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Offshore and onshore wind turbine blade waste material forecast at a regional level in Europe until 2050

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Declarations of interest: none

Abstract:

Wind power is a key renewable electricity source for Europe that is estimated to further develop significantly by 2050. However, the first generation of wind turbines is reaching their End of Life and the disposal of their blades is becoming a crucial waste management problem. Wind turbine blades consist primarily of reinforced composites and currently there is a lack of a sustainable solution to recycle them.

The aim of this study is to estimate the wind turbine blade waste material for Europe until 2050 and is the first study adopting a high geographical granularity level in Europe, while distinguishing between offshore and onshore. In addition, the wind turbines' lifespan is not considered as a fixed value, but rather as a stochastic distribution based on historic decommissioning data. This study can support researchers, practitioners and policy makers to understand the future evolution of the blade waste material availability, identify local hotspots and opportunities and assess potential circular economy pathways.

The results indicate that wind power capacity in Europe will reach 450 GW in 2050 with the respective total yearly blade waste material reaching 325,000 t. Findings for selected countries reveal that in 2050 Germany will have the majority of blade waste material from onshore wind and the United Kingdom from offshore. There is also a significant fluctuation in the yearly amount of waste expected at the country level, for several countries. Finally, local hotspots of blade waste material are identified.

Keywords: offshore, onshore, wind turbine blades waste, Europe, forecast

1. Introduction

The recent renewable energy directive has set a target for Europe to cover at least 32% of its energy needs with renewables by 2030 (EU, 2018). Wind, along with solar and biomass are promising sources of renewable energy (Boemi et al., 2010). However, wind power has the highest rate of increase and it was estimated that in 2017 wind power was the second largest power generation source accounting for almost 170 GW (Fraile and Mbistrova, 2018). It is forecasted that 25% of the electricity generation in Europe by the year 2050 will be provided by wind turbines (EuropeanComission, 2016).

The lifetime of a wind turbine is assumed to be around 20 years (Andersen et al., 2016) and the wind turbines aging rate appears similar for the different turbines models (Staffell and Green, 2014). In the last decade the first generation of onshore wind turbines in Europe have been reaching their End of Life (EoL) and for offshore, four wind farms were recently decommissioned (Topham et al., 2019).

Wind turbine blades constitute one of the main components of the wind turbines and an average of 10kg of blade material is required per 1 kW generating capacity of a turbine

(Albers, 2009). The main material of wind turbine blades is glass or carbon reinforced composites and it is estimated that by the year 2034, approximately 225,000 t of waste blade material world-wide and 100,000 t in Europe will be generated per year (Albers, 2009). A common approach to deal with the wind blades waste currently is landfilling in pieces of size depending on each landfill regulations. However, in some countries taxes have been introduced for landfilling composites, which can be quite high. For example, in the UK, the price for 2018-2019 is approximately £90 per t, or in other countries like Germany, landfilling of wind turbine blades is entirely banned. It should be noted that there is a wide range of landfill costs and policies among European countries, reflecting differences in economic conditions, industrial structures and environmental regulations. Another approach is the incineration of the blades for energy recovery, which has many drawbacks. Firstly, the glass fibres are non-flammable, they have a negative impact on the flue gas cleaning systems and the large amount of residue from the combustion process requires to be disposed of in the end (Beauson and Brøndsted, 2016). The blades can also be incinerated in cement kilns after cutting and shredding. Few companies in Germany recently incorporated mechanically recycled fibres into concrete (Gu and Ozbakkaloglu, 2016), increasing the structural integrity of the material; however, this process reduces the value of the glass fibres to that of calcium carbonate (Job, 2013). Other options that have been recently proposed are to use the blades as thermal insulation or noise cancelling screens (EnergyCentral, 2019). Even though technologies for mechanical and thermal treatment exist, the connection to end users does not currently exist, plus the low cost of virgin material and landfilling limits the incentive for recycling.

Despite the high amounts of waste material expected and the high cost of disposal, currently there is a lack of a sustainable solution to recycle the blade waste material (Liu et al., 2019), even though the repurposing or recycling of EoL wind turbines has been shown to have both environmental and economic benefits (Mamanpush et al., 2018). In principle, Glass Fibers from wind blades could potentially be recycled using existing technologies of mechanical or thermal treatment, but this has not progressed significantly up to now due to the lack of demand for recycled Glass Fibers, the low cost of virgin Glass Fibers, the lack of consistent waste material supply and the accessibility and low cost of landfilling as a disposal method in most countries. In general, 'closing the loop' of the product EoL and its production allows the resources' circulation and enables to maintain the energy and economic value of the product in the loop for more than one lives (Ragossnig and Schneider, 2019).

In order to investigate and come up with any recycling or circular economy solutions, quantifying the evolution of wind blade waste material availability over time is necessary, as it will affect the scale, location and feasibility of any solutions investigated.

In the existing literature, very few studies have provided forecasts for the future blade waste material. In previous research, the global life cycle waste inventory of onshore wind blades was estimated until 2050 for China, United States, Europe and the rest of the world (Liu and Barlow, 2017). Other authors, incorporated an assumption regarding the material that will be required to be recycled and estimate the amount of wind blades that will be decommissioned in 2050 in Europe (Andersen et al., 2014). Regional estimations for the current capacity for each region were employed, however the same growth rate was used for all the regions except Europe, due to lack of data. Other authors presented a forecast for the waste blade material in Europe (Albers, 2009) estimating that more than 200,000 t of blade waste will be available in 2034. At a country level, the amount of blade waste material in Germany until 2050 (Albers, 2009) and in Sweden until 2034 (Andersen, 2015) was forecasted.

In the existing literature the forecasts either do not distinguish between offshore and onshore (Albers, 2009) or do not include the offshore due to the small percentage it currently has on the total power generation and installed capacity (Andersen, 2015; Andersen et al., 2014; Liu and Barlow, 2017). However, the offshore wind sector is developing rapidly and is expected to continue growing in the coming years in several European countries (Nghiem and Pineda, 2017). In addition, the level of granularity, i.e. the level of detail of the data (Dale, 1992), of the existing results in the literature is low and the forecasts are not performed at the country or more detailed level (Albers, 2009; Andersen et al., 2014; Liu and Barlow, 2017). This does not allow assessment of circular economy opportunities that may exist at the country or even at a higher geographical granularity level, which could be promising, considering the high logistical cost and other challenges of transporting the waste material for long distances and between countries. In the few cases where the granularity level has been the country, the focus has only been on one particular country (Albers, 2009; Andersen, 2015), in which case cross-country opportunities cannot be assessed. Furthermore, previous studies made a rough assumption that the 1/20th of the cumulative capacity installed by 2030 will need to be decommissioned by 2050 (Andersen et al., 2014), whereas Liu and Barlow (2017) proposed three different scenarios of 18, 20 and 25 years lifespan. However, in reality the wind turbines lifespan is uncertain and ‘technical, economic and legal aspects drive the decision-making process’ of whether to extend the lifetime, repower or decommission a turbine (Ziegler et al., 2018). Therefore, there is currently a lack of studies that provide scenarios for the future blade waste material availability from offshore and onshore wind blades for high geographical granularity in Europe until 2050, while simultaneously considering the uncertain lifetime of wind turbines.

The aim of this study is to estimate the offshore and onshore wind turbine blades waste material that will be available in Europe until 2050, at a high level of geographical granularity. The novelty of this study is twofold. Firstly, the blade waste material forecast in Europe is performed at both the country and a more detailed level in comparison to the existing literature. Secondly, it is the first study that considers and distinguishes between the offshore and onshore wind turbines. In addition, in this study a more realistic assumption is made regarding the wind turbines lifespan by developing a stochastic distribution based on historic data of decommissioning instead of making a rough estimation of the wind turbine's lifespan.

Therefore, this work contributes to identifying hotspots of wind turbine blades material availability until 2050 at a high geographical level of regions equivalent to NUTS2 (Nomenclature of Territorial Units for Statistics 2) level in Europe. This information can be used to support decisions on potential circular economy pathways at both the local, country or European level.

The methodology adopted in this study is presented in Section 2. The blade waste material forecasts until the year 2050 at a NUTS2 region, country and European level are presented in Section 3. Finally, the concluding remarks and policy implications are discussed in Section 4.

2. Material and methods

In this section, the methodology and the data used to estimate the amount of EoL wind blade material for onshore and offshore wind turbines until 2050 for each European country and for each NUTS 2 region is discussed. NUTS classification is used by the European Union to divide the economic territory of Europe, with NUTS 2 representing 'basic regions for the application of regional policies' (Eurostat, 2016). In this study, the word 'region(s)' will be used to refer to 'NUTS 2 region(s)' henceforward.

The forecasting process followed is depicted visually in Figure 1 and consists of 12 steps, which are discussed in detail. More details on the methodology are provided in the e-component accompanying this paper.

Data from the currently operational wind farms in Europe were considered in step A1 of Figure 1, namely the location (latitude and longitude), commissioning date, turbine type, installed capacity and rotor characteristics. Only the existing and under construction projects were considered excluding the planned ones, due to high uncertainty.

Each wind farm was allocated to the NUTS 2 region that it belongs to geographically, using GIS software (steps A2 and A3 of Figure 1). The offshore wind farms were allocated to the NUTS 2 region where the nearest port belongs to. The decommissioning of offshore wind turbines is a novel challenge, therefore there is limited knowledge about which ports are or will be in the future suitable for offshore wind farm decommissioning. In this study, ports listed in the Core and Comprehensive traffic network of the European Commission (EuropeanCommission, 2014) as well as ports explicitly designated as suitable for offshore wind installing and maintenance (4Coffshore, 2019) were considered.

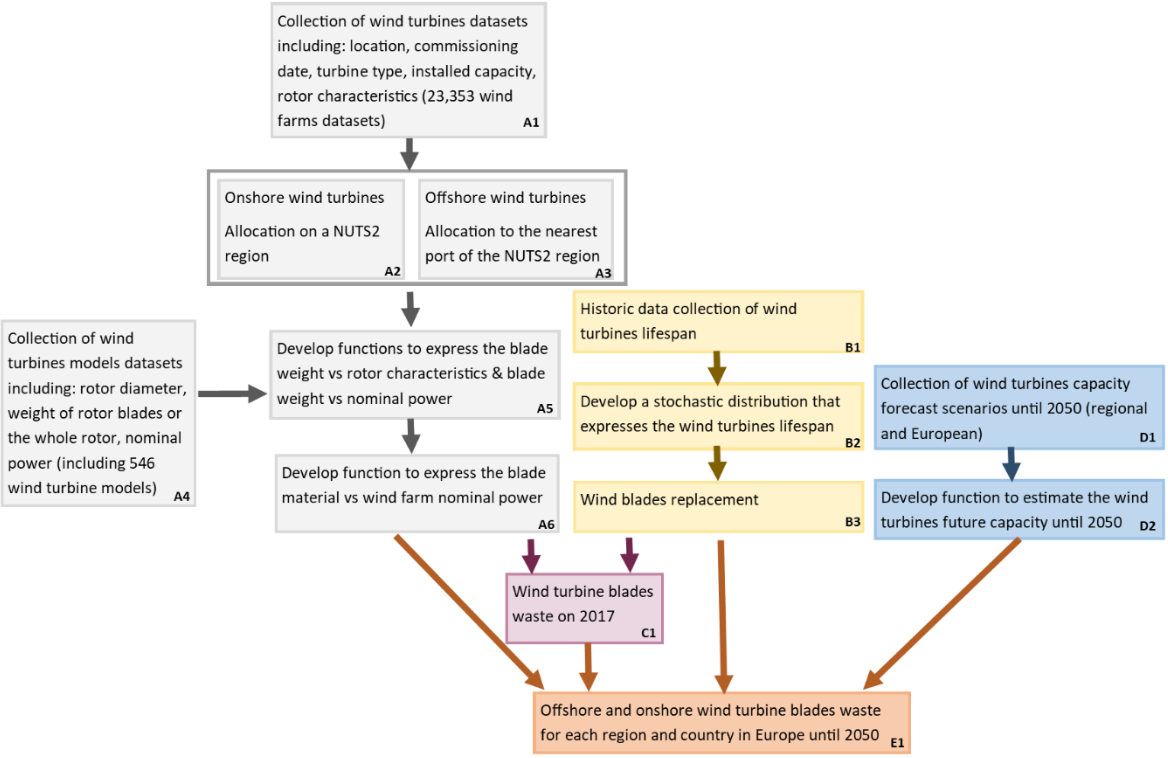


Figure 1 Flowchart of wind turbine blade waste forecast process

The turbine blade weight could be identified explicitly for only 167 wind turbine models of the original database and this information was used. As a result, for the other wind turbines relationships were required to express the blade waste material as a function of their other known characteristics. Therefore, detailed manufacturer data from 546 wind turbine models were collected (A4) and relationships were developed to express the blade weight (A5) as a function of the rotor diameter, weight of rotor blades or the whole rotor, the nominal power of the turbine as well as the wind farm. The database was created mainly from data published by TheWindPower (2018) and Wind-turbine-models (2019), as well as from published manufacturer technical datasheets, wind turbine operators data and scientific papers (Arias, 2016).

To estimate the EoL blade material, the expected lifespan of the wind turbines is required, to link the operational starting date with the date when the material will become available due to decommissioning. The operational life time of wind turbines is highly uncertain and depends on many technical and commercial factors. For this reason, in order to incorporate this uncertainty into the forecasting, a stochastic distribution was developed for the wind turbines lifespan. Firstly, official data on the age of decommissioned wind turbines from Denmark and Germany were combined and used to develop a histogram (step B1). Then, a continuous distribution function was fitted in the histogram (Step B2).

This study focuses on the total wind turbine blade waste arising during the wind turbines lifetime, which also includes waste due to the replacement of blades during their operational lifetime (step B3). The replacement rate due to unexpected failure during the wind blade lifetime is non-negligible and is assumed as 2% of the installed blade material annually, according to technical reports (Sheng, 2013). Therefore, combining the wind turbine lifespan with the existing operational wind turbines, an inventory of the onshore and offshore wind blade material waste per NUTS 2 region on the year 2017 was developed in step C1, including both EoL and blade replacement sources.

In order to forecast the EoL wind blade material until 2050, reliable scenarios for expected evolution of the wind power installed capacity in Europe are required. In this work, both regional and country level scenarios were considered (step D1 in Figure 1) and were used to develop functions to estimate the future wind turbines installed capacity in Europe (D2).

Multiple sources were used in order to assure reliability and validity. Three studies are considered for the offshore and onshore wind power capacity forecast until 2030 (Ho and Pineda, 2015; Nghiem and Pineda, 2017; TradeWind, 2009). All three studies consider a low, medium and high scenario. In this study the scenario selected from each previous study is the one that has the lowest absolute deviation from the existing historical data on 2015. The average value of the selected scenarios for the year 2030 for each country is then estimated and a linear interpolation is performed between the reference year 2017 and 2030, to estimate the wind power installed capacity per year.

To forecast the blade waste for each NUTS 2 region, detailed information was used for specific countries and regions wherever it was available in order to increase the validity of the results in the high granularity cases.

After the year 2030, only forecasts for the offshore and onshore wind energy capacity in the UK are provided (Nationalgrid, 2018) and used. For the rest of the countries, the EU reference scenarios (EuropeanComission, 2016) are employed that include forecasts of cumulative offshore and onshore wind energy capacity until 2050 at country level. Therefore, with interpolation of the forecasted wind power capacities for the years 2030, 2035, 2040, 2045, 2050 from the EU reference scenarios, a growth rate is estimated for each country. The country specific growth rate is applied on the 2030 country-level offshore and onshore wind power capacity values previously estimated and as a result, forecasts are derived for the years 2030 to 2050.

For offshore specifically, wind turbines waste material is estimated at a country level according to the forecast scenarios; however, the estimated material is allocated at the regional level following the existing planned and approved offshore wind turbines distribution. Due to lack of data and detailed resources, the planned and approved wind farms are used as an indication to identify hotspot areas for the future offshore wind turbines installation.

The forecast for the wind farms capacity is applied to the existing 2017 inventory and as a result the future installed capacity in Europe until 2050 is estimated. In cases where only country level information was available then a blanket approach of using the same rate for all the NUTS 2 regions of the country was adopted. On the other hand, when regional information was provided then the capacity of each region was estimated independently. Then the blade material per year is estimated according to the relationships expressing the blade material as a function of the turbine characteristics. The available blade waste material of the turbine EoL is estimated according to the stochastic lifetime distribution whereas the replacement blade waste material is based on the assumed replacement rate. As a result, the future inventory of wind blades material is developed at a yearly basis and allocated to each NUTS 2 region (step E1)

3. Results and discussion

3.1. Europe-level forecasts

The forecasted installed wind power capacity in Europe is presented in Figure 2. The data until 2017 was obtained from databases on historic data (TheWindPower, 2018). It is inferred from the figure that the total installed capacity is increasing at a rate of almost 8400 MW/year. It is evident that the onshore capacity constitutes the greatest part of the total installed capacity throughout the 30 years with a percentage above 70% throughout the years. The average increase rate of the onshore capacity is 6,000 MW/year whereas for the offshore it is 2,700 MW/year. In addition, it is observed that the onshore capacity has a higher growth between the years 2020-2030 and 2040-2050, whereas between the years 2030 to 2040 the growth is modest with a lower growth rate of almost 2,000 MW/year. Along these lines, the offshore capacity has the highest growth in the decade 2020 to 2030 while from 2030 to 2050 the growth rate is lower at almost 1,500 MW/year. These findings can be interpreted as a saturation of the offshore capacity after the year 2030, following a period of rapid growth.

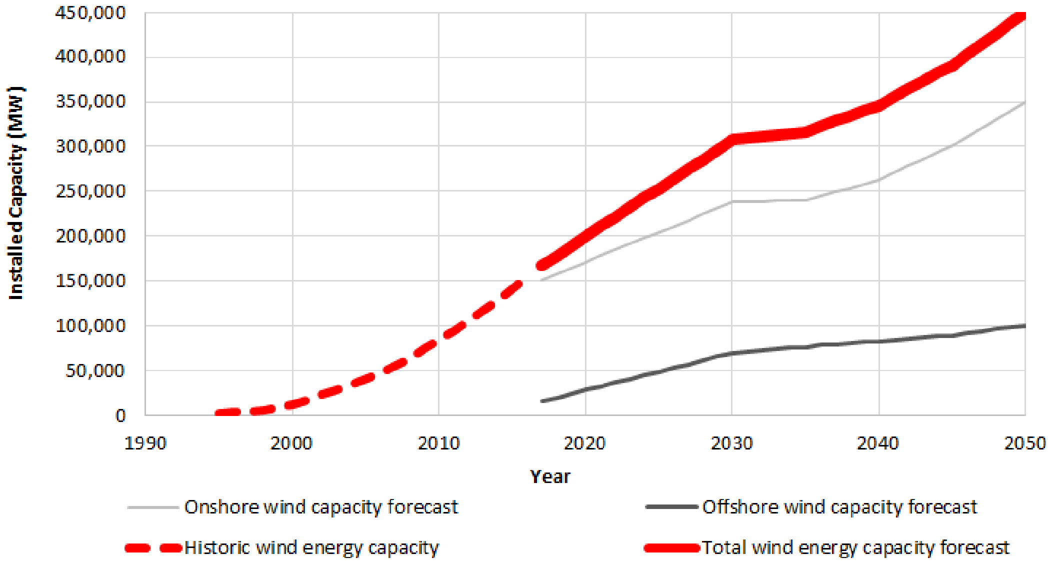


Figure 2 Wind power capacity forecast for Europe until 2050

The resulting blade waste material derived from offshore and onshore wind farms is displayed in Figure 3, further analysed into material from decommissioning and from blades replacement. It is observed that there are significant amounts of waste from blades replacement, which is a natural outcome of the high replacement percentage assumed in line with technical reports.

As expected from Figure 2, the total amount of blade waste material from onshore is greater than offshore, since the installed capacity and blade waste material are highly correlated. It is forecasted that the total waste blade material in 2050 will reach 325,000 t, 76% originating from onshore and 24% from offshore. Even though the offshore wind farms account for a lower percentage than the onshore, it is not an insignificant amount of material and therefore, it should not be neglected in any forecasts. The findings are in the same level of magnitude with the existing literature and sitting between two independent sources, where it was estimated that the waste will be more than 100,000 t in 2034 (Albers, 2009) and around 500,000 t in 2050 (Liu and Barlow, 2017).

For the onshore wind turbines, the waste blade material consists mainly of decommissioning waste and it is evident that over time this percentage increases over replacement waste. This is due to the fact that there is already currently a significant stock of installed onshore wind turbines that is reaching EoL in the near future, in combination with the rapid growth in new installations in the future, as identified from Figure 2.

However, it is identified from Figure 3 that for the offshore blades waste material until 2030 the replacement waste is higher that the decommissioning and in specific almost until 2025 the total offshore blade waste consists only of replacements. This is due to the fact that the offshore wind turbines are almost all quite recently installed and there are not many projects that have reached or will reach soon the end of their life (Topham and McMillan, 2017). Still, it is interesting to note that the blade waste material from offshore wind will significantly increase between the years 2025 to 2040.

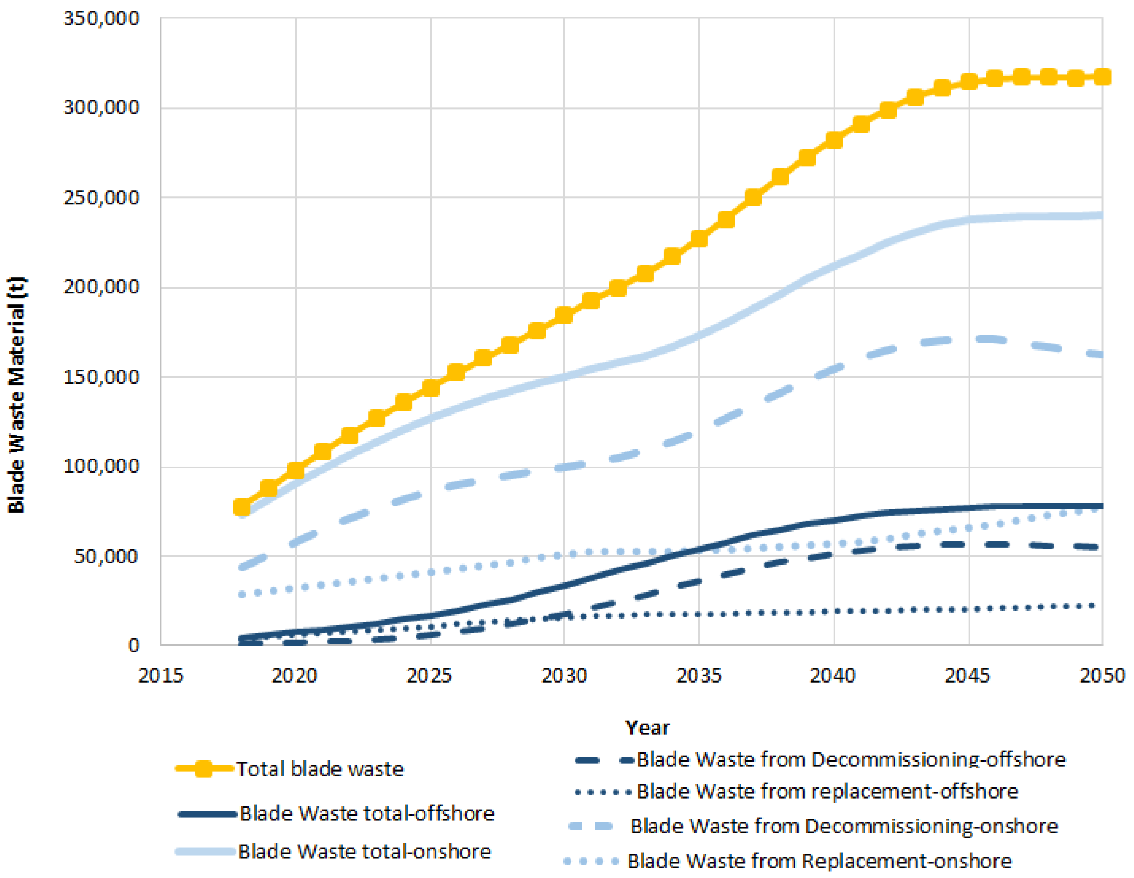


Figure 3 Blade waste material forecast from wind turbines in Europe until 2050

The analysis for the future waste material for every European country is also performed separately for onshore and offshore wind turbines in Figures 4a and 4b respectively. The blade material availability in Figure 4a reflects strongly the percentage of onshore wind turbines installed capacity per country. The results are in good alignment with European reports where it is indicated that by 2030 the order of the countries with the greatest onshore wind power capacity will be Germany, France, Spain, United Kingdom and Italy (Nghiem and Pineda, 2017). However, it should be noted that Figures 4a and 4b refer to blade waste material rather than installed capacity, explaining minor differences.

It is evident that Germany will have the majority of blade waste until 2050, however the percentage within Europe will decrease throughout the decades starting from 42% in 2020 and reaching 22% in 2050. This indicates a saturation on the wind capacity installed in

Germany. Spain will hold a percentage within the range of 14% to 17%. On the other hand, France will experience a 10% increase on the blade waste material reaching on 2050 a 15% of the total waste in Europe. This is aligned with estimates that after 2020 France will have an increase on onshore wind power capacity installed, which according to European reports will reach 36,360 MW in 2030 (Nghiem and Pineda, 2017). A modest increase is observed for Sweden and Poland, whereas the other countries remain stable or experience a small decrease like Denmark. Overall, the order of countries in terms of blade waste material available until 2050 does not change dramatically over the years.

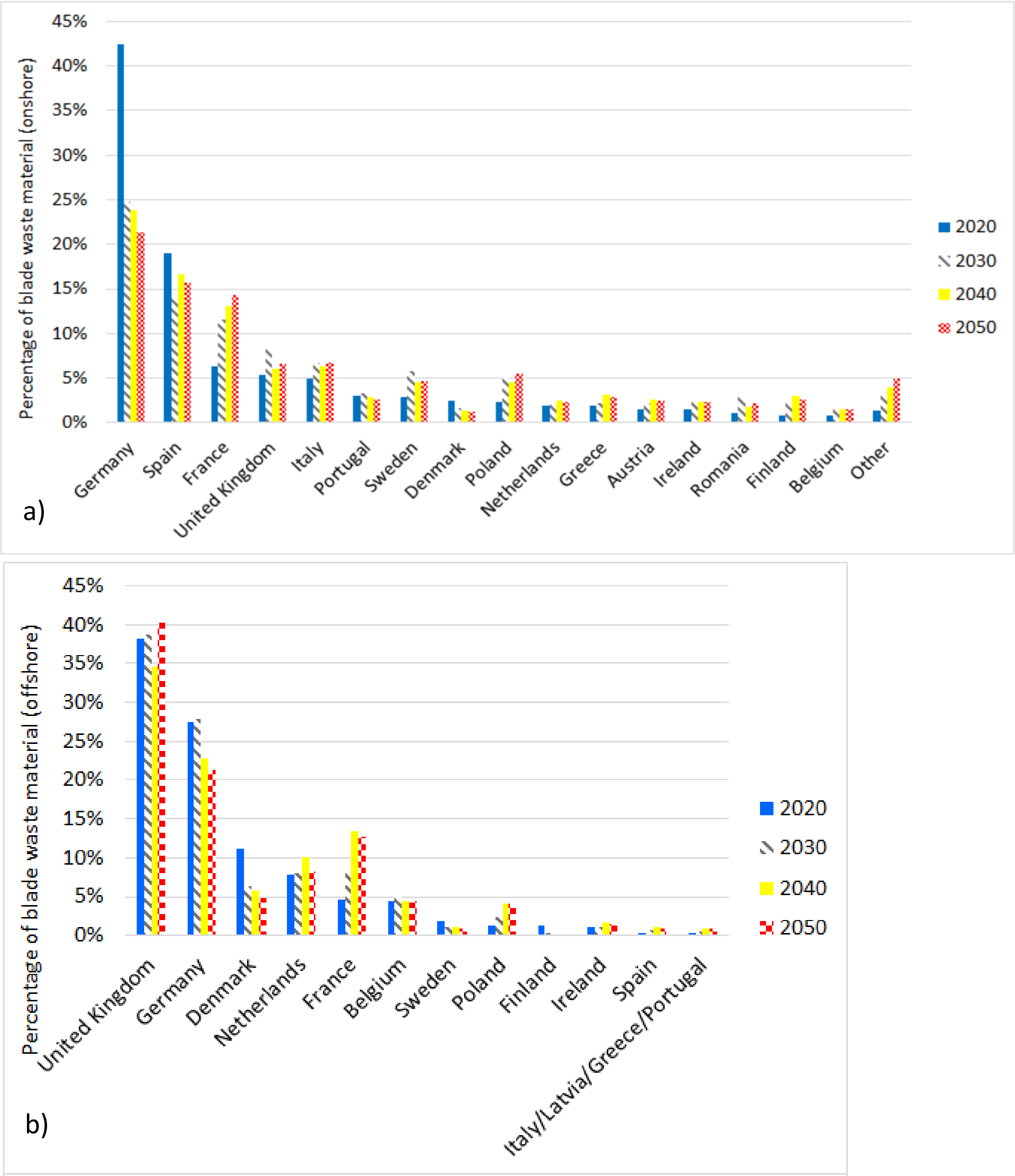


Figure 4 Blade waste material per country as percentage of total a) onshore and b) offshore

The results from the offshore wind turbines in Figure 4b indicate a different leading order for the countries compared to the onshore. This was also demonstrated from WindEurope (2017), where United Kingdom will have the highest capacity in 2030, approximately 22,500 MW, whereas Germany, Denmark and Netherlands will follow. United Kingdom will be leading, accounting for around 37-40% of European offshore blade waste material until 2050. On the other hand, Germany and Denmark will experience a significant decrease on their percentages over time. Other countries like Netherlands, Belgium and Ireland have a relative stable percentage of the waste material at approximately 8%, 5% and 2% respectively. France and Poland are expected to have a significant increase of offshore blade waste material contribution in the future. Spain is expected to have very low quantities of offshore blade waste material, despite the large amounts of onshore.

3.2. Country-level forecasts

A further, more detailed, analysis for selected countries of particular interest has been performed. In

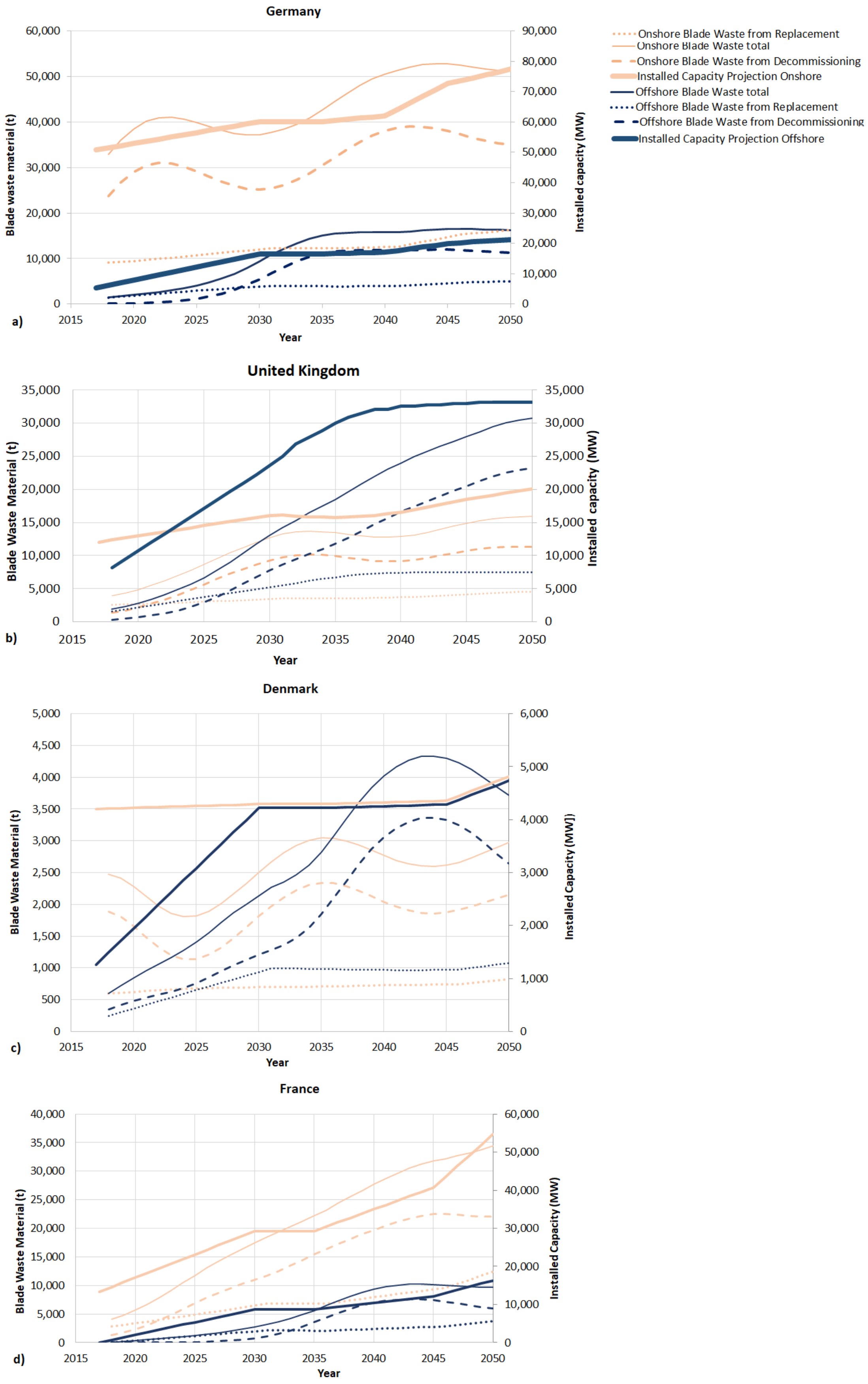

Germany
Blade waste material (t)
Installed capacity (MW)
60,000
50,000
40,000
30,000
20,000
10,000
0
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
2015
2020
2025
2030
2035
2040
2045
2050
Year
a)
Onshore Blade Waste from Replacement
Onshore Blade Waste total
Onshore Blade Waste from Decommissioning
Installed Capacity Projection Onshore
Offshore Blade Waste total
Offshore Blade Waste from Replacement
Offshore Blade Waste from Decommissioning
Installed Capacity Projection Offshore
United Kingdom
Blade Waste Material (t)
Installed capacity (MW)
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
2015
2020
2025
2030
2035
2040
2045
2050
Year
b)
Denmark
Blade Waste Material (t)
Installed Capacity (MW])
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
6,000
5,000
4,000
3,000
2,000
1,000
0
2015
2020
2025
2030
2035
2040
2045
2050
Year
c)
France
Blade Waste Material (t)
Installed Capacity (MW)
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
60,000
50,000
40,000
30,000
20,000
10,000
0
2015
2020
2025
2030
2035
2040
2045
2050
Year
d)

Figure 5a Germany is analysed, due to the fact that it has the highest installed capacity currently in Europe. The total installed wind power capacity in Germany for the year 2050 is estimated around 102,000 MW, where 75% is attributed to onshore wind turbines and 25% to offshore. The total blade waste material for 2050 is forecasted to be 67,590 t.

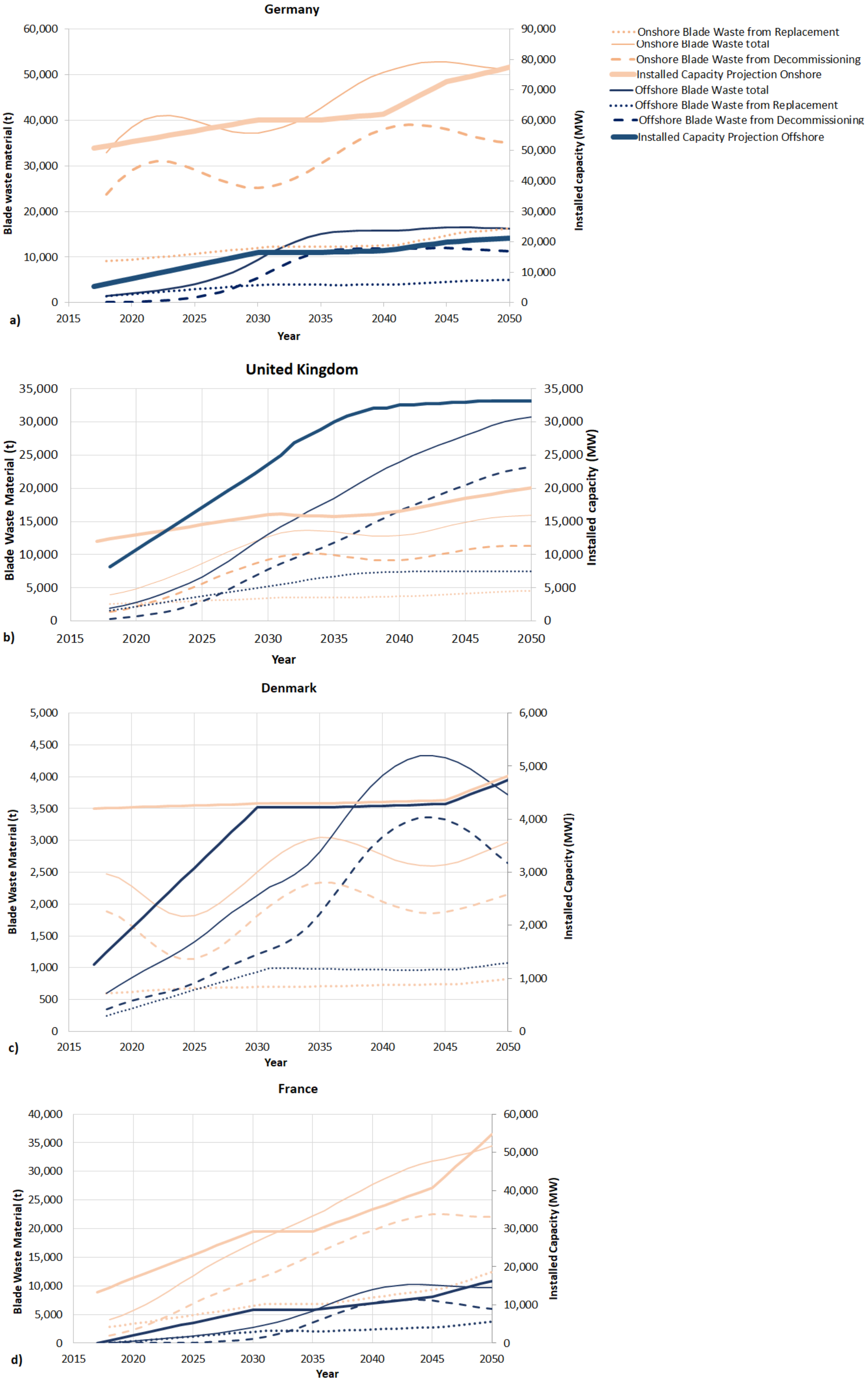


Figure 5 Blade waste material and installed capacity of wind turbines until 2050 in a) Germany; b) United Kingdom; c) Denmark; d) France

It is evident that the onshore capacity has a low rate of increase until 2030 and then it reaches a level of saturation, but it undergoes a 20,000 MW increase after 2040. It is interesting to note the significant fluctuation in onshore blade waste material availability from decommissioning, which is attributable to the significant change on the new installed capacity over the years. In addition, the decrease of the waste blades material due to the saturation on 2030 will begin to be evident after 2050, due to the approximately 20-year time lag between construction and decommissioning of a wind turbine. Regarding the offshore capacity, a low rate of increase of 465 MW/year is observed. Until 2025 the replacement waste constitutes the total blade waste as there are no existing wind farms expected for decommissioning.

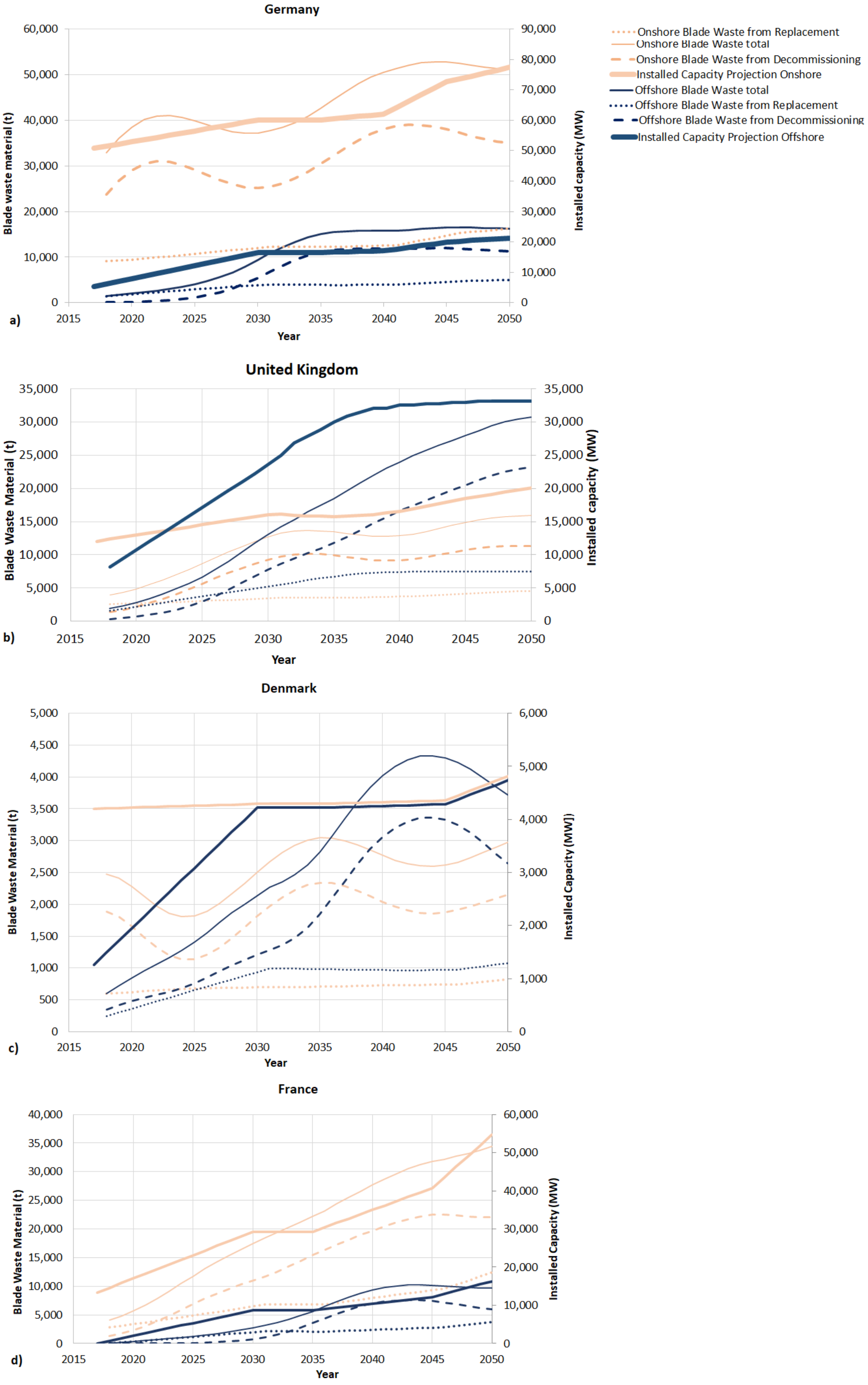

Germany
Blade waste material (t)
Installed capacity (MW)
0
10,000
20,000
30,000
40,000
50,000
60,000
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
a)
2015
2020
2025
2030
2035
2040
2045
2050
Year
Onshore Blade Waste from Replacement
Onshore Blade Waste total
Onshore Blade Waste from Decommissioning
Installed Capacity Projection Onshore
Offshore Blade Waste total
Offshore Blade Waste from Replacement
Offshore Blade Waste from Decommissioning
Installed Capacity Projection Offshore
United Kingdom
Blade Waste Material (t)
Installed capacity (MW)
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
b)
2015
2020
2025
2030
2035
2040
2045
2050
Year
Denmark
Blade Waste Material (t)
Installed Capacity (MW])
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
6,000
5,000
4,000
3,000
2,000
1,000
0
c)
2015
2020
2025
2030
2035
2040
2045
2050
Year
France
Blade Waste Material (t)
Installed Capacity (MW)
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
60,000
50,000
40,000
30,000
20,000
10,000
0
d)
2015
2020
2025
2030
2035
2040
2045
2050
Year

Figure 5b presents the offshore and onshore capacity as well as the waste material from wind turbines in the United Kingdom, as an example of a country with very high amounts of offshore blade waste material expected. The overall capacity in 2050 is forecasted to be a little lower than 55,000 MW, which is almost half of the capacity estimated for Germany. However, in United Kingdom the majority of the capacity will be offshore after 2022. As a result, the total waste material from offshore is expected to be higher than from onshore from 2030 onwards, and in 2050 the total blade waste material is anticipated to be approximately 45,000 t, 65% of which due to offshore. It is worth noting that the offshore capacity is increasing with a rate of 1,333 MW/year until 2035, which is very high and corresponds to half of the offshore capacity rate installed in Europe in total. After 2035 the offshore capacity appears to experience a saturation with almost no new installations. However, this saturation is not identified on the blade waste material due to the time lag between installation to decommissioning.

On the other hand, the onshore capacity is relatively saturated with an average rate of increase around 250 MW/year. The total onshore blade waste material increases until 2030 and then fluctuates until 2050, as seen in

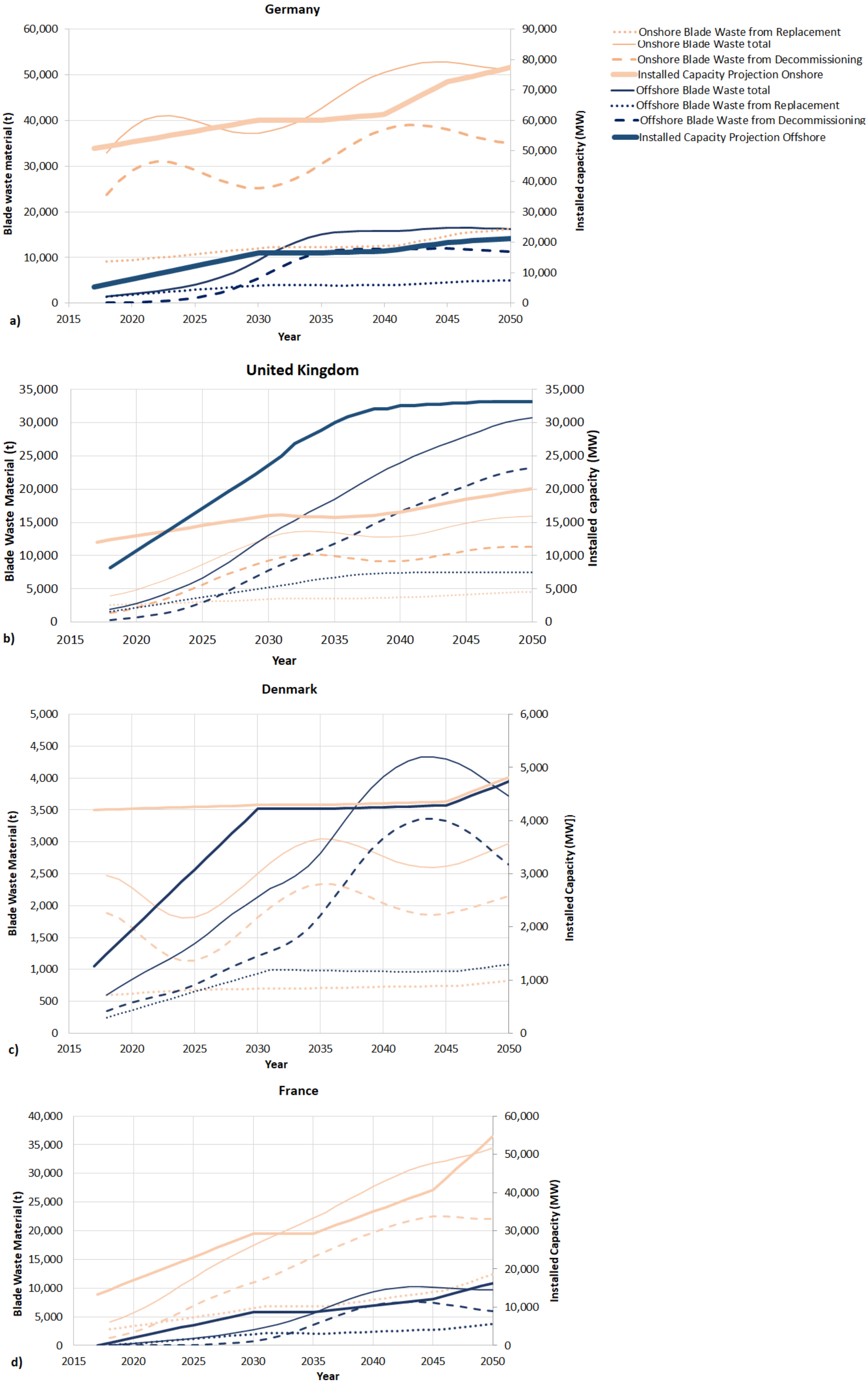

Germany
60,000
50,000
40,000
30,000
20,000
10,000
0
Blade waste material (t)
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
Installed capacity (MW)
a)
2015
2020
2025
2030
2035
2040
2045
2050
Year
Onshore Blade Waste from Replacement
Onshore Blade Waste total
Onshore Blade Waste from Decommissioning
Installed Capacity Projection Onshore
Offshore Blade Waste total
Offshore Blade Waste from Replacement
Offshore Blade Waste from Decommissioning
Installed Capacity Projection Offshore
United Kingdom
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
Blade Waste Material (t)
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
Installed capacity (MW)
b)
2015
2020
2025
2030
2035
2040
2045
2050
Year
Denmark
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
Blade Waste Material (t)
6,000
5,000
4,000
3,000
2,000
1,000
0
Installed Capacity (MW])
c)
2015
2020
2025
2030
2035
2040
2045
2050
Year
France
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
Blade Waste Material (t)
60,000
50,000
40,000
30,000
20,000
10,000
0
Installed Capacity (MW)
d)
2015
2020
2025
2030
2035
2040
2045
2050
Year

Figure 5b.

Furthermore, the forecast of the wind power in Denmark is presented in

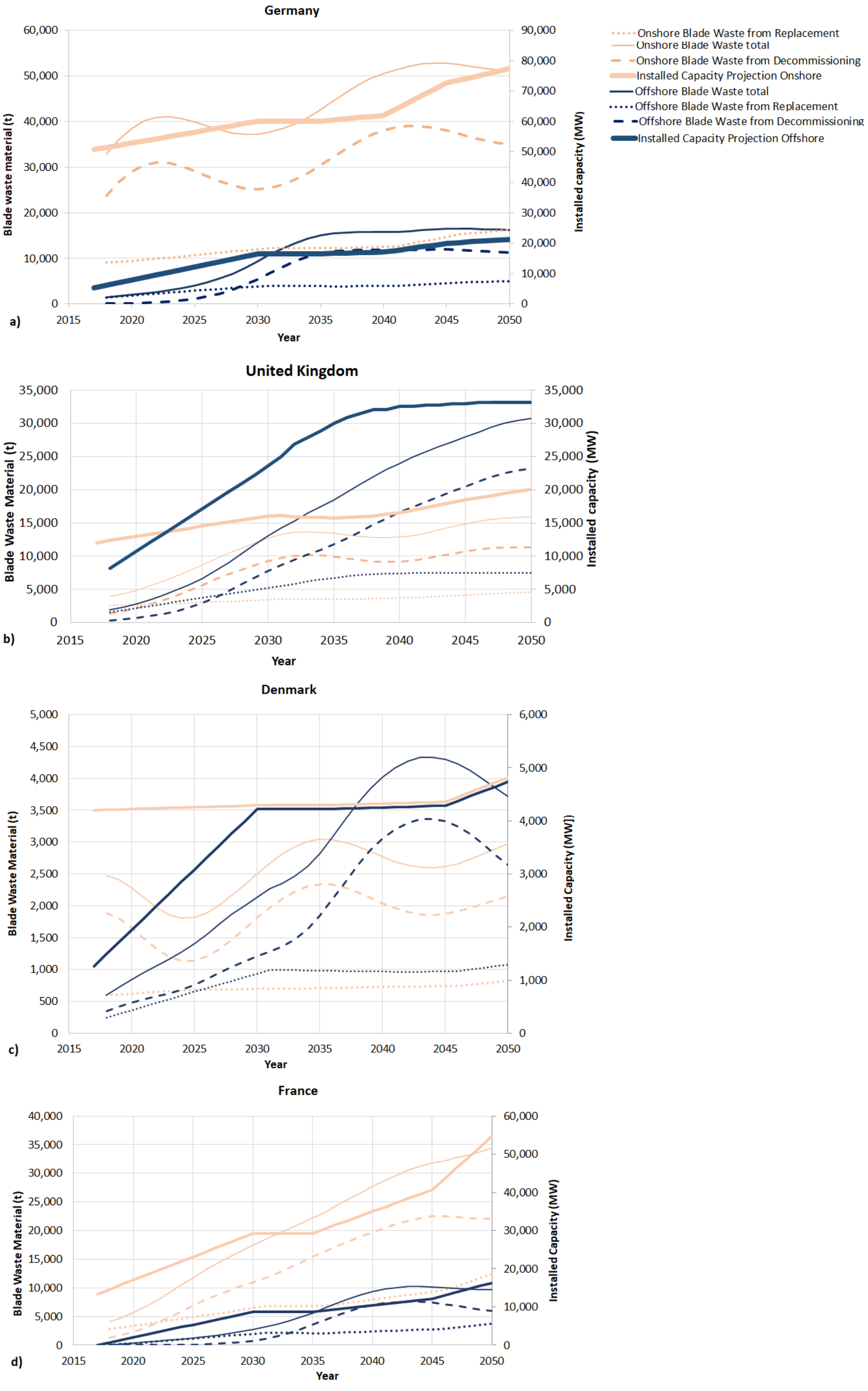


Figure 5c. Denmark currently has in total almost 5,200 MW of installed wind capacity, which is relatively low compared to Germany or the UK. However, it is discussed in this study because Denmark has a ‘strong pedigree’ in renewable energy, which in 2017 consisted 74% of the total electric energy generated in the country (Fleming, 2019). Therefore, it is one of the pioneer countries in Europe for renewable energy and specifically in wind power. Previous reports indicate that 41% of the electric energy in 2017 was covered by wind power, of which 28% was onshore wind turbines (Nghiem and Pineda, 2017). This percentage is the highest in Europe (Nghiem and Pineda, 2017).

The results in

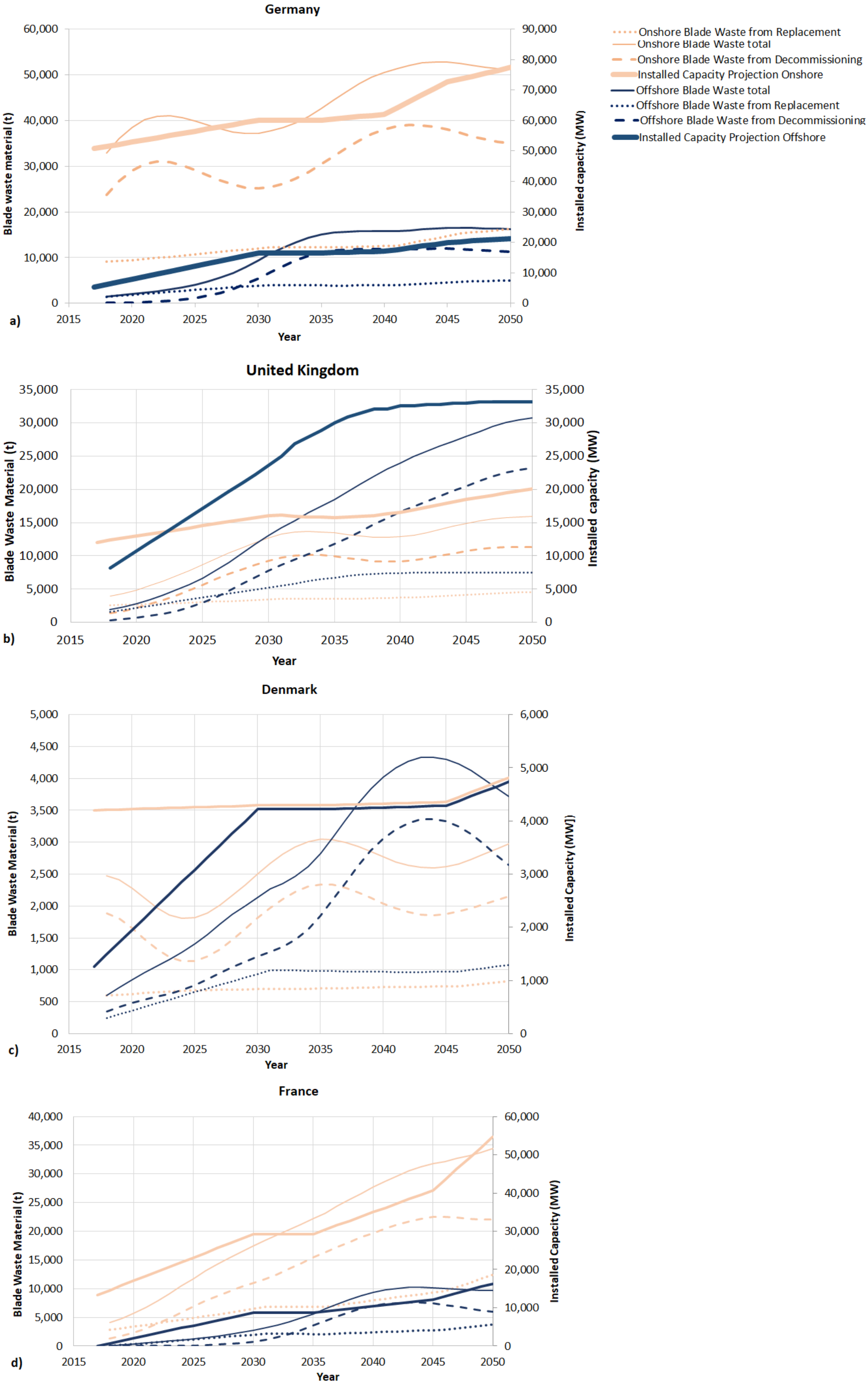

Germany
Blade waste material (t)
60,000
50,000
40,000
30,000
20,000
10,000
0
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
Installed capacity (MW)
a)
2015
2020
2025
2030
2035
2040
2045
2050
Year
Onshore Blade Waste from Replacement
Onshore Blade Waste total
Onshore Blade Waste from Decommissioning
Installed Capacity Projection Onshore
Offshore Blade Waste total
Offshore Blade Waste from Replacement
Offshore Blade Waste from Decommissioning
Installed Capacity Projection Offshore
United Kingdom
Blade Waste Material (t)
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
Installed capacity (MW)
b)
Year
Denmark
Blade Waste Material (t)
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
6,000
5,000
4,000
3,000
2,000
1,000
0
Installed Capacity (MW])
c)
Year
France
Blade Waste Material (t)
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
60,000
50,000
40,000
30,000
20,000
10,000
0
Installed Capacity (MW)
d)
Year

Figure 5c indicate that the onshore installed capacity in Denmark is very saturated and an increase on the installed capacity is forecasted after 2045. On the other hand, the offshore capacity experiences a high increase until 2030, which corresponds to 210 MW/year. However, after 2030 the offshore capacity follows closely the onshore forecast. Due to this rise of the offshore capacity it is observed that in the years 2040 to 2045 the blade waste material derived from offshore wind turbines will exceed the material from onshore and will reach almost 4,500 t. The onshore waste blade material available over the years appears to have significant fluctuations, following the changing growth rate of this industry with the time lag of the wind farm operational lifetime.

Finally, the results for France are displayed in

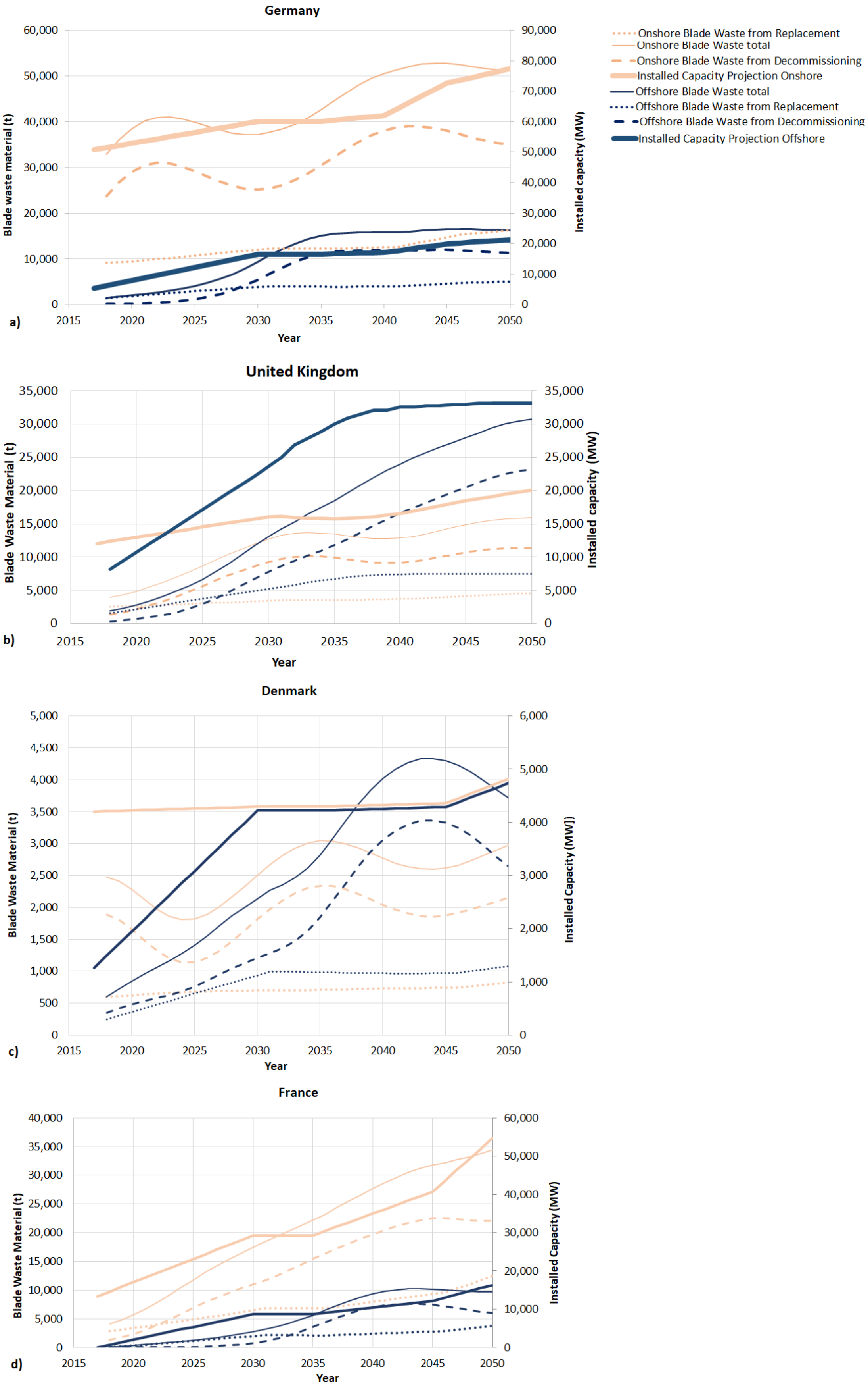

Germany
Blade waste material (t)
Installed capacity (MW)
Year
a)
United Kingdom
Blade Waste Material (t)
Installed capacity (MW)
Year
b)
Denmark
Blade Waste Material (t)
Installed Capacity (MW])
Year
c)
France
Blade Waste Material (t)
Installed Capacity (MW)
Year
d)
2015
2020
2025
2030
2035
2040
2045
2050
Onshore Blade Waste from Replacement
Onshore Blade Waste total
Onshore Blade Waste from Decommissioning
Installed Capacity Projection Onshore
Offshore Blade Waste total
Offshore Blade Waste from Replacement
Offshore Blade Waste from Decommissioning
Installed Capacity Projection Offshore

Figure 5d. France currently has less than 10,000 MW of wind power installed from onshore and zero from offshore. This capacity corresponds to a 6% of the total electric energy in France (Nghiem and Pineda, 2017). However, a significant increase is anticipated in the next decades and it is estimated that France will have in total 72,000 MW installed in 2050, which is over 70% of the wind power in Germany in 2050. Therefore, it can be inferred that in the next decades France will be one of the countries with the highest installed wind energy capacity in Europe with focus mostly on onshore wind turbines.

The rate of the onshore capacity increase in France is 1,333 MW/year on average, and the amount of waste material increase from onshore wind turbines is forecasted to be 1,060 t/year reaching 35,000 t in 2050. On the other hand, as discussed previously, the offshore wind power capacity in France is low compared to the onshore and it will not exceed 20,000 MW. Therefore, the offshore wind blades waste material in 2050 is forecasted to be about 10,000 t. However, a trend for increase in the offshore capacity is identified after 2045, which will correspond to blades waste material available after 2065.

3.3. NUTS 2 Regional-level forecasts

The next part of the analysis concentrates on identifying blade waste material hotspots from onshore wind turbines at a high granularity NUTS 2 regional level in Europe. This is performed in four time snapshots, for the years 2020, 2030, 2040 and 2050 in Figure 6. The maps were created using packages ggplot2 (Wickham, 2016)and rworldmap (South, 2011) in R.

In 2020 the majority of the blades waste material is concentrated in Germany, specifically in the central east and north part. In addition, it is observed that some regions in the central part of Spain also have a high amount of waste material. Some smaller hotspots are identified in parts of Finland and Sweden as well as regions in France, United Kingdom, Italy and Romania. From the 2030 year snapshot it is observed that the waste blade material increases around Europe and more countries are highlighted in the map. However, the highest increase appears to happen in the year 2020 hotspot areas. Germany still remains a key hotspot. In Spain the waste is increased and specifically in the North West part. In addition, the north part in France experiences an increase as well as Scotland, Ireland, Finland, Romania and Sweden. Less intense hotspots are observed in Poland, central Greece, Baltic countries and southern Italy. In 2040 the hotspots in Germany, Sweden, UK, Ireland, Italy and Eastern Europe remain similar to 2030. On the other hand, there is intensification of the hotspots in Spain, France, Finland and in central Greece. Finally, in the 2050 snapshot it is evident that there are limited differences compared to 2040. A small increase of waste material hotspots is observed in the Baltic countries and north part of the UK, north France as well as Poland.

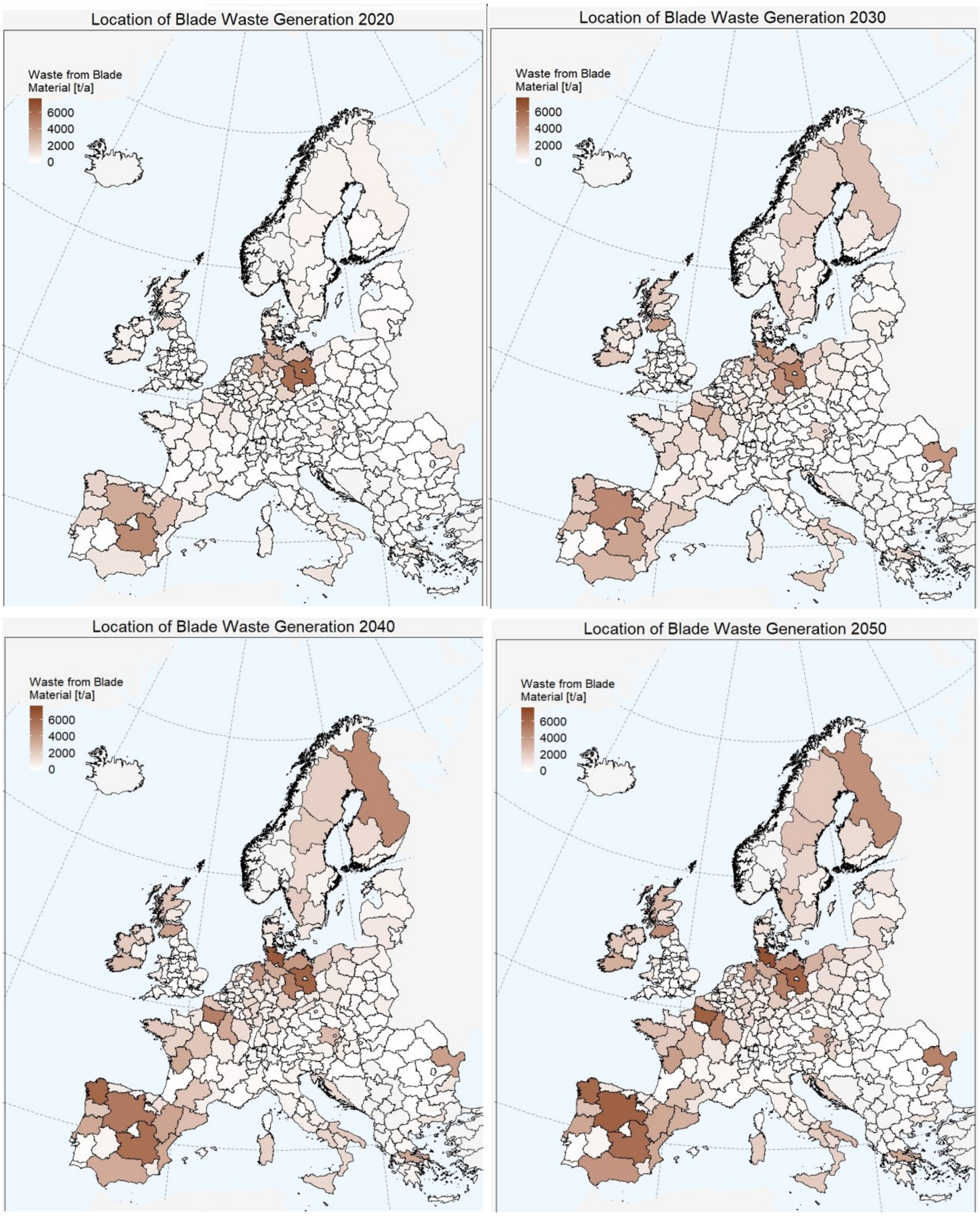


Figure 6 Blade waste material forecast from onshore wind turbines in regions of Europe for 2020; 2030; 2040; 2050

A similar analysis has been performed for the waste blade material from offshore wind turbines in regions of Europe, and is presented in 10-year time snapshots in Figure 7. In 2020 the waste material amount is negligible with no hotspots identified, which was expected since very few offshore projects will reach the end of their life by 2020. On the other hand, in the 2030 snapshot it is evident that hotspots begin to develop in the south west part of the UK, Denmark, the north part of Germany and in Netherlands. In 2040 hotspots in more regions of Europe begin to develop, and the existing ones intensify. In specific, new hotspots are identified in the coastal part of France and Poland in addition with some regions at the north of the UK and Denmark. On the other hand, the key hotspots will be in south east regions of the UK, Netherlands and Germany. Finally, in 2050 the amount of material in the south east regions of the United Kingdom will create a key hotspot, whereas there are minor changes in other regions of Europe compared to 2040.

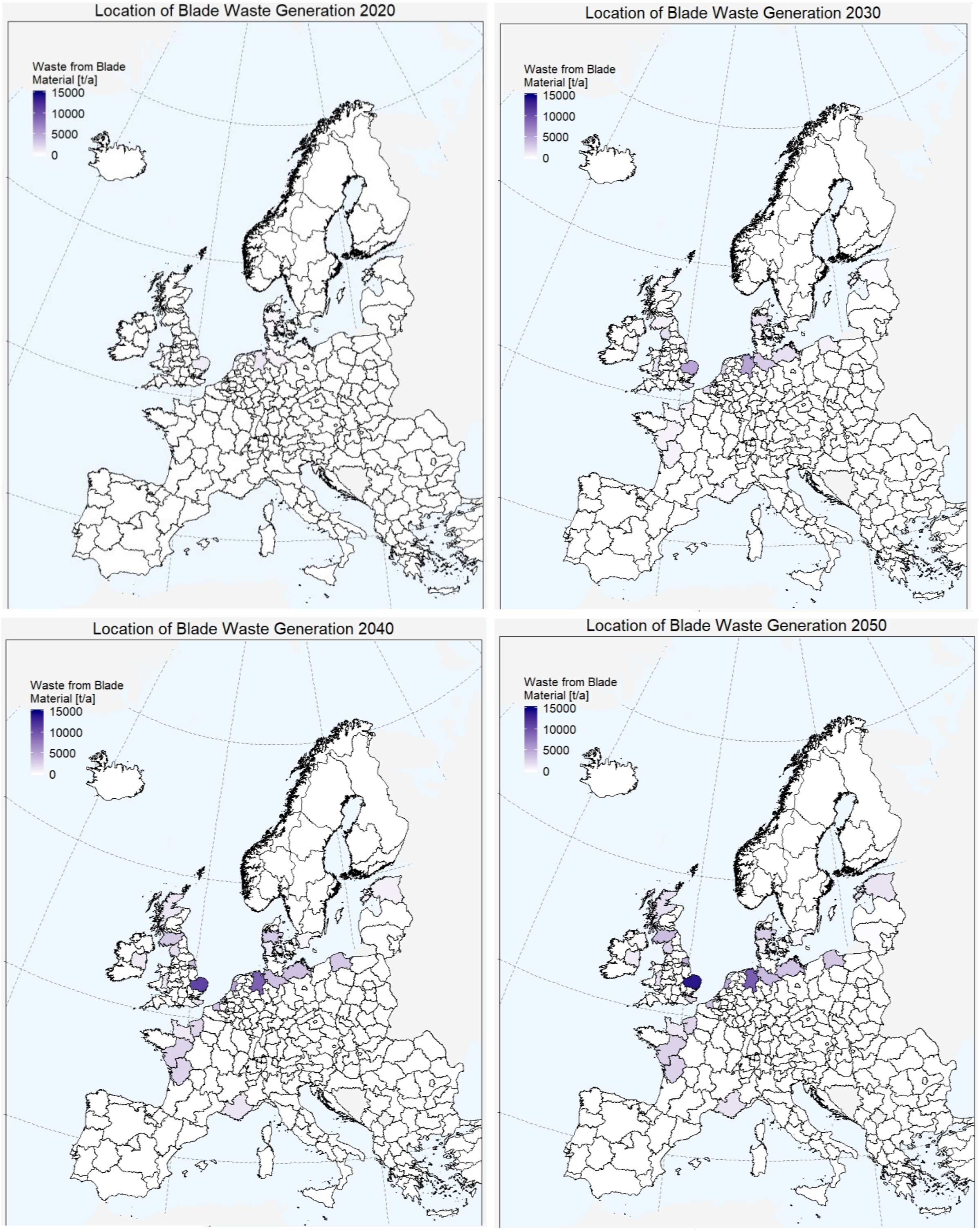
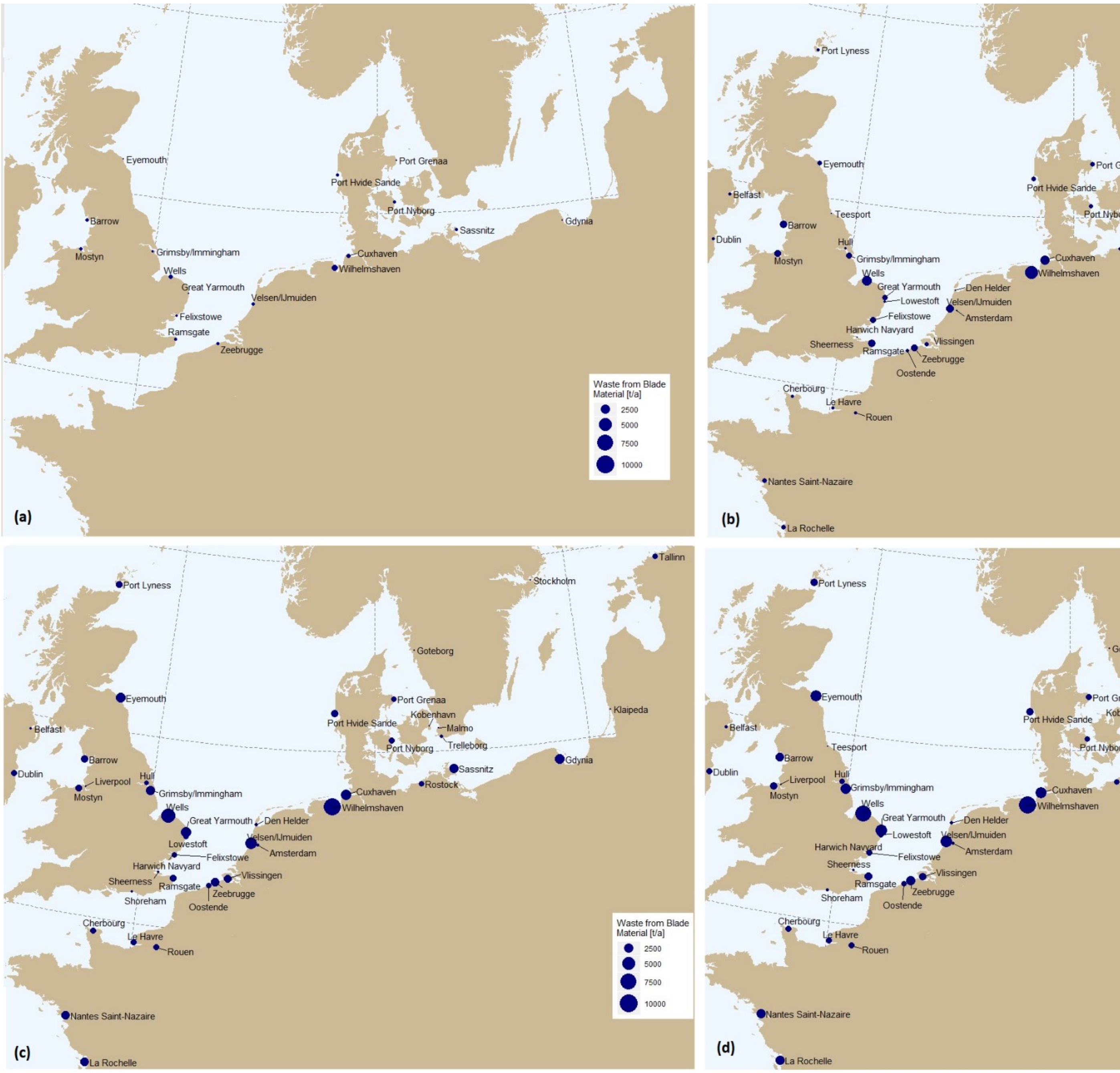


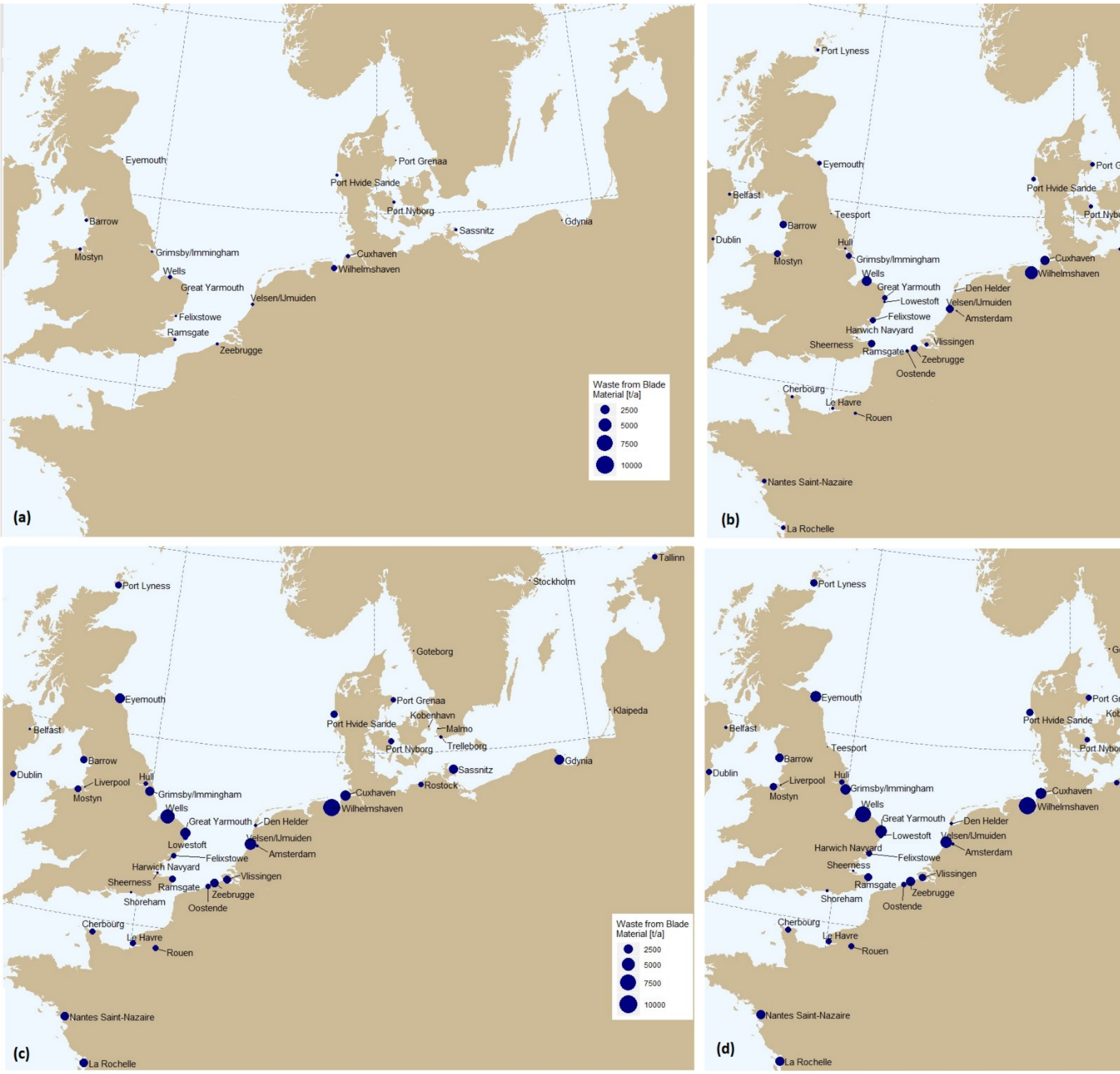
Figure 7 Blade waste material from offshore wind turbines in regions of Europe for 2020; 2030; 2040; 2050

Since decommissioning of offshore wind turbines will naturally bring the EoL blades to a port to be further processed, a further analysis has been performed in order to estimate which European ports will be expected to receive and handle most of this waste. In the following figures the material from the waste offshore wind turbine blades is allocated to the nearest available suitable port, which is an assumption based on current practices of the offshore wind and the offshore oil and gas industries. In the 2020 snapshot in



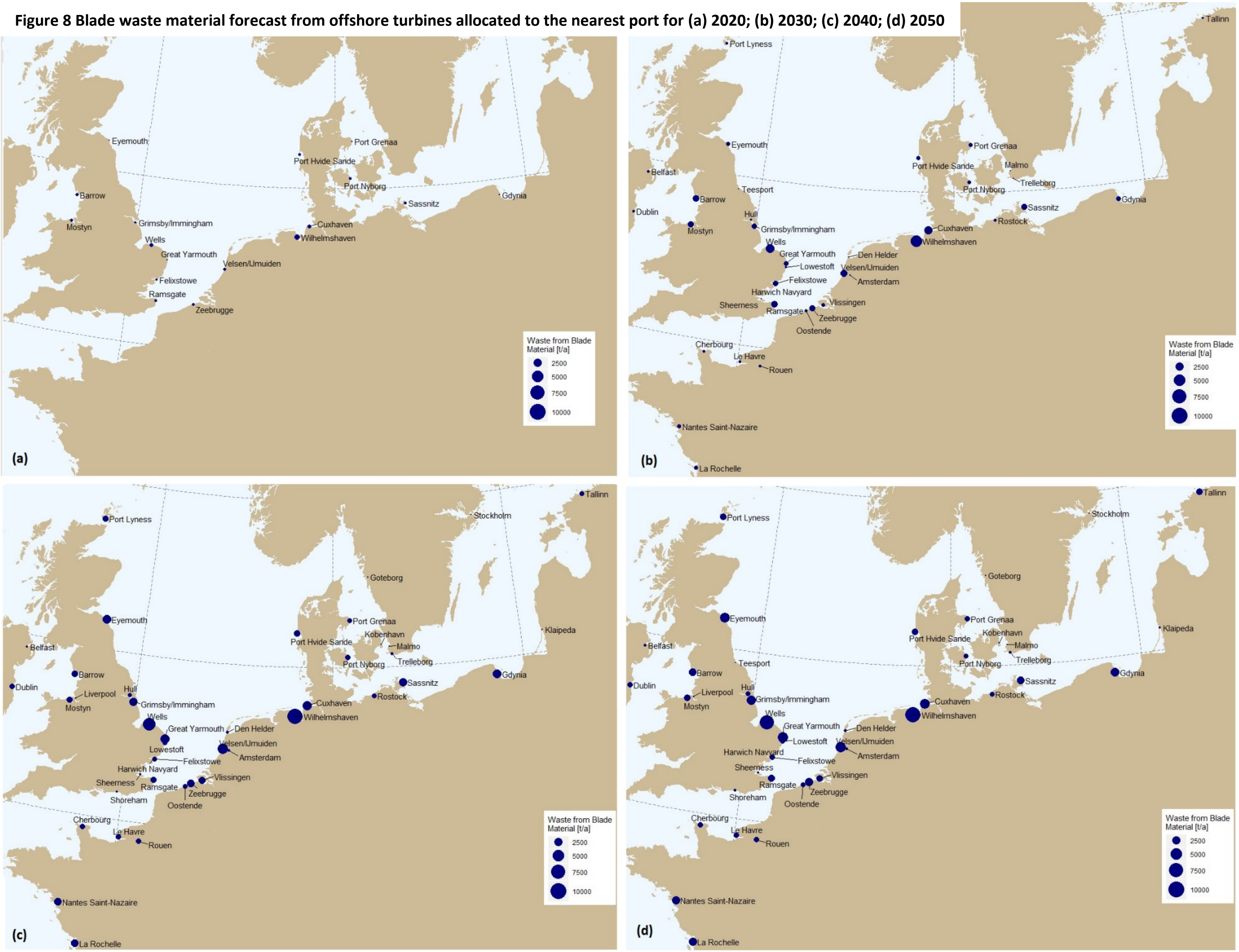
less than 2,500 t of material is gathered in any one of the ports in Europe, all in the Baltic and North Sea, with the highest amount expected at the Wilhelmshaven port in Germany. Small quantities of waste material will be also handled through ports of the United Kingdom, Germany, Poland, Belgium, Denmark and Netherlands. In 2030 the amount of material increases significantly and more ports are included in the map. The material handled will exceed the 2,500 t/year in some ports of Germany and United Kingdom. New ports that will receive material in 2030 are identified in France, Ireland, Sweden and Estonia.

From the snapshots of the forecasted material in the ports of Europe in 2040 and 2050 presented in



it is observed that the waste blade material is allocated to the same ports as 2030, however an increase on the material handled is expected in the majority of the ports. In specific, the highest amount that will exceed the 7,500 t/year of material is Wilhelmshaven in Germany, followed by ports in United Kingdom and Netherlands that will handle over 5,000 t of material. Finally, comparing the 2040 and 2050 snapshots the maps have limited differences. This can be attributed to a saturation on the offshore wind power capacity around the year 2030, which was also identified from the total blade waste material in Figure 3.

Figure 8 Blade waste material forecast from offshore turbines allocated to the nearest port for (a) 2020; (b) 2030; (c) 2040; (d) 2050



4. Conclusions and Policy Implications

The wind turbine blade waste material in Europe until 2050 was forecasted in this study considering both offshore and onshore wind turbines, following a systematic process. In this study, regional growth rates were used to estimate the blade waste material at a high level of granularity, i.e. per NUTS 2 region, and also per country, based on publicly available data on existing or under construction wind farms. In addition, a stochastic distribution was used to model the wind turbines lifetime derived from actual data of decommissioned turbines. Relationships were developed to express the EoL blade waste material as a function of the turbine characteristics. In addition, the waste due to blade replacement while the wind farm is operational was also considered.

The first stage involved forecasting the future installed capacity of wind power in Europe. It was identified that onshore will constitute the greatest part of the total installed capacity, accounting for more than 78% of the total in 2050, whereas offshore will experience a high growth in the installed capacity between 2020 to 2030. The second stage, indicated that the total wind blades waste material in Europe will reach 325,000 t in 2050, 76% of which from onshore wind turbines. It should be noted that a significant yearly increase of blade waste material should be expected until 2045, a fact that should be considered for designing any circular economy, recycling or disposal system for this type of waste.

The wind power capacity and blade waste material availability was for also forecasted at the country level. Findings for selected countries indicated that Germany will have the majority of blade waste material from onshore wind turbines, while the United Kingdom will have the highest capacity and blade waste material from offshore. Denmark, which has been a pioneer in wind power energy, will soon experience a saturation, whereas France is anticipated to have a significant increase on installed wind power capacity. Another important finding is that some countries will experience significant fluctuations of the yearly available blade waste material, both positive and negative. This is a fact that will be critical for the feasibility of any future circular economy pathway for this material, since the prospective processors, suppliers and end users will be focusing on the security and continuity of supply of the material. This implies that solutions should focus at a wider geographic context than a single country, to be able to mitigate these regional or country-level fluctuations in availability, and ensure security of supply.

This work has also identified hotspots at a high level of geographical granularity (NUTS2 regions in Europe), for the years 2020, 2030, 2040 and 2050. The findings can be useful for designing systems that could utilise and process the blade waste material adopting a circular economy approach, and diverting it from the waste streams. This is because the logistics costs of transporting the wind turbine blades to a processing facility are quite high, the process is complex, and also the downstream supply chain costs of supplying the processed material to end users can be significant. Therefore, it is important to understand the location of the hotspots of material availability expected in the future, to be able to efficiently match the demand with the supply.

Finally, this study has identified which ports around Europe are expected to handle significant quantities of offshore blade waste material in the future. Despite the fact that several key assumptions had to be made to perform this analysis and the low current level of maturity of the offshore wind decommissioning industry, which introduce uncertainty in the findings, the results are an indication of which ports could play a significant role in the future in decommissioning, handling and processing offshore wind blades. This information can be useful for the offshore wind operators, decommissioning industry, policy makers and port authorities in order to plan for the appropriate capacity and infrastructure that will be needed in the future.

The findings of this study can also support policy makers in understanding the magnitude of the waste management problem and both its geographical and temporal evolution. They can further support decisions on regulations regarding the landfilling, and potential incentives needed for new technology development and recycling facilities for this emerging type of waste. The findings can also be useful to prospective processors, suppliers and end users of the recycled material by supporting understanding the waste material availability hotspots and future geographical and temporal variability in waste material supply.

This study has limitations that are usually inherent in long-term forecasting. For example, the actual future installed capacity could be heavily influenced by political, macro-economic, regulatory or even technological changes; the forecasts performed are based on the information available at the time of writing. Despite every effort to triangulate data and sources of information, the offshore wind sector is still in its infancy providing very limited past data, affecting the level of certainty on the forecasts, compared to onshore. Detailed forecasts per country regions were used wherever available, however in other cases the overall country forecast was employed for each region. Therefore, more accurate predictions for the regions of each country should be used in the future. Another assumption made is that potential technological improvements of the wind turbines have not been considered due to lack of data. Finally, the blade replacement ratio can significantly influence the outcomes and can be affected by local climatic conditions, a factor which is not considered in this study.

An interesting future direction would be to investigate appropriate technologies and circular economy pathways to treat the wind blades waste material and design the required supply chain networks with a focus on minimising the cost. Apart from the technologies, suitable markets for the recycled material should be identified adopting a cross-sectoral approach, as recycled material from the wind blades may not have the required properties for being reused in the wind power industry, but may be used in other sectors with different material requirements. For example, mechanically treated wind blades could be used as reinforcement in screed flooring or as fillers in thermoset bulk molding compound and sheet molding compound (BMC/SMC), which are used in several sectors, including the automotive, transportation, electronics and construction. The information presented in this paper can be of critical importance to support research on this field, as the high level of granularity of data allows feasibility assessment of systems at a more local level with higher accuracy.

Acknowledgments

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