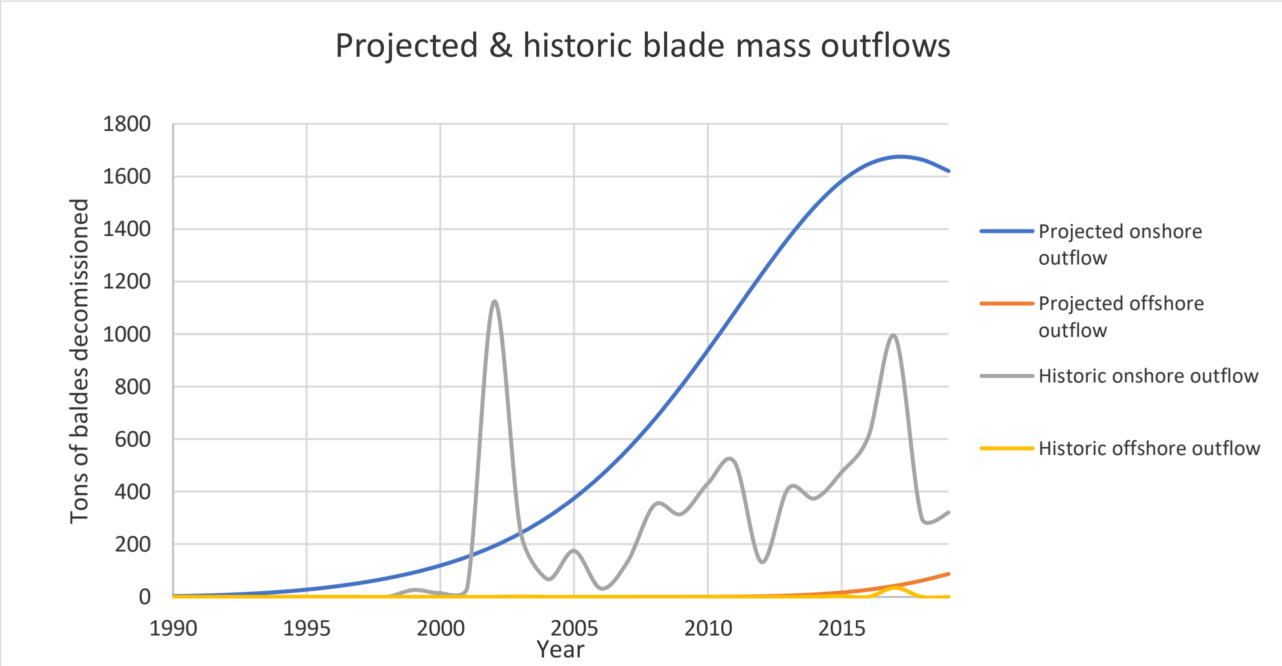

Figure 18- Projected and historic blade mass outflows

As can be derived from the figure, the projected and historic outflows do not have the same profiles, though the projected and historic outflows are still similar in amplitude.

Though the outflow profiles do not strongly follow each other, the onshore outflow and the offshore outflows still somewhat follow the same amplitude. Additionally, only 9.2 % of blade mass installed between 1978 and 2020 has been decommissioned up until now, which means that even small deviations between assumption on lifetime and actual lifetimes will result in large variations at this point. This is because larger variations occur at the extremes of the used distributions, though only small variations occur at the median.

Lastly, many historic turbines in Denmark are considered pilot projects, for which a total decommissioning of the entire wind farm would be expected at EoL, and not decommission on a per turbine basis, which would explain more rugged profiles of the historic outflows.

Therefore, the model is considered validated.

4.2.6 Inflow & outflow projections

The projected inflows and outflows for the investigated energy scenarios are shown in Figure 19 and Figure 28.

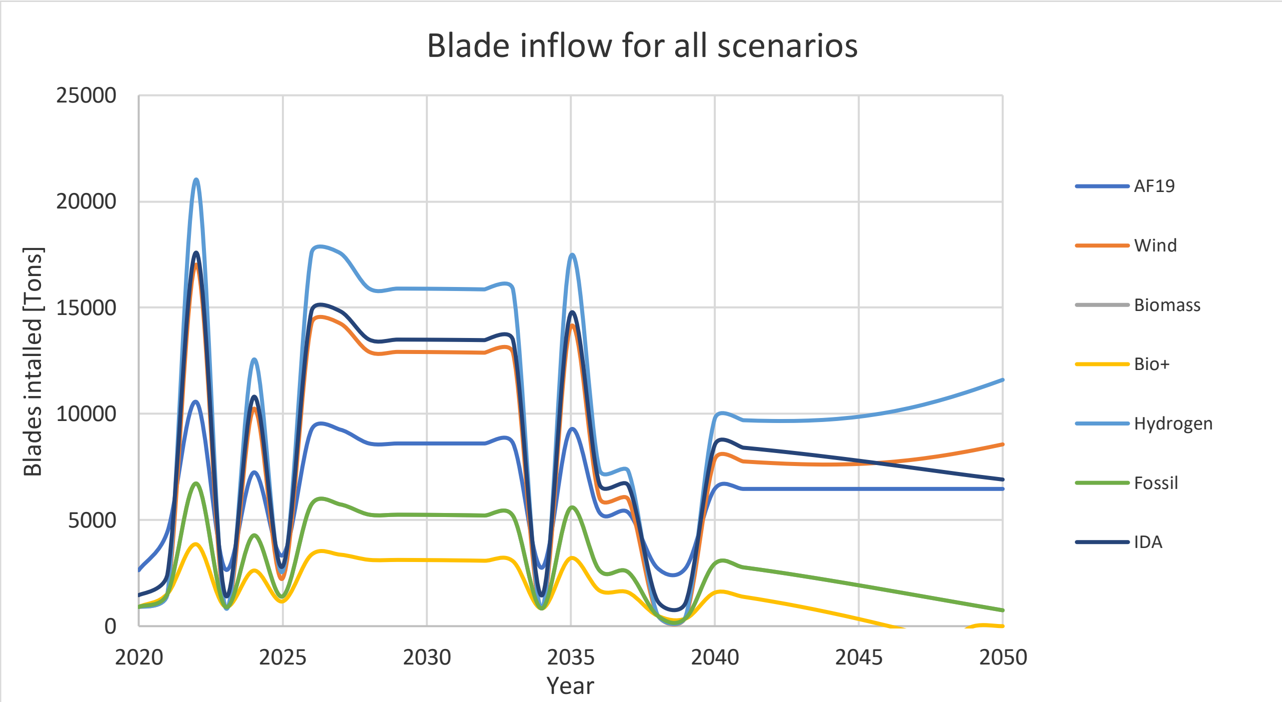

Figure 19- Blade inflows for all investigated scenarios.

Note how the inflows tend to follow the same general distribution, mostly having peaks and minimums in the same year. This is because the initial inflows are modelled after the inflow distribution of AF19. Differences in the inflows all stem from either difference in expected capacities by year or the accompanying differences in outflow, which means the inflow has been adjusted to reach the expected capacity. The last couple of years in the Bio+ case had negative inflow values which were substituted with values of 0.

This means that the inflow of the Bio+ scenario above would result in a slight overshooting of the expected capacity of the last years of the investigated period. This is an argument against simply scaling the same inflow distribution to fit each case, but since no alternative inflow distributions were found during research, and since this problem only occurs for a couple of years for one of the scenarios, this is considered negligible.

4.3 GIS-model

This section describes the method used to develop the GIS-model together with the assumptions and method relating to transport and turbine decommissioning. In short, a GIS-model is a mathematical model of a geographic system, in this case, Denmark. The model allows for mathematical optimization of the route distances driven during the transport part of the WTB decommissioning.

4.3.1 Coordinate systems & GIS software

Thousands of registered coordinate systems (CRS) exist, though only few yield high accuracy simulations for the Danish geographical area [62]. For the GIS-model, the CRS for the reference frame is "European Terrestrial Reference System 1989 (ETRS89). The plane coordinates used are Universal Transverse Mercator (UTM) Zone 32N. In short: ETRS89 UTM 32N. This has been used since it is generally regarded as the most accurate CRS for Denmark, though other CRS are more accurate in certain areas [63].

The software chosen to perform calculations on data represented by the above CRS is the free and open source; QGIS 3.4.15 Madeira [64].

4.3.2 QGIS tools & plugins

The tools used were:

'Measure area' for measuring investigated offshore areas, 'measure distance', for measuring the distance between the centroid of a wind farm and the closest Danish harbor, and 'Polygon centroid' for determining the centroid of the given offshore wind farm.

The plugins used in QGIS were: NNjoin, which calculates the straight distance between points, which was used to calculate the distance between offshore wind farms and harbors, accounting for necessary maneuvering, and QNEAT3.

QNEAT3 is a route optimization plugin, which for the purpose of this case has been set to minimize distance traveled between two points along a road network, in this case the Danish road network.

The Danish road network required for QNEAT3 to calculate the shortest driving route for every turbine was downloaded from Geofabrik's free download server [65].

4.3.3 Installed turbines

4.3.3.1 Placement of installed turbines

The coordinates for registered turbines installed in Denmark were acquired through the DEA's Master Data Register [58].

Out of the total 6250 turbines, 612 lacked coordinates, and were hence excluded. This left 5638 turbines to be projected onto a map, and have their decommissioning optimized. below is a representation of the placement of Danish turbines:

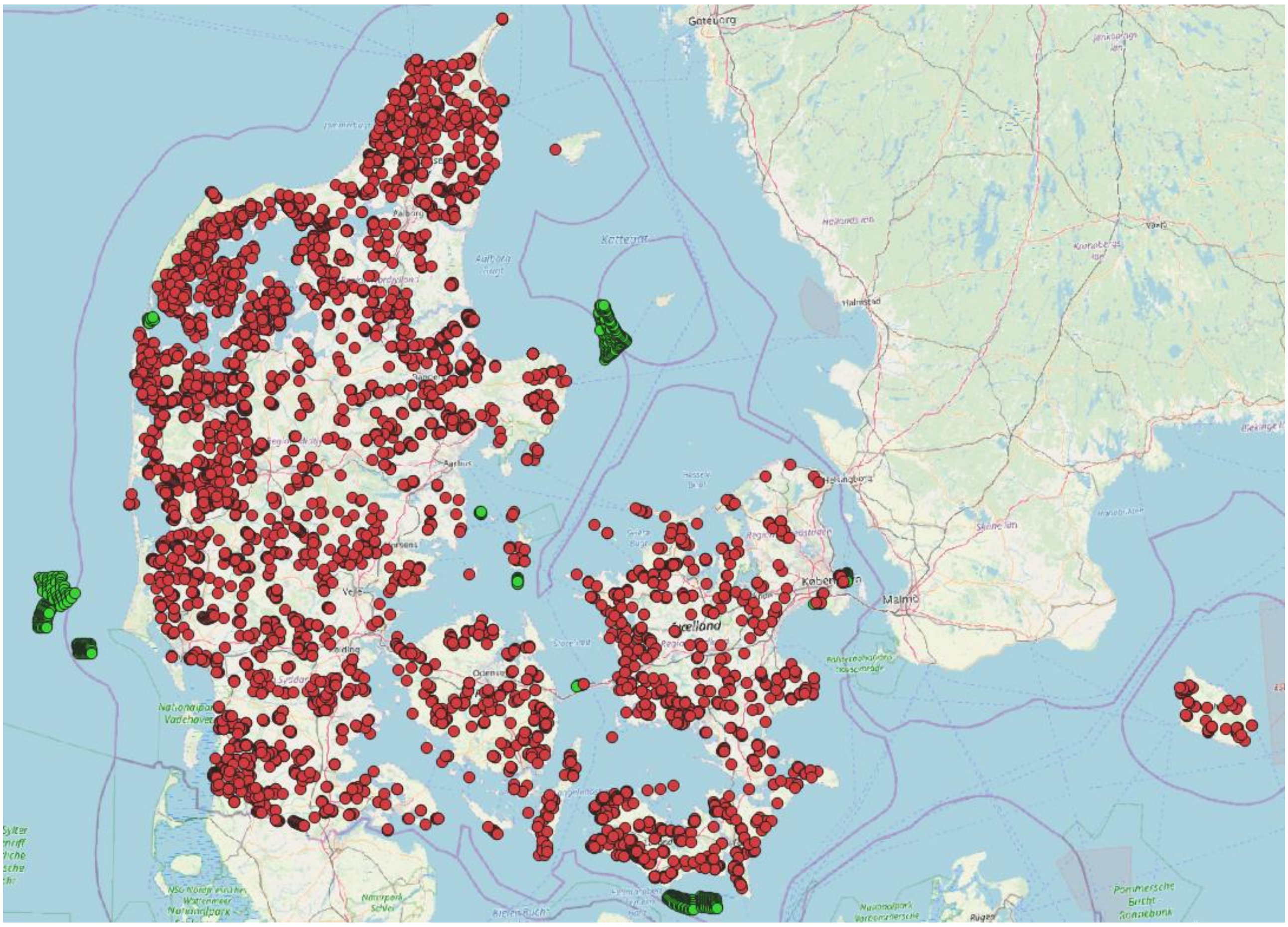

Figure 20- Turbines in Denmark. Offshore (green) and Onshore (red).

As can be derived from the figure, the onshore placement is quite evenly distributed, disallowing for using aggregate positions in the model without investing a large effort into doing so. Therefore, the distances will be calculated for each turbine.

4.3.3.2 Course of action for installed turbines

The general course of action for the GIS- model in the case of already installed turbines is illustrated in Figure 21.

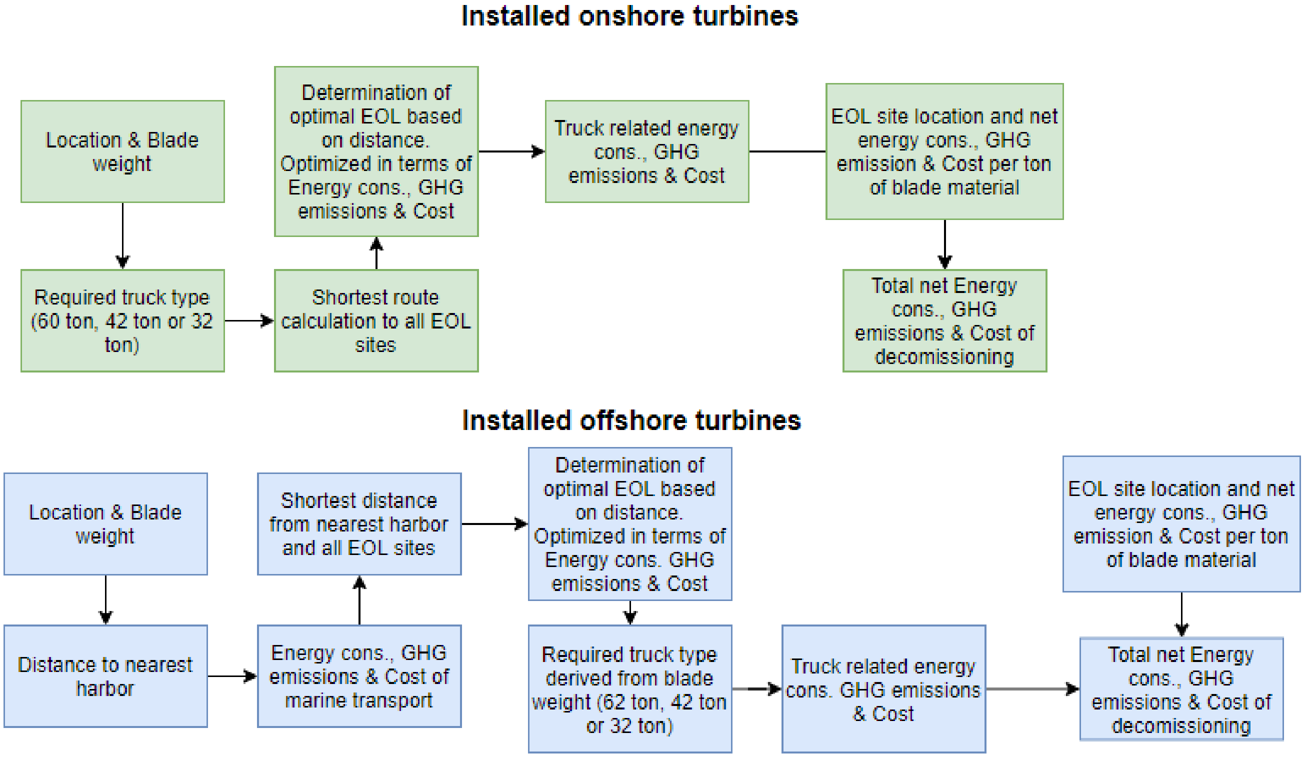

Figure 21- Course of action for the GIS-model, for already installed turbines

The courses of action presented above are quite alike, differing only with the added aspect of marine transport for already installed offshore turbines. It should be noted that the EoL data on energy cons. GHG emissions and Cost have been derived for; GF, HF and CF, in the comparative analysis of EoL types, but that it is assumed that all fibers in current Danish turbines are glass GF. Since EoL variables have been calculated for the other fibers as well, this can be changed if contradictory data is provided.

The following components of Figure 21 will be discussed in the coming sections:

- Blade weight estimation (Blade weight not provided by the Master Data Register)
- Truck Energy cons., GHG emissions & Cost, and truck types and the background for not using 1 truck type
- Marine transport

4.3.4 Future wind turbines

This subsection concerns itself with the future developments in MW capacity installed, material distribution for the blades, placement, size and more. Figure 22 illustrates the expected developments for installed capacity by WT category.

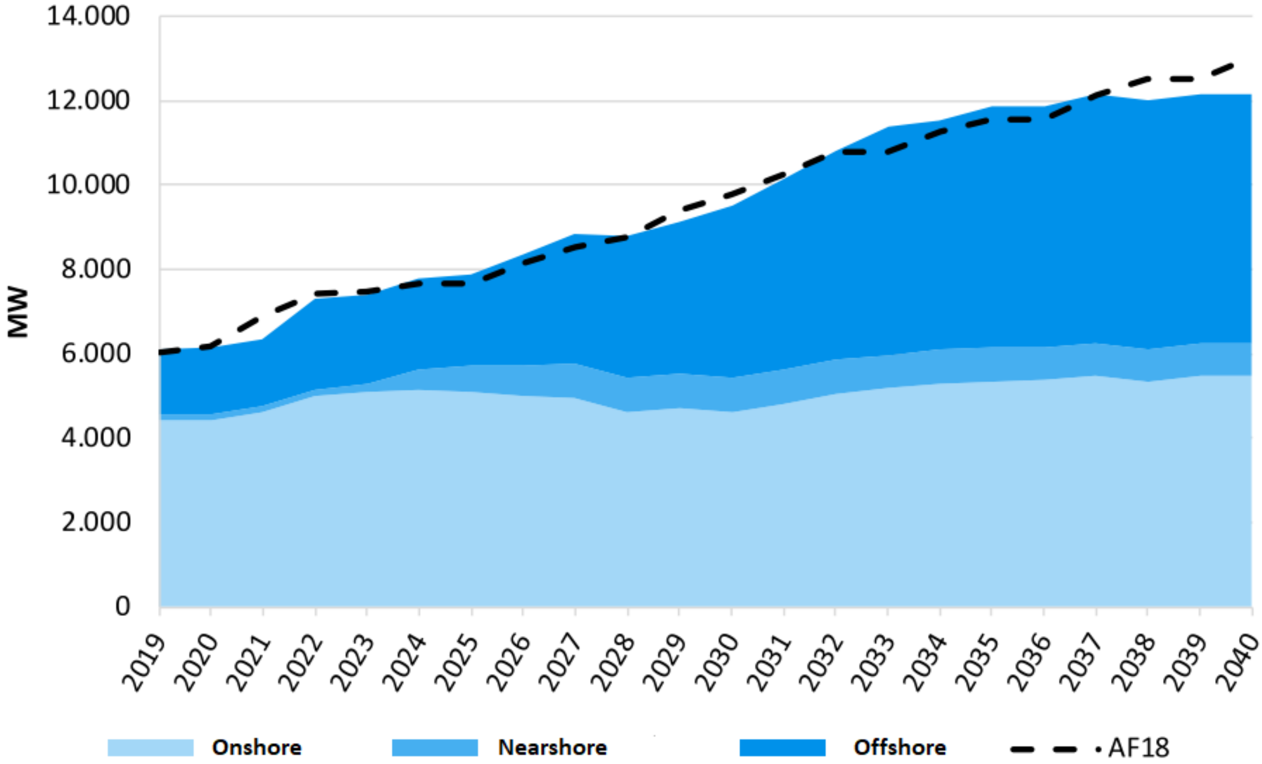

Figure 22- Development of installed MW wind capacity in Denmark (Energy scenario AF19). Taken from [11].

4.3.4.1 Future Onshore

Depicted in the Figure 22 is only a slight increase for installed onshore capacity in Denmark. There is a strong lack of data on were future onshore turbines will be installed, and so, it is reasonable to assume that future onshore turbines will be installed with the same spatial distribution as the currently installed ones. In terms of the number of onshore turbines, it is reasonable to assume that fewer turbines per MW capacity will be installed, though the technical developments in size and capacity do not have free reign for onshore turbines, for which local citizens may be more opposed to large, visually displeasing structures being installed. However, there has been a strong trend in installing increasingly larger onshore turbines in Denmark as depicted in Figure 23:

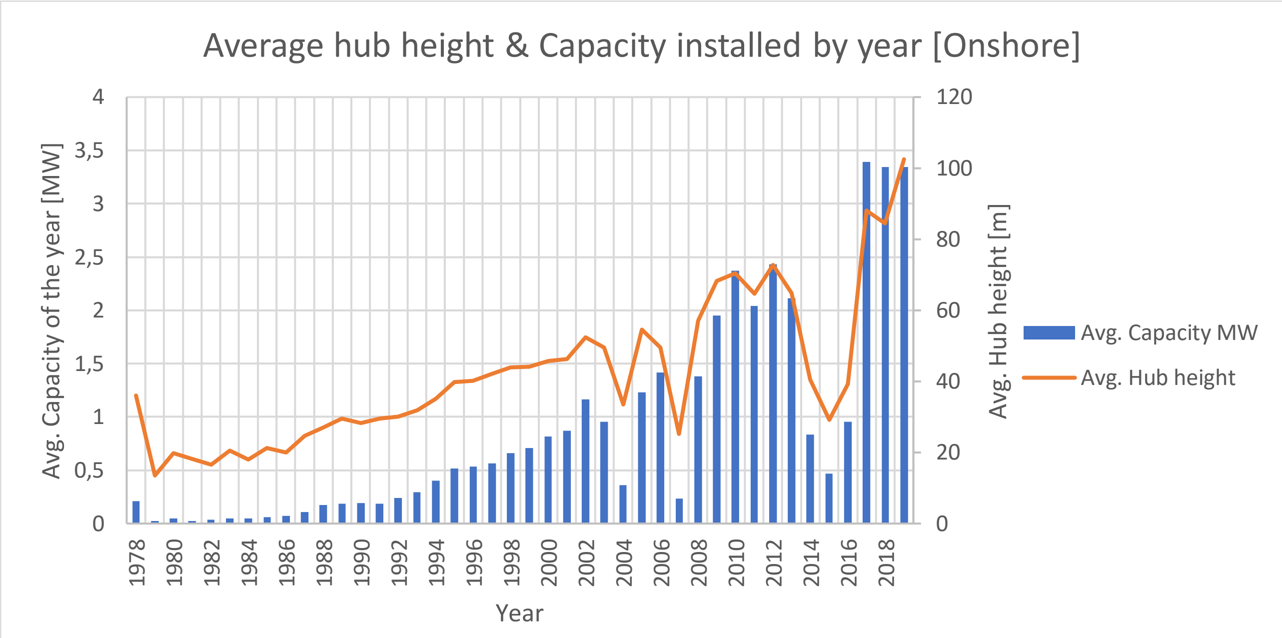

Figure 23- Average hub height [m] and capacity [MW] by year for onshore wind turbines. Data from The Master Data Register.

This trend may override the local resistance to continuously larger onshore turbines being installed, though the specific degree to which this may occur is not known. The combination of the size tending to increase, and the installed capacity predicted to only increase slightly, suggests that the future onshore turbines will be quite a bit larger, on average, than is the case currently. This is supported by Figure 23.

Whilst the material intensity of fiberglass is expected to decrease [6] the rotor mass intensity is expected to remain fixed for onshore turbines up until 2050, meaning that the composite stock is assumed to follow the onshore capacity [35].

4.3.4.2 Future Offshore

Currently, many sea areas have been reserved for either preliminary investigations or governmental contract auctioning for constructing wind farms. The areas for such offshore areas can be seen in Figure 24.

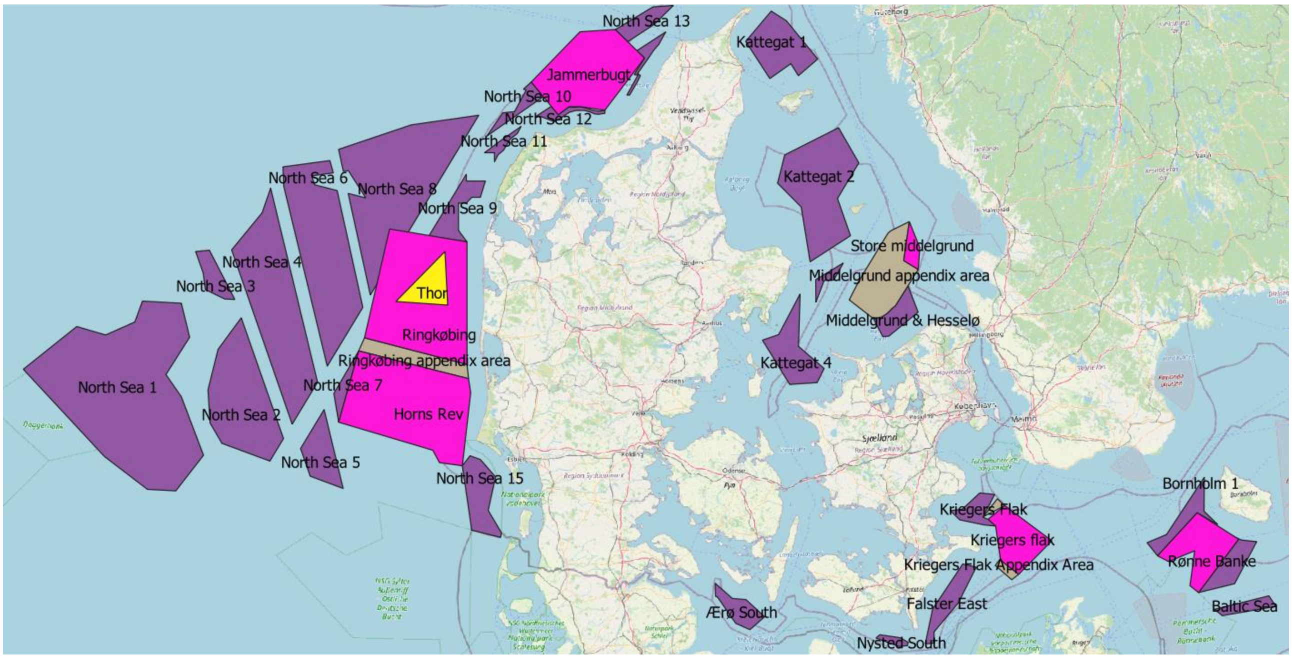

Figure 24- Reserved areas for screening and auctioning. Purple: New area reservations. Pink: Existing area reservations. Brown: Appendix areas for screening. Yellow: Thor wind farm (future). Green: Reserved nearshore areas.

It is reasonable to assume that new offshore wind farms will lie within the colored areas in Figure 24, as is the case for Thor, since these are the only areas currently reserved [66], [67].

Currently, the Danish government has a goal of installing 3 wind farms before 2030, the first of which is Thor (depicted in Figure 24 in yellow). While its location is not final, it is the most certain data on future Danish wind turbines placements. Its capacity is planned to be 800 MW-1000 MW [67], whilst the 2 following farms, whose location has not been decided yet, will be 800 MW or above. The DEA is evaluating the above areas according to multiple variables, including wind profiles, raw material interests, water depth, military zones and many more.

As there is a trend in the size of onshore turbines increasing, so is there a trend for offshore turbines in Denmark. This trend is depicted in Figure 25 for offshore turbines currently in operation.

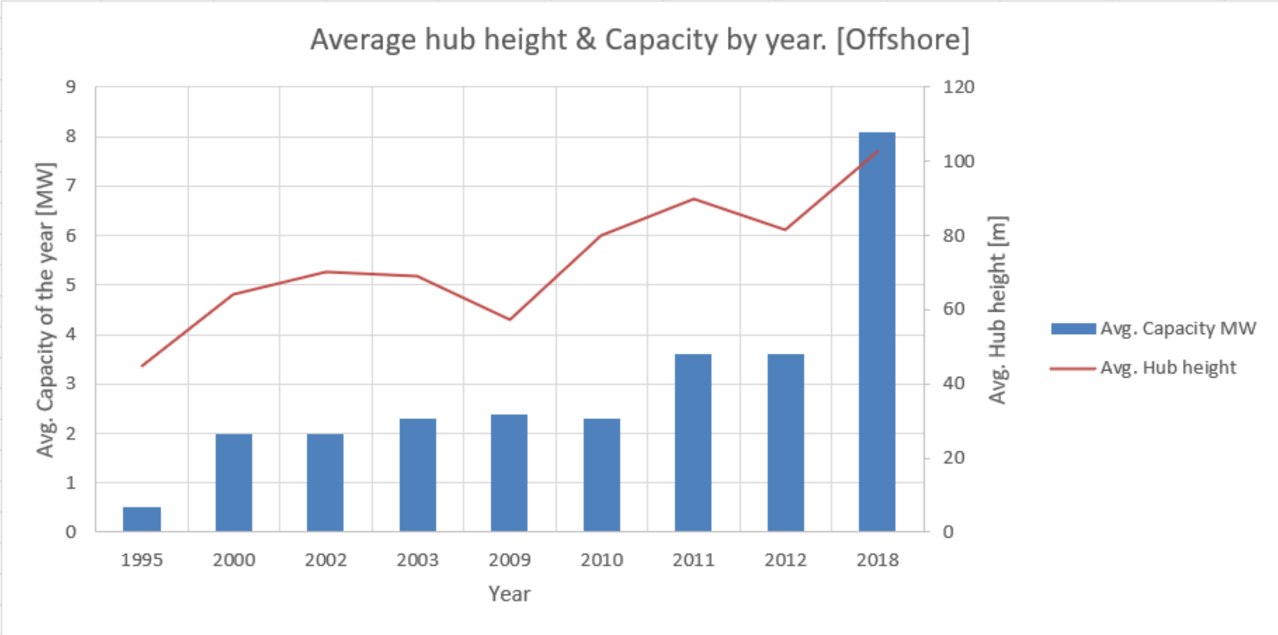

Figure 25- Average hub height & Capacity by year [Offshore]. Data from The Master Data Register.

As can be derived from the figure, a steady increase has occurred for most of the period depicted, up until 2018, in which a heavy increase was experienced, due to the size of Horns Rev 3's WT [68]. Note how only a few years are projected, since only these years have had installations of offshore wind turbines in Denmark.

4.3.4.2.1 Scenarios & Layouts for future offshore wind turbines

From the investigations of Danish sea areas, 4 areas were highlighted for installing future offshore wind farms.

- The North Sea
- Jammerbugten
- Hesselø
- Kriegers flak

The 4 areas were evaluated on their ability to support an 800 MW wind farm, accounting for wind profiles, sediment conditions, environmental disturbances, and human interest in the areas. Multiple layouts (turbine placements constituting a wind farm) were evaluated for each area, and the LCOE was estimated, which works as a general guideline as to where future offshore wind farms will be installed. At least 2 layouts were investigated for each area, all of which with an 800 MW farm, except for Kriegers flak, for which one of the layouts had an installed capacity of 240 MW, which was made to optimize for turbine shadowing. This optimization was due to the collective area of Kriegers Flak A & B being too small to satisfy the condition of 0,22 km^2/MW [61].

All the layouts and areas are depicted in Figure 26.

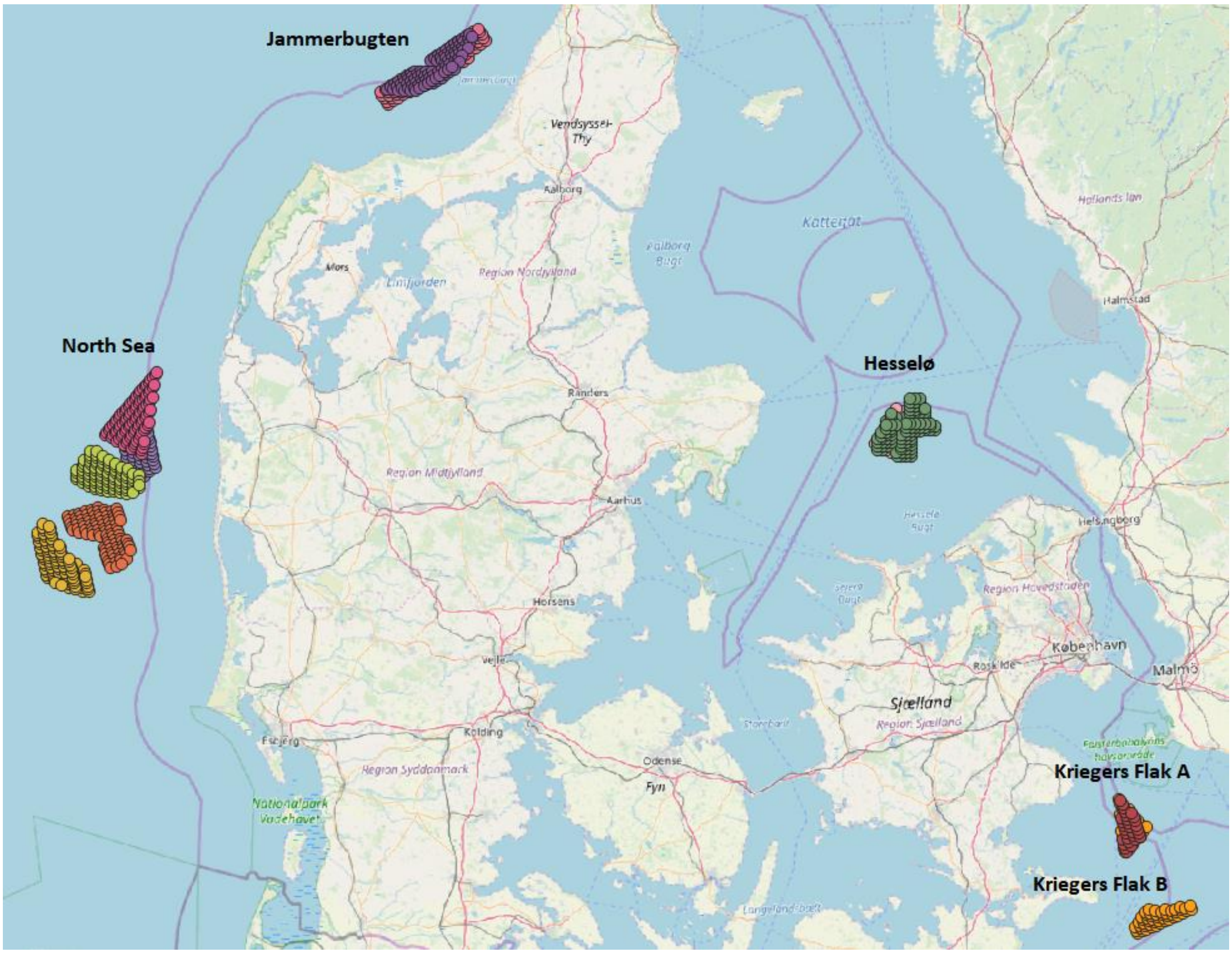

Figure 26- The 4 areas highlighted and investigated after screening of Danish sea territory.

To see the individual layouts, see Appendix C.

4.3.4.2.1.1 Future offshore installations

The method behind calculating the energy consumption, GHG emissions and Cost for future turbines is largely the same as for installed turbines. The main difference is that the prediction of the placement of offshore turbines will be done by assuming that the placement will be wherever the LCOE is lower.

The installed capacity by energy scenario and offshore area can be seen in Table 6.

Layout	Maximum Capacity	AF19	Wind	Biomass	Bio+	Hydrogen	Fossil	IDA
Nordsøen 1	800	800	800	800	800	800	800	800
Hesselø 1	800	800	800	800	800	800	800	800
Hesselø 2	800	800	800	800	800	800	800	800
Nordsøen Syd	800	800	800	800	159.8	800	800	800
Jammerbugt 2	800	800	800	800	0	800	800	800
Jammerbugt 1	800	800	800	800	0	800	800	800
Kriegers Flak 2	240	240	240	240	0	240	240	240
Thor	800	800	800	19.8	0	800	19.8	800
Kattegat 1	1524	1524	1524	0	0	1524	0	1524
North Sea 9	753	753	753	0	0	753	0	753
North Sea 10	349	349	349	0	0	349	0	349
North Sea 11	141	141	141	0	0	141	0	141
North Sea 12	246	80	246	0	0	246	0	246
Kattegat 2	3513	0	3513	0	0	3513	0	3513
Kattegat 4	1266	0	1266	0	0	1266	0	1266
North Sea 8	6463	0	428	0	0	3928	0	428
Summed capacity	**20095**	**8688**	**14060**	**5060**	**2560**	**17560**	**5060**	**14060**

Table 6- Theoretical maximum capacity together with installed capacity in the given area for the investigated energy scenarios in MWe.

Certain areas have been excluded since their areas are reserved for Thor wind farm, whilst others do not work in practice due to unacceptably high WT densities. Which can be seen in the excel appendix: Future offshore net EoL costs.

In the case of future onshore turbines, it is assumed that they will be placed in existing onshore turbines' stead. Therefore, the average distance will be scaled up to fit the future onshore capacity for each energy scenario. This is not entirely true, but due to the spatially diffuse placement of onshore turbines, this is believed to be a fair assumption [69].

For both future onshore turbines and future offshore turbines, the future inflows, from the Mass flow model are used as inputs for the GIS-model.

The theoretical capacities are calculated by scaling the capacity relative to the area. This can be done since the wind profiles have negligible differences [70], as can be seen in Appendix D. This means that twice the area would yield ~twice the theoretical capacity. The reason why Nordsøen 4, Nord, and Nord 2 have been excluded is that Thor is planned to be installed in their area, making these layouts unlikely, and technically impractical. Lastly, Kriegers Flak 2 was chosen above Kriegers Flak 1, since Kriegers Flak 1 has an undesirably high turbine density [61].

From this point, the course of action for future turbines in the GIS-model is the same as for currently installed turbines, shown in Figure 21.

4.3.5 Transport

There are multiple methods of transport related to the decommissioning of WTB. However, the length of contemporary and future WTB restricts the use of railroads for transport. Additionally, railroads would require truck for transporting the blades from the turbine site to the loading dock.

Therefore, the transport options are as follows:

- Special transport offshore (transport of whole blade by use of crane vessel)
- Truck transport with large trucks (truck type dependent on blade size) [10]

Unfortunately, the exponential length to weight ratio of blades makes standard transport less attractive since trucks with high payloads cannot freight a blade though its weight may be far below the peak payload. This is only expected to become more of a problem as emerging turbines, whose blades are much larger, are installed [71].

This creates a strong incentive for shearing of the blades on site, which is one of the main things that can be done to improve efficiency in transport logistics [26].

This is likely most lucrative for offshore turbines, since one shearing installation can be made and used for all the turbines of the offshore wind farm. If done for onshore turbines, the shearing installations would need to be transportable, which may not be preferable to simply using a special transport from the turbine site to the shearing site. However, shearing is assumed to not occur until the final EoL treatment in this model.

4.3.5.1 Trucks

As mentioned, the structure of WTB limits the types of transport that are available. Additionally, the dimensions mean that the size of the used trucks is displaced upwards [72]. This will continue to be the case when on-site shearing is not performed. This increases the cost and environmental impact of freight, since the base fuel consumption is higher for larger trucks.

The fuel consumption of different size classes of trucks is available, but since most trucks will not be loaded fully, it is important to account for the fuel consumption by payload.

Unfortunately, such data is not available for 32 tons trucks, and the fuel consumption has therefore been scaled from such data on 42 tons trucks and 60 tons trucks [73].

From the fuel consumption regression, the GHG emissions and costs related to transport were calculated. The way in which the truck type used is determined is illustrated in Table 7.

Blade weight [Tons]	Truck type
<10	32 ton truck
10<20	42 ton truck
>20	60 ton truck

Table 7- Determination of truck type based on weight of 1 blade of the given turbine

This table is based off assumptions meant to account for the impractically transportable shape of the blades.

4.3.5.1.1 Truck route calculation

The shortest route calculation was, calculated using the QNEAT3 plugin in the case of onshore distance, and the NNjoin plugin in the case of Offshore distance.

The Danish harbors and the produced EoL sites are shown in Figure 27.

Figure 27- Danish Harbors. Data from Danske Havne [74] *& produced EoL site locations and types.*

Note how the EoL sites are all placed in Denmark, though it is unlikely that all types will be found at commercial scale, and even more unlikely that they will be found in Denmark. This is not a problem since the purpose of the data represented in Figure 27 is to demonstrate the functionality of the GIS-model.

The reason why the EoL sites had to be artificially produced is because not all EoL options are available at a commercial level at present. Additionally, certain decommissioning companies did not want to disclose which EoL type they use.

The purpose of the EoL sites is to prove the functionality of the model, so artificial data for the EoL sites will suffice.

The reason why Rønne Harbor is excluded will be elaborated in in 'Harbors & Islands'. The reason that reuse and repurposing are not included as EoL sites is that finding specific data for these proved largely unavailable. Also, they are considered deposits and not final EoL options.

4.3.5.1.2 Acceptable truck freight distance by EoL

The savings in terms of energy, GHG emissions and cost related to each EoL option were presented earlier in this thesis. However, these calculations do not account for the impact of transport.

The impact of transport by truck will be accounted for by calculating at what transport distance the most prioritized EoL option loses its priority to the second most prioritized EoL option, and so forth. This has been done for; net energy expenditure, net GHG emissions and net cost. Importantly, the marine transport is not included in this optimization since it is assumed that the high costs of operation results in always freighting to the nearest harbor.

Furthermore, the calculation has been done for 3 blade sizes; 5 tons (denoted; A), 15 tons (B), 25 tons (C).

The calculations assume that diesel is used for the trucks, accounting for truck driver salaries and the energy- GHG- and cost efficiency of various EoL technologies [13], [75]–[79]. Lastly, this has been done for 3 blade types; Full glass fiber, HF and Full CF.

The results are presented in Table 8.

Distance to be driven before the second EOL priority overtakes the first EOL priority [km]			
	Energy A	**Energy B**	**Energy C**
Full glass fiber	1862.4	819.7	526.1
Hybrid fiber	4063.8	1788.6	1148.0
Full carbon fiber	8233.1	3623.7	2325.8
	GHG A	**GHG B**	**GHG C**
Full glass fiber	655.6	288.5	185.2
Hybrid fiber	4089.5	1800.0	1155.3
Full carbon fiber	9923.8	4367.8	2803.4
	Cost A	**Cost B**	**Cost C**
Full glass fiber	272.3	202.7	161.6
Hybrid fiber	276.8	206.1	164.2
Full carbon fiber	1097.8	817.3	651.4

Table 8- Distance before second EoL priority overtakes the first EoL priority.

Energy A denotes how many additional kilometers can be driven before a blade of 5 tons (A) has its first EoL technology priority overtaken by its second EoL technology priority, in terms of energy consumption. GHG B denotes the additional kilometers that can be driven before a blade of 15 tons (B) has its first EoL technology priority overtaken by its second, and so forth.

The largest distance is had by Full carbon fibers GHG A, with a value of 9923.8 km. This means that the second highest prioritized EoL technology would need to be almost 10 thousand kilometers closer than the highest prioritized EoL technology to be the most preferred one, in terms of GHG emissions.

The lowest value overall is had by Full glass fibers' Cost C, at 162 km. This means that the second highest EoL technology priority would become the highest priority if it were at least 162 km closer than the highest priority, in terms of cost.

Note how blades made from CF tend to have higher values, since the larger energy expenditure, GHG emissions and costs associated to their production increase the potential savings from effective decommissioning.

Importantly, the lowest values tend to be those relating to cost, which is likely the variable that the market will optimize for.

Note that Table 8 only shows the distance to be driven before the second priority overtakes the first. The same calculations have been done for all investigated EoL options and can be seen in the excel appendix: Truck- Distance of acceptance. This means that the EoL technology with the highest cost to it could, theoretically, be the cheapest EoL option when accounting for transport costs.

4.3.5.2 Multitask decommissioning vessel

For installation and deinstallation of turbines in the order 3MW-10MW, a minimum crane vessel lifting capacity of 2000 tons is recommended [80]. Finding data on specifications on such boats is difficult, due to the closed nature of such markets. Therefore, it is assumed that 1 model will be used for all dismantling of offshore turbines, namely, the OSA goliath, which, using its Liebherr MTC 78000 slewing crane, can allegedly lift a maximum of 2000 tons. As mentioned, data on specifications is hard to come by for such vessels.

Therefore, the fuel consumption of the vessel crane is derived by scaling down the fuel consumption of a vessel weighing 70.000 tons linearly. It is known that fuel consumption is related to many variables, such as wind speed and direction, vessel form, fuel type, speed traveled, vessel weight etc., and so, the fuel consumption should be regarded as a qualified guess, more than an exact value [81].

The energy consumption, GHG emissions and costs per kilometer can be seen in the excel appendix: Marine freight expenditures [81]–[83].

The size of the OSA Goliath allows for transporting all 3 blades of the given offshore turbine at a time, but whether the on-deck installations allow for this depends on which boat specifically is used at the time of decommissioning. It is assumed that the vessels used have the capabilities to transport all 3 blades at a time, which means 1 roundtrip is performed for each offshore turbine during its marine transport.

For the purposes of this project, it has been assumed that transport of offshore blades from initial location to port is done by the crane vessel (multitask decommissioning vessel) though it might be more economically viable to only use the crane vessel for dismantling and loading freight boats for cases in which multiple turbines need to be decommissioned at the same time. One should also bear in mind that which vessel is used depends on many factors, including the size of the turbine, the depth, the seabed type etc.

This variability is not only relevant for the vessel used, but also for the time frame (e.g. only decommissioning during warmer months), whether barge vessels are required, and much more [84]. The assumptions made in this thesis should therefore be fitted to the relevant decommission scenario investigated.

4.3.5.3 Harbors & Islands

In at least one case, it is possible that boat transport will be required twice, one time to the harbor of the island, and one time to the harbor of the mainland on which the EoL site is placed. This may be the case for Bornholm, if no EoL treatment plant is present on the island. Bornholm is the designated installation harbor for the German offshore wind farm Arcadis Ost 1 [74]. For the purpose of this thesis, all transport of Danish offshore windfarms close to Bornholm will simply be directly transported to a Danish bridged island or peninsula from which transport by truck is available, to minimize the high costs associated to marine freight.

5 Results

This section concerns the results yielded by the Mass flow model & the GIS-model. How they were yielded specifically can be seen in excel appendices: GIS-model & Mass flow model.

5.1 Mass flow model results

The outflows are presented below.

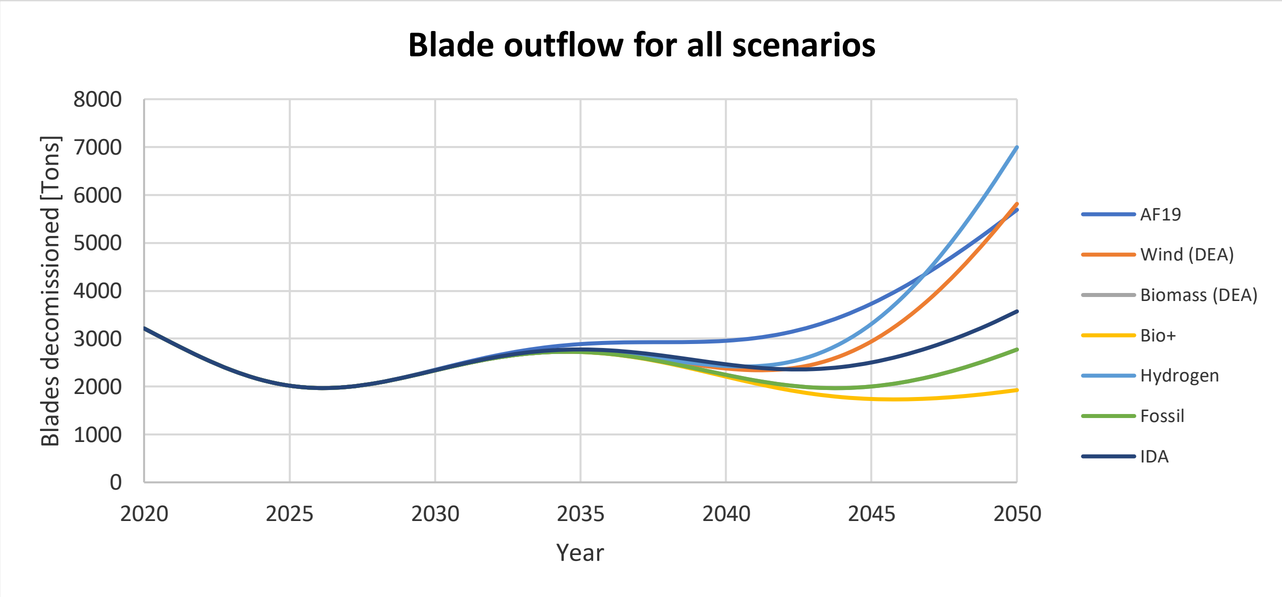

Figure 28- Blade outflow for all scenarios.

As can be derived from the figure, the outflows stay very similar up until around year 2033, from which they diverge. Note how the outflows can cross each other, which is a result of the different inflows of each case. Assuming each ton of blades requires 2 m^2 of landfill area, the average requirements of landfilling area of the investigated cases is equivalent to ~23 large football fields [85]. The accompanying WTB stock projections can be seen in Appendix E.

5.2 GIS-model results

The optimal EoL option is given in Table 9. It accounts for the fiber type of the blade and its placement.

Percent of WTB mass by EoL option (cost minimisation)				
EoL option	Onshore WTB	Offshore WTB	Future onshore WTB	Future offshore WTB
Solvolysis	50.05	51.3	50.05	9.16
HVPF	0	0	0	0
Fluidised bed	0	0	0	0
Pyrolysis	0	0	0	0
Mechanical Grinding	49.45	48.7	49.45	90.84
Incineration	0	0	0	0
Landfill	0	0	0	0
Cement kiln	0.01	0	0.01	0

Table 9- Percent of blade weight by optimal EoL option in relation to energy consumption, GHG emissions & cost.

From this, it can be understood that the impact of transport on which EoL option is optimal has a moderate impact. For the above EoL distribution, the EoL costs for the following turbine categories were calculated:

- Currently installed onshore turbines
- Currently installed offshore turbines
- Onshore turbines projected to be installed in 2020-2050
- Offshore turbines projected to be installed in 2020-2050

All the costs are relative to the reference scenario of landfill. Additionally, the results are calculated for the cheapest decommissioning scenario.

Lastly, the costs accounting for the benefits of the EoL are presented as well as the costs without the benefits of the EoL.

Net cost of cheapest decommissioning scenario [mio.DKK]										
Net cost with EOL benefits [mio.DKK]						Cost without EOL benefits [mio.DKK]				
Scenario	Onshore	Offshore	Future onshore	Future offshore	Total	Onshore	Offshore	Future onshore	Future offshore	Total
AF19	-60.72	-62.89	-124.55	-235.2	-483.36	37.90	111.48	62.35	447.80	659.53
Wind	-60.72	-62.89	-42.78	-383.54	-549.93	37.90	111.48	21.42	739.90	910.70
Biomass	-60.72	-62.89	-42.78	-153.4	-319.79	37.90	111.48	21.42	259.90	430.70
Bio+	-60.72	-62.89	-42.78	-78.01	-244.40	37.90	111.48	21.42	135.64	306.44
Hydrogen	-60.72	-62.89	-42.78	-463.0	-629.39	37.90	111.48	21.42	966.81	1137.61
Fossil	-60.72	-62.89	-42.78	-153.0	-319.39	37.90	111.48	21.42	259.87	430.67
IDA	-60.72	-62.89	-68.93	-383.0	-575.54	37.90	111.48	34.51	739.87	923.76

Table 10- Net cost of cheapest decommissioning scenario in million DKK, with and without the benefits of EoL.

Note how the cost benefits of EoL are sufficiently large to have a net negative cost for all investigated scenario and turbine types. This underlines the strong socioeconomic benefit of not simply using landfill as the decommission option.

The results in the right side of the table are the above-mentioned direct costs, which are what is expected to be paid to perform decommissioning. For the reference scenario of AF19, the expected direct costs per Danish capita for decommissioning all current WTB and all WTB projected to be installed in the period 2020-2050 is around an annual 3.7 DKK over the course of 30 years [86].

The accompanying energy consumption and GHG emissions of decommissioning can be found in Appendix F.

The energy consumption, GHG emissions and costs related to the decommissioning of individual onshore turbines, and offshore farms can be seen in the excel appendices: Onshore turbines net EoL costs & Future Onshore turbines net EoL costs.

Lastly, the proportion of the EoL costs constituted by transport are given in Table 11.

Proportion of total EoL costs constituted by transport	
Onshore turbines	86.50%
Offshore turbines	81.30%
Future onshore turbines	35.90%
Future offshore turbines	72.80%

Table 11- Percent of total EoL cost from transport.

As can be derived from the figure, a significant part of the EoL costs stem from transport, which underlines the importance of optimizing this part of the decommissioning. Note how the cost proportion of transport for future turbines is lower than their concurrent counterparts. This is mainly due to the increased average turbine size. The reason why the onshore transport cost proportion decreases as heavily as it does, is that the average size of future onshore WTB is much higher, which means the transport costs per unit of mass is lower. In part, this is also the case for future offshore WTB, but since the crane vessel has tremendous cost associated to its operation, the costs of future offshore WTB are not decreased as heavily.

The results presented in Table 9 and Table 11 describe how transport not only has a significant impact on which EoL option is optimal, but additionally constitutes a very significant part of the overall decommissioning cost.

6 Sensitivity analyses

The results of the sensitivity analyses are projected on the assumption that decommissioned turbines are replaced by new turbines in the same location. How they were yielded is available in the excel appendix: GIS-model.

6.1 Varying lifetimes

To investigate the impact of having selected different average lifetimes for Danish WTB, scenarios for which all turbines have the same average lifetime have been simulated for various average lifetimes, which resulted in similar, yet different inflow and outflow distributions, as can be seen in Appendix G. This also offers an insight into the effect of prevention on the cost of decommissioning.

From these projected inflows, the direct cost of decommissioning all turbines given various lifetime assumptions were projected using the GIS-model and can be seen in Table 12.

Direct cost of decommissioning current & future wind turbines [mio.DKK]					
	VL. 17.75	VL. 20	VL. 22	VL. 25	VL. 28
Varying Avg. Lifetimes	835.87	781.17	710.25	653.23	604.86

Table 12- Direct cost of decommissioning current & future WTB for varying lifetime assumptions in million DKK.

The simulated costs differ from the results by 1%- 26%. This means that the direct cost results are not very sensitive to the assumptions made on the average lifetime, at least for the investigated interval. Whilst the cost change is not significant, it still underlines the importance of designing WTB for longevity.

6.2 Replacement of broken blades

Turbines, especially offshore ones, are prone to damage, which can sometimes be to an extent beyond repair [30], [87]. Though specific data on the proportion of blades replaced are difficult to obtain, it is unlikely that replacement does not occur to some degree. Additionally, the seabed is often leased for twice the lifetime of the wind turbines, which could make replacement more relevant in cases with structurally sound towers [84].The potential effect of having blades replaced on the overall direct cost of WTB decommissioning has therefore also been investigated.

Firstly, the blade inflows and outflows were projected for a 20 % replacement of WTB after 15 years, for the investigated energy scenarios, which resulted in the data presented in Appendix H. From these new inflows, the direct costs were calculated using the GIS-model, as shown in Table 13.

Direct cost of decommissioning current & future wind turbines [mio.DKK]							
	AF19	**Wind**	**Biomass**	**Bio+**	**Hydrogen**	**Fossil**	**IDA**
Without replacement	659.53	910.70	430.70	306.44	1137.61	430.67	923.76
With replacement	1204.94	1028.06	497.39	379.83	1280.87	497.36	1043.29

Table 13- Direct cost of decommissioning for current & future turbines, with and without blade replacement, for all energy scenarios, in million DKK.

As is clear from Table 13, the direct cost is unanimously higher when accounting for replacement, which is expected. The increased direct cost ranges between 13%- 82%, depending on the energy scenario. This means that replacement can have a significant impact on the total costs of decommissioning WTB and underlines the importance of accounting for the proportion of blades that are replaced.

7 Discussion

This section discussed the decisions made throughout the project.

7.1 Delimitations

Many parts of this project are based on generalized data. An example hereof would be the net energy consumptions related to the investigated EoL treatment types. These were derived in another study from exemplified blade types, which was used to derive the associated GHG emissions and costs in this thesis. Since e.g. the catalyzers used in solvolysis may be influenced negatively by certain filler materials, the specific energy consumption, GHG emissions and costs should account for the specific materials of the given WTB [9]. Since tests on the impact of specific materials on the investigated EoL treatment types have not been carried out, it is considered fair to not include such data in the thesis, since performing tests is outside the scope of this thesis.

In line with this, many material types were excluded from the study. Whether these materials have gained foothold in future Danish WT should be accounted for when planning their decommissioning. Furthermore, the energy consumptions, fuel types, and costs should be projected temporally. Whilst the impact of such projections on the costs is considered only slight, the GHG emissions and energy consumptions are likely to heavily change cf. the Danish energy goals [1]. The same is true for the energy consumption, GHG emissions and costs related to transport.

In terms of the weight of WTB, it is expected that the weight of real turbines will not deviate significantly from the predictions of Equation 1 & Equation 2. However, the regression does not account for the year of installation, which might yield slightly different weight results for future turbines, due to future changes in mass intensity [35]. It should also be noted that the regression used to determine the weight of WTB assumed that each turbine has 3 blades. Whilst it is considered fair to use such a regression on Danish turbines, Denmark has many pilot projects, which may or may not include turbines with fewer or even more blades. An extreme example hereof would be the concept WT with 4 rotors and 12 blades, of Vestas [88].

7.2 Mass flow modelling

In terms of the projected outflow of blade material, the mass flow model does not account for the potential clustering of decommissioning that one would expect to occur in the case of offshore wind farms and onshore wind farms. Implementing a function to account for this is considered outside the scope of this thesis. However, the influence that such a function would have on the outflow is considered moderate and should therefore be included in further developments of the mass flow model. To exemplify this point, consider Figure 18. The slight bump that occurs around 2017 in the historical offshore outflow graph is Vindeby Wind farm [89]. The fact that all WT in this wind farm were decommissioned in the same period supports the point made on clustered decommissioning. Developing a mass flow model for which clustering is included could help determine the decommissioning of specific turbines with higher statistical accuracy.

Since the mass flow model validation can only compare simulated and historical data for a small portion of turbines, the model is considered validated conceptually. Whether slight changes in the lifetime assumptions should be made cannot be determined from the model validation.

7.3 GIS-modelling

Not having projected transport expenditures and fuel types & costs argues against calculating the total cost of decommissioning for all current and future Danish turbines installed up until 2050. Since the main purpose of the model is to optimize the decommissioning of turbines as they become antiquated, this is considered a fair delimitation. Accounting for changes in the above-mentioned variables can be carried out when new data is obtained, which would yield time-specific decommissioning costs. The reason why a projection of the total decommissioning cost was used instead of an annual decommissioning cost, is that the mass flow model does not predict the decommissioning of specific turbines, but only the total mass to be decommissioned.

7.3.1 Transport

Multiple assumptions have been made for the GIS-model. Firstly, the transport energy consumption, GHG emissions and costs have been based off inter- and extrapolated data, together with assumed average speeds and hourly wages for Danish truck drivers. A more fitting approach would have been to get this data from the relevant providers. The contacted firm, however, did not want to disclose this data.

Additionally, the Distance of Acceptance is calculated from exemplified blade types, weighing 5, 15 and 25 tons, respectively. Calculating this distance in a more continuous fashion would be more correct, but the accuracy gains associated to this higher complexity are considered negligible. Therefore, the data is considered valid for the trucks.

The crane vessel has been subject to large assumptions. Obtaining the price from the provider would be preferable in this case. Furthermore, there is likely a beginning price of rent, which means the likelihood that the decommissioning of offshore turbines would be clustered is high. Again, this should be accounted for in further developments of the mass flow model.

The topic discussed in 'Harbors & Islands' is important. Whilst the assumption that no islands have EoL sites on them works fine for most cases, it is likely that larger islands such as that of Great Britain would have such sites. Therefore, accounting for instances in which EoL sites are placed on islands would increase the applicability of the GIS-model to encompass all land formats and hence, other countries. For Denmark, however, this is considered a fair assumption.

Moreover, the driving routes of the freight trucks has been yielded by optimizing for the shortest distance driven. It may be of interest to hold these together with the fastest routes possible and compare the transport costs of both scenarios. In line with this, the GIS-model does not account for the inaccessibility of certain roads to large trucks, nor does it include pay roads. Having the model account for this is outside the scope of this thesis, yet it should at least be considered before using the model to plan the decommissioning of Danish turbines. Accounting for this would also increase the applicability of the model to countries such as the US, which has many pay roads. Additionally, accounting for pay roads would immediately account for the Great Belt Bridge connecting Funen with Zealand.

7.3.2 Turbine data

Recall that certain registered turbines do not have their location data included in the Master Data Register, which will of course impact the overall projected decommissioning costs. It is believed that these turbines are likely low in capacity, and hence, do not change the results significantly.

In relation to the location of future turbines, the assumption that onshore turbines are placed in the same areas as current onshore turbines is considered fair. This is because the requirements of projecting the placement of future onshore turbines are many, and outside the scope of this project [69].

The predicted location of future offshore turbines might differ from the one used in this thesis, given technological developments, more information on Danish offshore areas etc. Yet, it is still believed that the LCOE will be used to determine which wind farm is installed. Hence, this assumption is considered valid.

7.3.3 Legislation

In addition to the background data and the model assumptions, certain variables have not been included. One example hereof would be legislative pressures in the form of fees or restrictions on landfilling. Whilst such pressures are not included in the model, this is partly included in the form of energy consumption and GHG emissions, on which fees might be placed. Performing an in-depth analysis of possible legislative changes on this area was outside the scope of this project, but if legislative pressures were to occur, they should be accounted for in the model.

7.3.4 Throughput

As derived in the results section, one of the most used EoL options of the the cheapest decommissioning scenario for all Danish turbines was solvolysis. Since the throughput of solvolysis is it may be that it is more optimal to select one of the alternative EoL options[26]. Especially Cement kiln co-processing is relevant here, given its high throughput, and the fact that it is already available as a complete solution in Europe. The main point of this is that the projected optimal EoL option for a given turbine is subject to real world processing capacity limitations, which should be accounted for when planning the decommissioning.

7.3.5 Accuracy

Though the model is based on many assumptions, the decommissioning cost per MWe is around 1.63-1.68% of installation costs, for current offshore turbines and future offshore turbines, respectively. This can be seen in the excel appendix: Percentual decommissioning costs [90]. This is in line with the estimated percentual decommissioning cost of the entirety of offshore turbines which is 2-3 % of installation costs [84]. This suggests that the GIS-model is accurate.

8 Conclusion

The future blade inflows and outflows have been projected in tons for multiple energy scenarios, by use of a developed Mass flow model, which accounts for the individual scenario's expected capacity and outflows.

Furthermore, a GIS-model has been developed which considers the shortest route between the given turbine and the available EoL sites, the fiber type of the given blade and its size, as well as whether it is placed onshore or offshore. From this, the optimal blade decommissioning option is determined, including which EoL treatment type is optimal. The projections from the mass flow model were inserted into this model to yield the expected costs associated with decommissioning the blades of the following 4 turbine categories:

- Currently installed onshore WT
- Currently installed offshore WT
- Future onshore WT
- Future offshore WT

The future capacities projected for multiple investigated energy scenarios for Denmark, and the blade decommissioning costs associated to each turbine category can be seen below, both for direct costs and for indirect costs.

Net cost of cheapest decommissioning scenario [mio.DKK]										
Net cost with EOL benefits [mio.DKK]						Cost without EOL benefits [mio.DKK]				
Scenario	**Onshore**	**Offshore**	**Future onshore**	**Future offshore**	**Total**	**Onshore**	**Offshore**	**Future onshore**	**Future offshore**	**Total**
AF19	-60.72	-62.89	-124.55	-235.2	-483.36	37.90	111.48	62.35	447.80	659.53
Wind	-60.72	-62.89	-42.78	-383.54	-549.93	37.90	111.48	21.42	739.90	910.70
Biomass	-60.72	-62.89	-42.78	-153.4	-319.79	37.90	111.48	21.42	259.90	430.70
Bio+	-60.72	-62.89	-42.78	-78.01	-244.40	37.90	111.48	21.42	135.64	306.44
Hydrogen	-60.72	-62.89	-42.78	-463.0	-629.39	37.90	111.48	21.42	966.81	1137.61
Fossil	-60.72	-62.89	-42.78	-153.0	-319.39	37.90	111.48	21.42	259.87	430.67
IDA	-60.72	-62.89	-68.93	-383.0	-575.54	37.90	111.48	34.51	739.87	923.76

The sensitivity of the results was investigated in terms of the lifetime assumptions made and in terms of blade replacement. Changes in lifetime assumptions yielded cost results that differed up to 26 % from the reference scenarios. Replacement had a much higher potential impact on the cost of decommissioning. It changed the cost of decommissioning 13%-82% and was heavily energy scenario dependent.

Lastly, blade decommissioning costs per MW were derived and compared to the estimated total decommissioning cost of another source. The blade decommissioning cost was around 1.63-1.68% of installation costs, which suggests that the model is accurate, given the estimated total WT decommissioning cost from the source of 2-3 %.

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Appendices

Appendix A-Technology readiness levels (TRL)

The following technology readiness levels are the ones defined by EU. They have been extracted from [91].

TRL 1 – basic principles observed

TRL 2 – technology concept formulated

TRL 3 – experimental proof of concept

TRL 4 – technology validated in lab

TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)

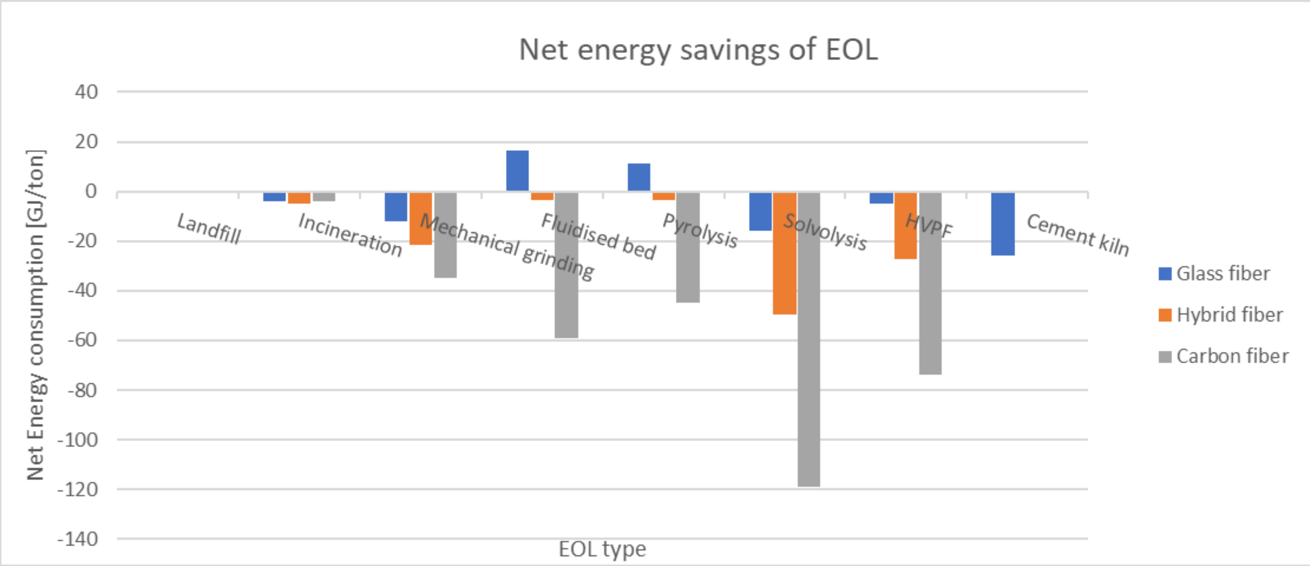
TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)

TRL 7 – system prototype demonstration in operational environment

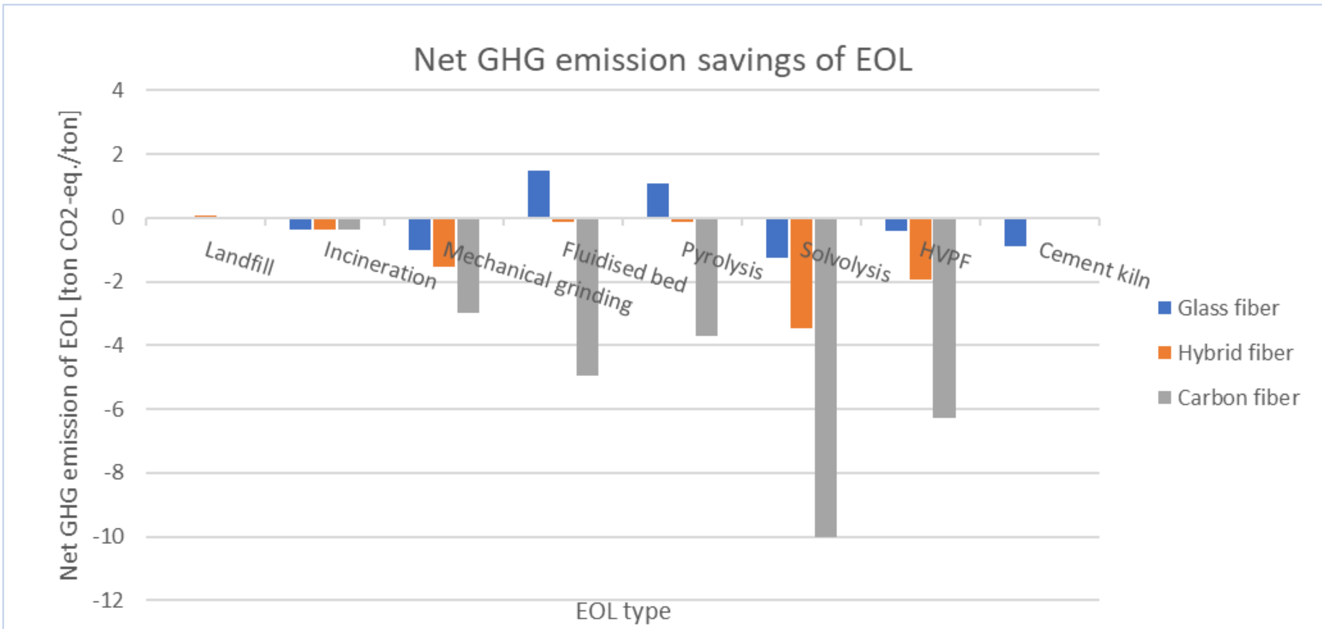
TRL 8 – system complete and qualified

TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

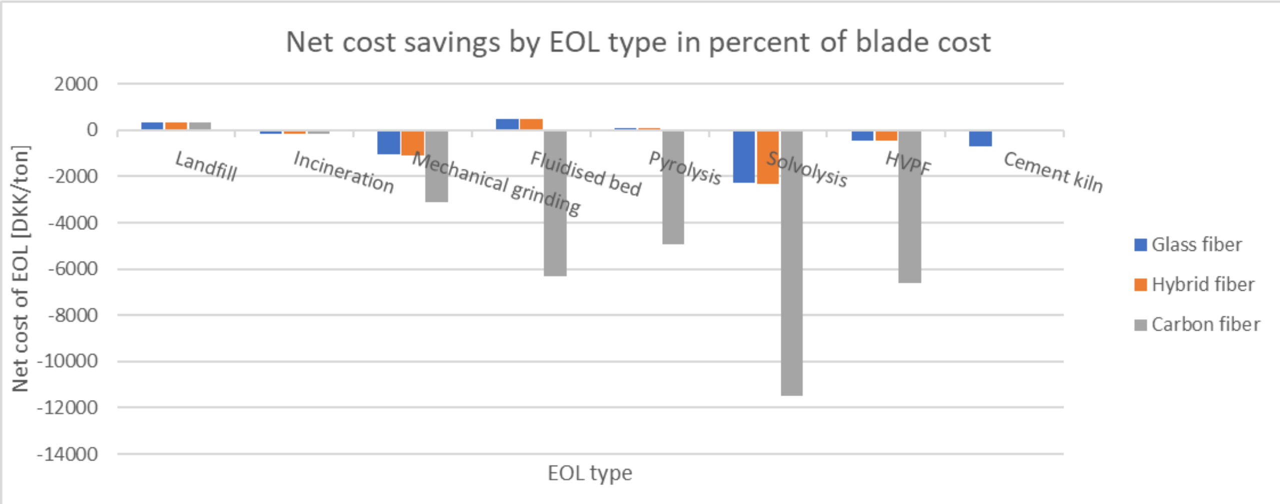
Appendix B- Absolute net energy consumption, GHG emissions and cost of EoL treatment by blade type.



The above figure relays the net energy savings of EoL. It is clear how the savings related to CF are much larger, which underlines the importance of developing effective decommissioning options as the previously discussed shift in WTB material composition occurs.



Here, it is also the case that the importance of decommissioning CF based WTB is greater than for the other fiber types.

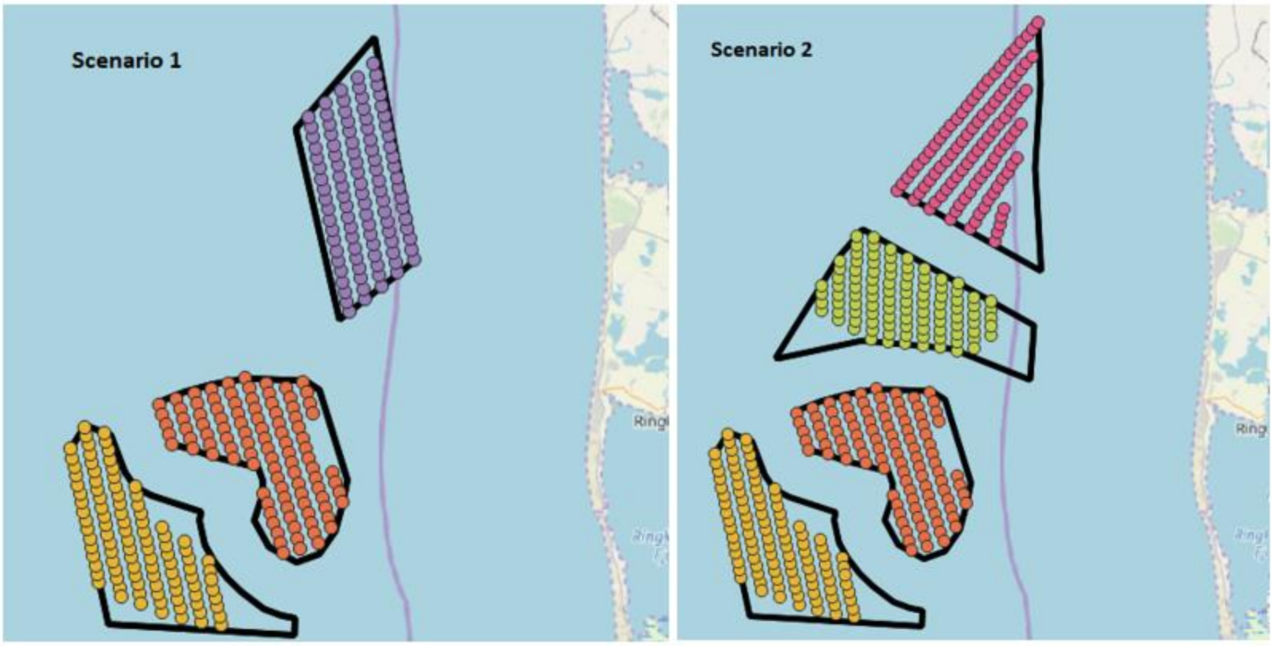


Just as it was the case for the previous figures, the above figure also supports how much more important properly decommissioning CF based WTB is, per ton.

Appendix C- Layouts investigated for future offshore wind farms in Denmark

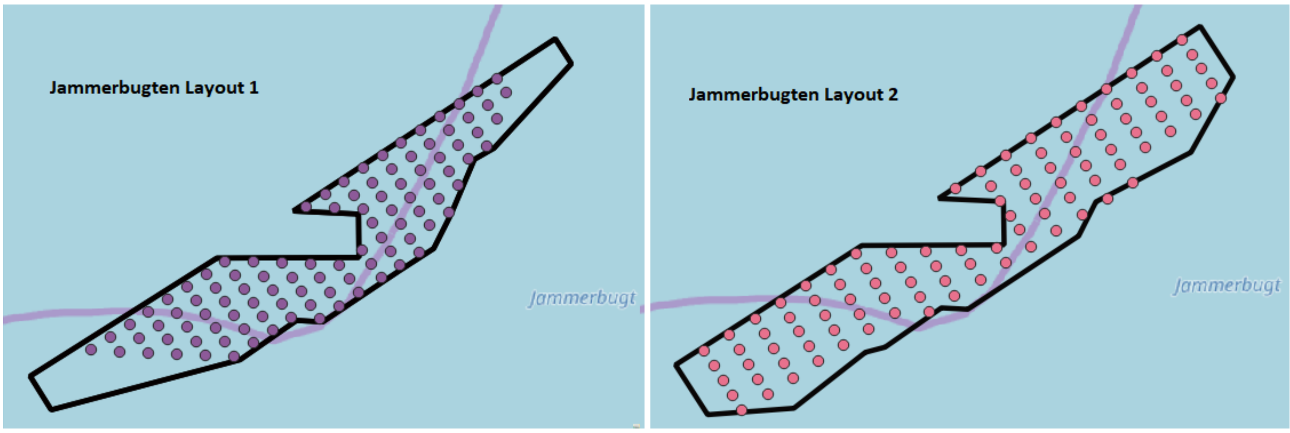
Appendix C1- The North Sea area

The 5 layouts considered for the North Sea. Divided into 2 scenarios for which wind shadow is negligible.



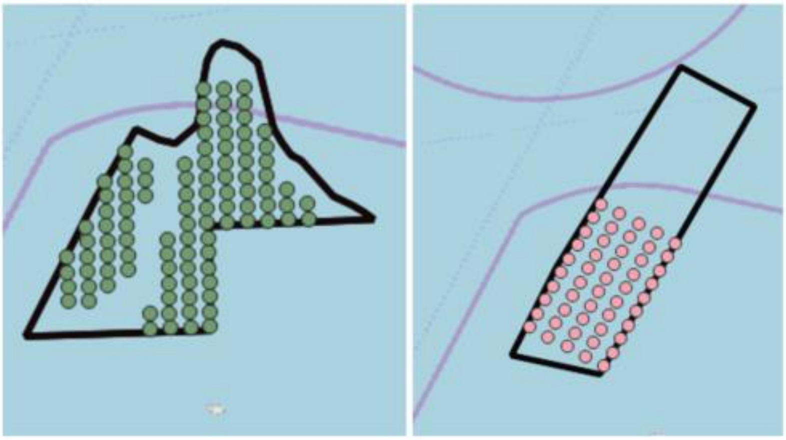
Appendix C2- Jammerbugten

The 2 layouts of Jammerbugten.



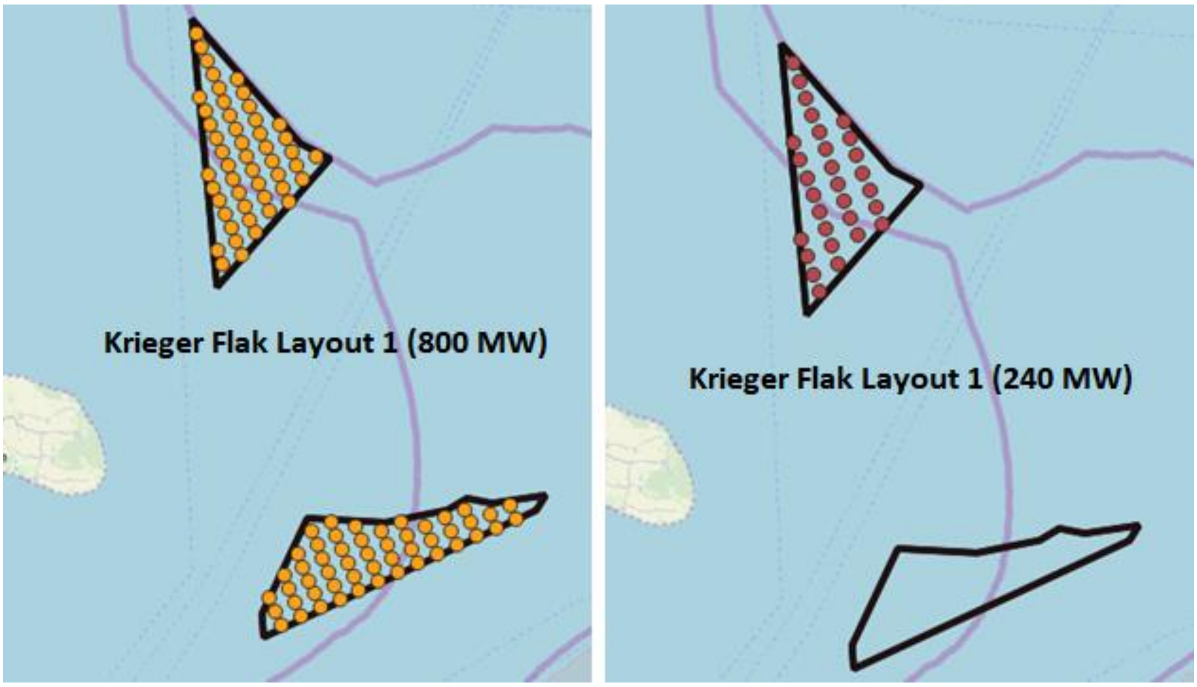
Appendix C3- Hesselø

The 2 layouts for Hesselø, for which the right-hand layout has been optimized for shadowing.



Hesselø has a third layout as well, but due to setbacks in terms of environmental impact, the worse wind profile in the eastern side of the Hesselø area, and limitations on placement, this layout has not been presented.

Appendix C4- Kriegers Flak



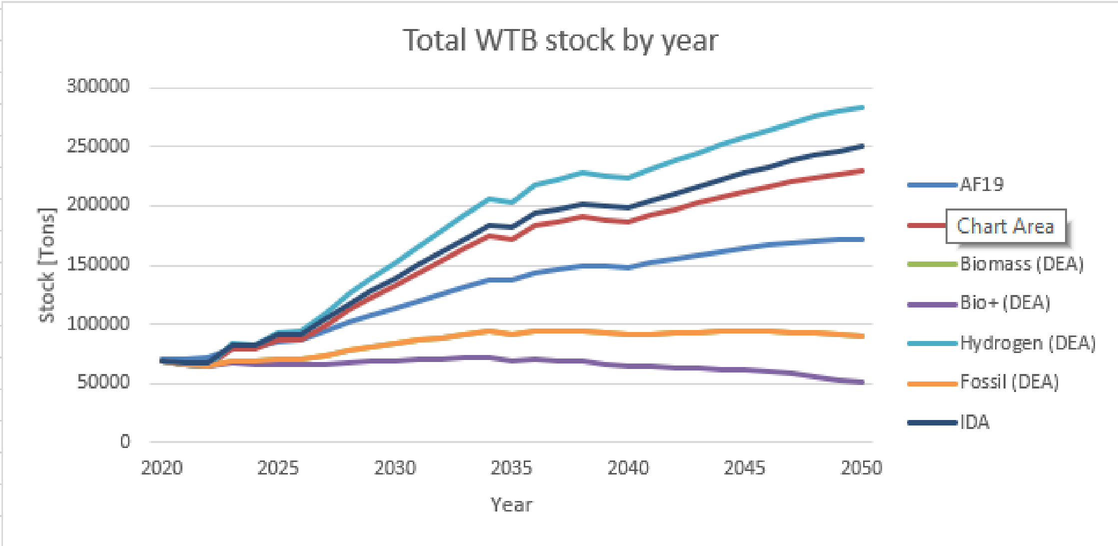
Note not only the general difference in the number of installed turbines (100 to 30), but also the much lower turbine density in the right-hand side of the figure above. This lower density is, as mentioned, made to optimize in terms of shadowing, which means that Kriegers flak is not likely to be installed, since the government would like 3 800MW+ wind farms installed within the next 10-15 years.

Appendix D- Wind speeds of all investigated offshore areas

New area reservations	wind speed [m/s	Area [m2]		Appendix Areas	wind speed [m/s]	Area [m2]
North sea 1	9.61	5.9E+09		Ringkøbing Appendix area	9.75	4.86E+08
North sea 2	9.62	2E+09		Store middelgrund Appendix area	9.75	1.07E+09
North sea 3	9.63	2.8E+08		Kriegers flak Appenix area	9.75	58857041
North sea 4	9.64	2.7E+09		Kriegers flak Appendix area	9.75	24454089
North sea 5	9.65	5.4E+08				
North sea 6	9.66	2.7E+09		**Reserved nearshore areas**	**wind speed [m/s]**	**Area [m2]**
North sea 7	9.67	1.5E+08		North sea North	9.75	58393540
North sea 8	9.68	3.6E+09		North sea South	9.75	48787501
North sea 9	9.69	4.1E+08		Sæby	9.5	22595216
North sea 10	9.7	1.9E+08		Sejerø	9.75	61276152
North sea 11	9.71	8.1E+07		Smålandsfarvandet	9.75	65560833
North sea 12	9.72	1.1E+08		Bornholm	9.5	34707554
North sea 13	9.73	2.5E+08				
North sea 14	9.74	1.1E+08		**Existing reservations**	**wind speed [m/s]**	**Area [m2]**
North sea 15	9.75	6E+08		Ringkøbing	9.75	3.08E+09
Kattegat 1	9.5	8.4E+08		Horns Rev	9.75	3.13E+09
Kattegat 2	9.73	1.9E+09		Jammerbugt	9.75	1.93E+09
Kattegat 3	9.74	8.2E+07		Store middelgrund	9.5	1.49E+08
Kattegat 4	9.75	7E+08		Kriegers Flak	9.75	8.17E+08
Middelgrund & Hesselø	9.5	3E+08		Rønne Banke	9.5	9.79E+08
Ærø South	9.75	2.9E+08				
Nysted South	9.5	6.3E+07				
Falster East	9.5	4E+08		**Maximum wind speed**		
Kriegers Flak	9.75	2.4E+08		9.75		
Rønne	9.5	7.8E+08		**Minimum wind speed**		
Baltic Sea	9.5	1.7E+08		9.5		
				Maximum percentual variation in wind speed		
				2.631578947		

Data extracted from [70].

Appendix E- Total WTB stock by year



The total WTB stock by year yielded form the Mass flow model.

Appendix F- Energy consumption & GHG emissions of cheapest decommissioning scenarios. GIS-model.

The figures below are illustrations of the direct and indirect energy expenditure and GHG emissions related to the cheapest decommissioning plan, the cost results of which can be seen in 'Results'.

Net energy consumption of cheapest decomissioning scenario [PJ]					
Scenario	Onshore	Offshore	Future onshore	Future offshore	Total
AF19	-1.10	-0.39	-1.15	-7.11	-9.75
Wind	-1.10	-0.39	-0.39	-11.5	-13.38
Biomass	-1.10	-0.39	-0.39	-4.14	-6.02
Bio+	-1.10	-0.39	-0.39	-2.1	-3.98
Hydrogen	-1.10	-0.39	-0.39	-14.38	-16.26
Fossil	-1.10	-0.39	-0.39	-4.14	-6.02
IDA	-1.10	-0.39	-0.63	-11.53	-13.65

The energy consumption incl. EoL benefits of the cheapest EoL decommissioning plan, for all energy scenarios.

Energy consumption without EOL benefits [PJ]				
Onshore	Offshore	Future onshore	Future offshore	Total
0.87	0.08	0.93	6.12	8.00
0.87	0.08	0.32	10.45	11.72
0.87	0.08	0.32	3.21	4.48
0.87	0.08	0.32	1.61	2.88
0.87	0.08	0.32	13.30	14.57
0.87	0.08	0.32	3.21	4.48
0.87	0.08	0.52	10.45	11.92

The energy consumption excl. EoL benefits of the cheapest EoL decommissioning plan for all energy scenarios.

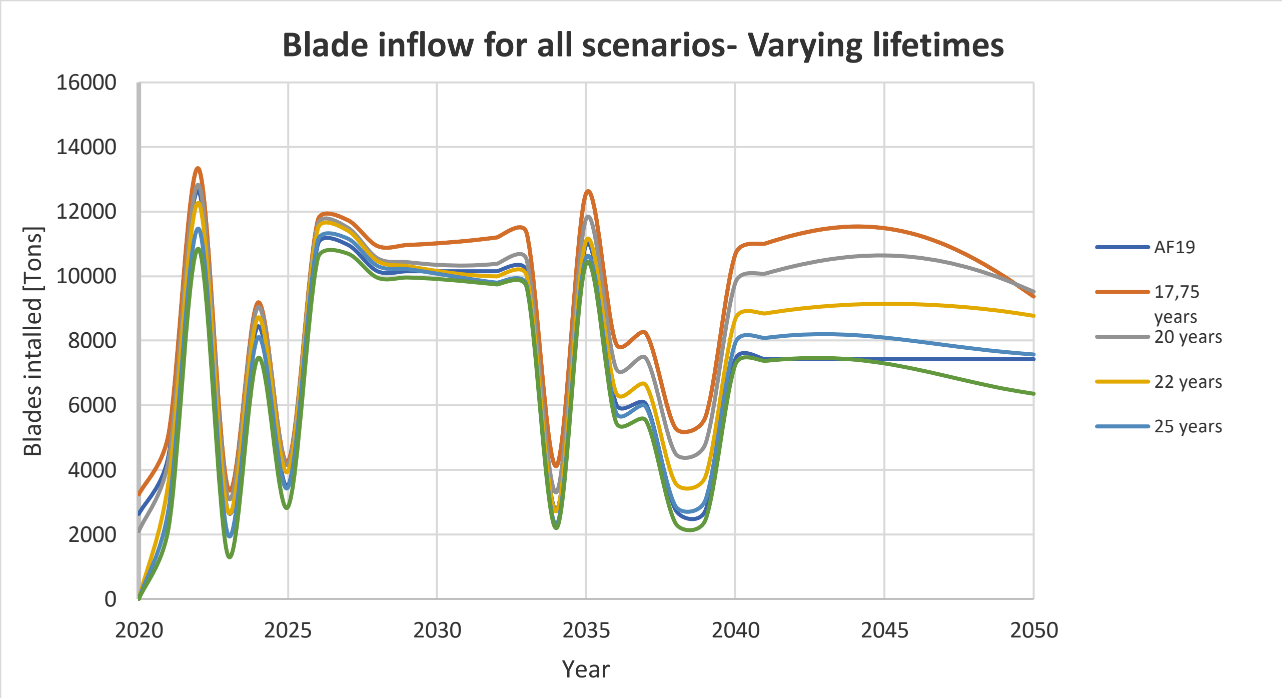
Net GHG emissions of cheapest decomissioning scenario [ktonCO2]					
Scenario	Onshore	Offshore	Future onshore	Future offshore	Total
AF19	-50.60	-30.82	-94.70	-510.4	-686.52
Wind	-50.60	-30.82	-97.53	-826.01	-1004.96
Biomass	-50.60	-30.82	-97.53	-297.26	-476.21
Bio+	-50.60	-30.82	-97.53	-150.34	-329.29
Hydrogen	-50.60	-30.82	-97.53	-1031.63	-1210.58
Fossil	-50.60	-30.82	-97.53	-297.26	-476.21
IDA	-50.60	-30.82	-96.62	-826.01	-1004.05

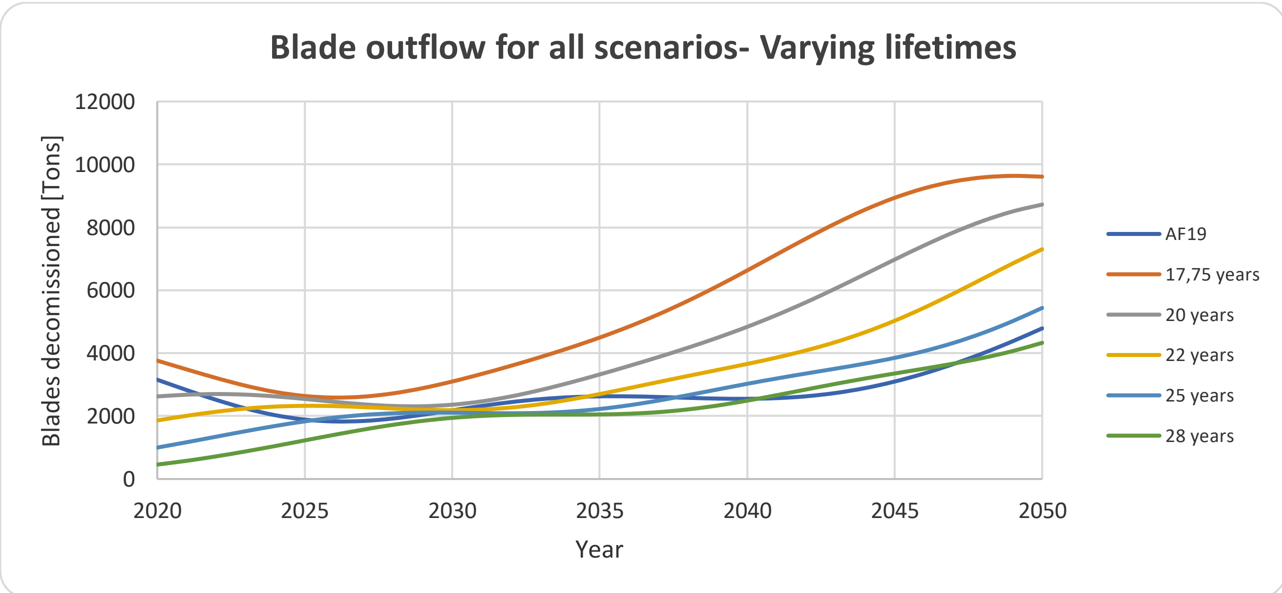
The GHG emissions related to the cheapest decommissioning plan, for all energy scenarios. Includes EoL benefits.

GHG emissions without EOL benefits [ktonCO2]				
Onshore	Offshore	Future onshore	Future offshore	Total
55.70	47.32	82.75	445.23	631.00
55.70	47.32	79.92	773.67	956.61
55.70	47.32	79.92	223.47	406.41
55.70	47.32	79.92	99.30	282.24
55.70	47.32	79.92	987.70	1170.64
55.70	47.32	79.92	223.50	406.44
55.70	47.32	80.82	773.70	957.54

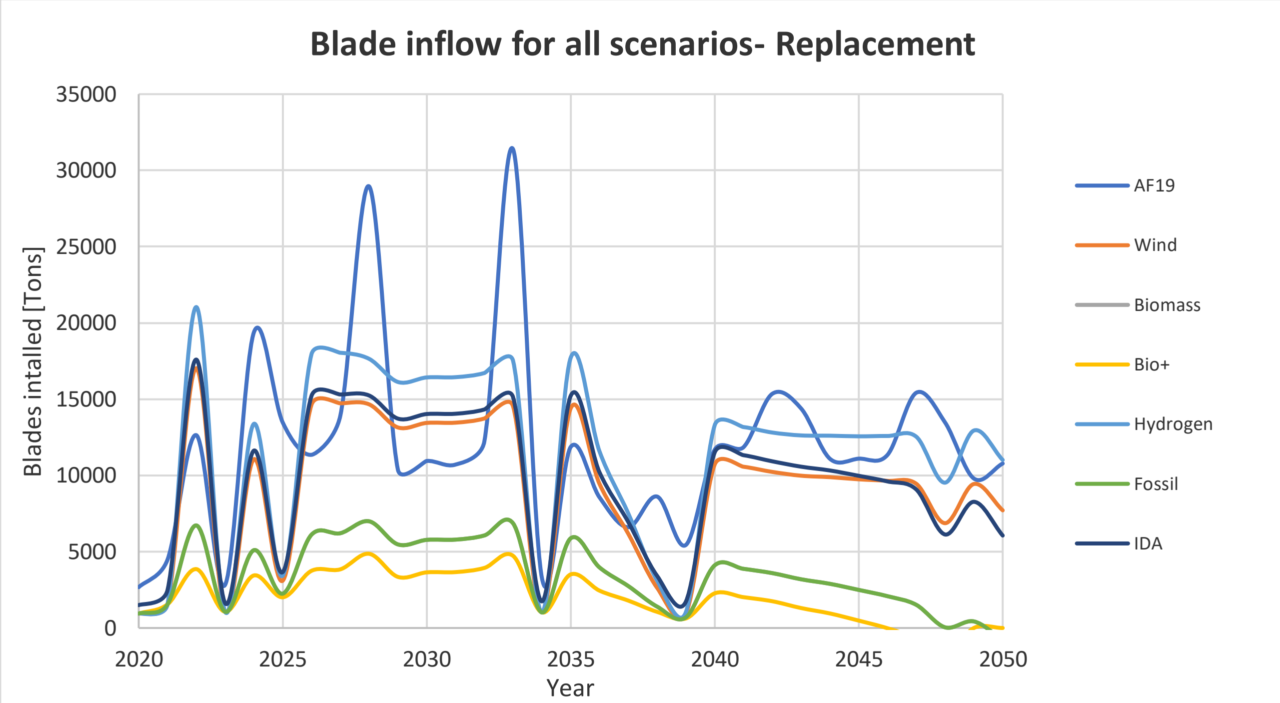
The GHG emissions associated to the cheapest EoL decommissioning plan, for all energy scenarios. Includes EoL benefits.

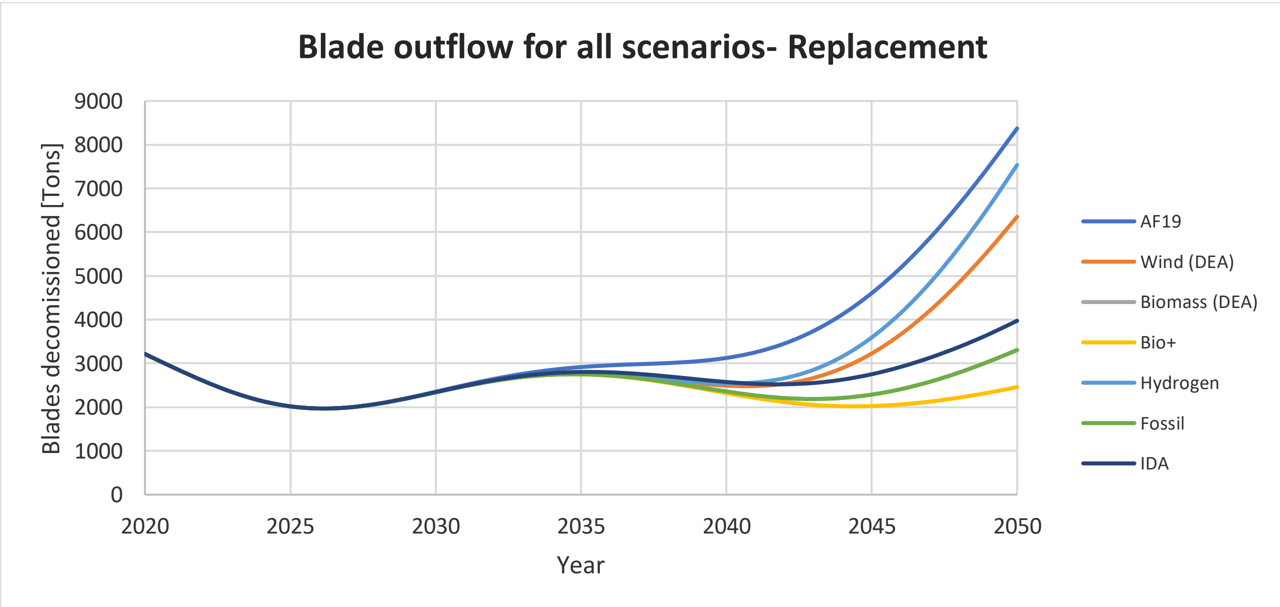
Appendix G- Inflow & outflow projections for varying lifetimes





Appendix H- Inflow & outflow projections incl. blade replacement





Appendix I- Excel appendix reading guide

The excel appendix consists of 3 main folders. The first one; "EOL & Turbine location data" contains the data from the master data register as well as the EOL rank order file.

The second folder; "GIS-model" contains the location data for currently installed turbines in Denmark, the produced EOL-sites, and the Danish Ports. Additionally, the Danish road network file and the offshore area reservations and wind farm layouts are included.

Furthermore, the GIS-model itself, its results and the excel file "Truck- Distance of acceptance" are found in this folder. In short, all data that goes into the GIS-model, except for the turbine location data is found in this folder. Lastly, the excel file: "Marine freight expenditures" and "Percentual decommissioning costs" are included.

The last folder; "Mass flow model" contains the background data it was based upon as well as the projections of inflow and outflow for: All scenarios, replacement, varying lifetime and lastly, the model validation of the mass flow model. As mentioned earlier, a reading guide is attached as the first sheet of each excel file, describing the workings of each sheet, together with the overall purpose of the file.