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Abstract: Since Vindeby in 1991, more than 100 projects have been installed in Europe, and will need decommissioning one day. Despite the increasing number of projects reaching this phase, decommissioning is still an area that has received relatively little attention. This paper considers the practicalities and economic implications of recycling offshore wind components as part of an end of life strategy. There is no existing source that gathers together materials data for currently operational wind turbines in Europe relevant to recycling. Since this information is necessary for any economic analysis of component recycling, such a dataset was generated. The results illustrate the specific wind turbine materials suitable for recycling, expressed in percentage values of the wind turbine's total mass. An economic analysis is then performed to study how recovering these materials and selling them as scrap metal can impact the decommissioning costs. As concluding remarks, recycling offshore wind components could pay for nearly 20% of the total wind farm decommissioning costs if monopile foundations are considered. Furthermore, the volatility of scrap prices is such that this could even help define when it would be best to decommission an offshore wind farm.

COVER LETTER

Thank you very much for considering our article. It has a lot of effort with diverse expertise from people with different backgrounds. It is a topic that is currently receiving a lot of attention and causing concerns, and is the first outcome of a wider research we are producing.

We are proud of submitting it to Energy Policy as we consider this journal is ideal for generating the corresponding concerns and in consequence, enable a transition to a potential improvement and make this end of life stage, more sustainable.

Title:

Recycling offshore wind farms at decommissioning stage

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HIGHLIGHTS

- Uncertainties in end of life strategies of offshore wind projects make decisions complex and challenging
- An inevitable decommissioning era is arriving which must adequate to project's characteristics
- Recycling should be included as a target and taken into consideration since the planning
- An appropriate recycling could pay part of the decommissioning costs while making the process more sustainable
- The volatility of scrap value can help determine when it is best to decommission

In general, all the valuable comments from the reviewers have been taken into consideration and therefore all the document has been meticulously reviewed while introducing them or acting in consequence.

Taking advantage of this revision, the data base that acts basis of this research has also been updated which leads to a change in the results. Furthermore, a big change in the results is due to the new consideration of monopiles being removed just up to the seabed, as these are embedded and their complete removal would involve high environmental impacts and extreme costs. This new perspective reduces the recoverable amounts but makes the analysis more realistic.

The graphs have now been standardised so that they have the same format, the legends are bigger and 2D visualisation is now the preference. Moreover, the tables have also been modified so that they are self-explanatory.

To finish, a section has been included regarding the volatility of scrap values (at the decommissioning costs sections) which now also contains a small sensitivity analysis. The values have also been corrected and updated to current prices.

A summary of the comments is shown below:

Section	Reviewer's Comments	Modification
Figures in general	Do legends clearer and bigger and use same formatting for all the graphs. 3D visualisations changed to 2D	All implemented
3. Methodology	Make clear that research was done on the European offshore wind	Included throughout the manuscript
4. Results	Figure 1	Differences between Figure 1 and Figure 3 clarified
	Figure 4	Yes, now has been corrected
	Page 26, Line 38	Specification offshore wind turbines now included throughout the manuscript
	Page 26, Line 51	Corrected
	Page 27, Line 10	Corrected
	Page 27, Figure 6	Included; the graph had shrunk and therefore the legend became incomplete
	Page 27, Figure 7	Circles have now been made equal, as size did not have a meaning, just the colours
	Page 27, Table 2	Description included which mentions that direct drive was not analysed due to lack of available data
5. Recoverable quantities	Page 27, Line 54/55	Yes, comment about future research regarding the evolution to direct drive turbines included
	Page 27, Line 58	Corrected
	Page 28, Line 10	Corrected
	Page 28, Line 12	Rephrased. It
	Page 28, Figure 10	Corrected
6. Decommissioning costs	General comment about section being weaker	It has now been improved by included a section regarding scrap values
	Volatility of scrap prices	Section included to see how a change in the scrap values changes the cost reduction in decommissioning costs
	Table 4	Corrected
	Table 5	Rephrased so that it is better understood
7. Discussion	Page 29, Line 18/19	Corrected
	Page 29, Line 28	Corrected

ABSTRACT

Since Vindeby in 1991, more than 100 projects have been installed in Europe, and will need decommissioning one day. Despite the increasing number of projects reaching this phase, decommissioning is still an area that has received relatively little attention. This paper considers the practicalities and economic implications of recycling offshore wind components as part of an end of life strategy. There is no existing source that gathers together materials data for currently operational wind turbines in Europe relevant to recycling. Since this information is necessary for any economic analysis of component recycling, such a dataset was generated.

The results illustrate the specific wind turbine materials suitable for recycling, expressed in percentage values of the wind turbine's total mass. An economic analysis is then performed to study how recovering these materials and selling them as scrap metal can impact the decommissioning costs. As concluding remarks, recycling offshore wind components could pay for nearly 20% of the total wind farm decommissioning costs if monopile foundations are considered. Furthermore, the volatility of scrap prices is such that this could even help define when it would be best to decommission an offshore wind farm.

KEYWORDS

Offshore wind farms, Offshore wind energy, Decommissioning, Dismantling, Recycling, Sustainability, Cost reduction

1. INTRODUCTION

The wind energy sector is faces challenges regarding aging fleets, structural integrity, and decisions concerning lifetime extension or decommissioning [1]. To date, nearly 115 European offshore wind energy projects have been installed or are currently under construction [2]. Of these, and not including floating demonstration projects (Hywind and Windfloat) or prototypes, 4 have already been decommissioned. Yttre Stengrund (10MW, Sweden) was the first, in 2015, after only 15 years of operation [3]. This was then followed by Lely (2MW, Netherlands) which was removed from the sea in 2016 after operating for 20 years [4]. Vindeby (5MW, Denmark), the first offshore wind farm to be installed in 1991, was the third project to be dismantled in 2017, operational for 26 years [5]. And the most recent project to be decommissioned was Utgrunden I (10.5MW, Sweden), in operation for 18 years [6].

The life time of a project is estimated to be between 20-25 years, but as it can be seen, there is still too much uncertainty in the sector as only four of them have reached this stage. Blyth, the first United Kingdom's offshore wind farm (EON, 4MW, United Kingdom) also ceased its operation in 2013 after only 13 years of operation. Its decommissioning programme was not prepared

and in consequence, the project is expected to be dismantled by 2019 [2]. This has also happened with the Beatrice Demonstration Project (10MW, UK) [2].

Besides, there are currently 3 projects that have been operational for more than 20 years such as Tunø Knob (5MW, Denmark), Irene Vorrink (16.8MW, Netherlands) and Bockstigen (2.75MW, Sweden) and will soon require an end of life strategy. This adds to a total of 5 wind farms needing dismantling measures by 2020 and increasing to 30 more by 2030.

Decommissioning is referred to, as the procedures performed when a project reaches to an end and ceases its operation, ensuring that the site is returned to its original state before the project was deployed [7]. In the offshore wind energy sector, these measures will imply removing components such as wind turbines, meteorological masts, offshore substations, its corresponding foundations and transition pieces, cables, scour material (if applicable) and any onshore constituents build for the purpose [7]. Many of these elements involve materials such as steel, cast iron or copper, that can eventually be recycled or even reused as spare components [8]. Due to this, it is important to understand the benefits and challenges of this potential recycling market when decommissioning offshore wind farms, which has been the objective of this study.

2. LITERATURE REVIEW

Sustainability is an important matter that is gaining more and more popularity nowadays, where climate change and environmental impacts are significant concerns worldwide. Regarding the offshore wind energy industry, developers are expected to follow legal regulations such as the United Nations Convention on the Law of the Sea (UNCLOS) [9], but at a national level, other countries also have own regulations such as United Kingdom with the Energy Act [10], or Ireland with the Coast Protection Act [11]. All these have been developed with the purpose of reducing the impact of installing offshore wind farms on a local marine environment, and highlight the responsibility of a wind farm owner to conduct a complete dismantling and reduce the project's impact on the marine ecosystem. Nonetheless, there is a current lack of well-defined guidelines, standards and recommendations on the general procedures to follow with regards to the impacts from seabed activities under national jurisdictions [7] [12].

As offshore wind farms are relatively new, owner/operators have been mainly concerned in improving installation techniques and in achieving operational efficiency. Despite the potentially large costs, logistical difficulties and environmental impacts, lifetime extension, refurbishment, repowering and decommissioning phases of a project have been given little attention to date. This is currently changing due to the rising concerns of developers about their aging assets, and is becoming an important matter

as end of life strategies are a significant part of any project and require consideration from an early design stage. If this is not done, impacts can be severe, and costs can be higher than expected [7].

The end of life strategy of a project involves technical, economic and legal aspects that drive the process where the operator decides which option would be best for its aging wind farms. It can vary from going straight into decommissioning or having intermediate stages such as lifetime extension, refurbishment or repowering, and which will eventually lead to decommissioning, which is an irredeemable phase of any project. This end of life decision will merely depend on an adequate failure mode identification throughout the operational life of the offshore wind farm [13].

Lifetime extension implies the operation of the wind farm for more years than what it was designed for and is usually referred to 20-25 years. On this regard, wind turbines must have enough structural life remaining so that the safety level is not compromised. In addition, wear-out of components translate into higher operation and maintenance (O&M) costs and turbine downtime [1].

Refurbishment (or partial repowering), involves the replacement of minor elements of the project such as the drivetrain or the rotor and keeping if possible, the tower, foundations and cables. This would allow the existing projects to increase efficiency and consequently, energy production [7], but in the end, certain decommissioning is required as elements are removed.

Repowering (or full repowering) consists in trying to use most of the original electrical system while installing more powerful turbines on the existing foundations, if possible. This is because foundations can be designed for a longer design life than the 20-25 years of the wind turbines [14]. The estimated lifetime of a gravity-based foundations is 100 years [15] while for the electrical system (interray and transmission lines) is 40 years [16]. But these estimations are still vague and difficult to predict, as every project has its own unique characteristics, which lead to the loading factors and aging of the asset.

Decommissioning can be identified as the most important of all the end of life strategies, as it will always be present in any project and all the paths lead to it as all the other end of life decisions will end up, either way, with this stage. It is the last phase in a project's lifecycle and can be considered as the opposite of the installation phase [17]. The principle "the polluter pays" applies [10], which ensures the site is left as it was before the deployment of the project, and includes a two-year period of monitoring and remediation [18].

In contrast, the removal of these offshore structures is also generating controversy as in some cases marine life has flourished around the foundations (which can create an artificial reef) and should not be disrupted [19]. This would imply the abandonment of these offshore structures [20] and would of course benefit the owner by saving the costs associated with its decommissioning.

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2 In consequence, if owners do not save the appropriate amount for this final stage, it could lead anyway to the abandonment of
3 these structures.
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6 Therefore, it is highly likely that before the complete dismantling of a site, life extension, repowering or refurbishment options
7 will be studied, but the high degree of uncertainties due to an inadequate planning and the limitation on the literature available at
8 present, can make this decision process complex and challenging.
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14 What is clear is that an inevitable need for decommissioning is arriving, and these new processes must deal with an enormous
15 diversity in the number and model of offshore wind turbines, foundation types and site conditions. The selection of the wind
16 turbine type in a project determines the foundation characteristics, but these structures must also be suitable to the seabed and
17 weather conditions [14]. These result in decommissioning programmes that are exclusive and unique for each wind farm,
18 complicating the creation of a general methodology. Additionally, recent studies are suggesting that these decommissioning
19 programmes are underestimating costs as well as being performed vaguely [7].
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28 End of life decisions previously described have an enormous potential in becoming sustainable by means of reusing or recycling
29 the dismantled components, which has been the focus of this study, and where the contributions of this research can be
30 summarised as follows:
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35 1. As decommissioning will always be the final stage of an offshore wind energy project, efforts must be attempted on making it
36 as sustainable as possible by means of enhancing the recycling of the removed components,
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38 2. A quantification of the different materials that have already been deployed at European waters in offshore wind energy
39 projects and that could eventually be recycled,
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41 3. An estimation on how the recycling of the main components of an offshore wind farm affect the overall decommissioning
42 costs.
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50 3. METHODOLOGY

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52 For the purpose of this study, a market analysis of the European offshore wind energy sector was thoroughly performed. Data
53 was collected for all existing offshore wind projects that have already been installed, are currently under installation or
54 construction, or have already been decommissioned. Planned projects were considered too far in the future and uncertain, so
55 were excluded from this analysis.
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60 Each project's main characteristics were gathered together from the available sources, and include the location of the project, the
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number and model of offshore turbines, the water depth, distance to shore and foundation type, amongst others. It is important to understand the market drivers, since all these different project's components will subsequently need to be dismantled and thus, any developed methodology and analysis should be as general as possible.

An overview of this collected dataset and the tendencies found within, is presented in the following section. This collection has also enabled the investigation of relevant trends. An example of this is that two wind turbine manufacturers have been recognised to be in control of the vast majority of the market, involving unique strategical resource use proportions. The most implemented turbine model specifications were also acknowledged while searching for the principal materials used, enabling further study. These could be found mainly from the manufacturer's brochures and specifications [21] [22] [23] [24] [25].

4. RESULTS

Offshore wind turbines are comprised of many different materials, and these vary depending on the manufacturer. This is shown in Figure 1, where the 7MW 154m rotor Siemens Wind Power turbine is the market leader of the offshore wind turbines being installed up to date, with a share of 17% of the market. Another 2 Siemens machines follow: the 3.6MW 120m rotor and the 6MW 154m rotor with 15% and 13% respectively. The "other" section is composed of the remaining models that were less than 2% of the installed capacity. Figure 2 describes the market penetration by manufacturer, where many smaller companies such as Repower, Neg Micon, NedWind, Nordtank, Bonus, Adwen and Enron Wind have been consolidated into multinationals like Senvion, Vestas (which includes MHI Vestas), Siemens or General Electric, and this helps explain why so much of the market is controlled by so few companies and how they gained design and operational experience. Siemens is a strong market leader with 69% of the total installed capacity, followed by Vestas with 20%. The market can be seen to be dominated by 5 manufacturers, since the rest account for less than 0.3%.

Figure 1: Offshore wind turbines installed by model in Europe.

Figure 2: Offshore wind turbine market share by manufacturer in Europe.

For the purpose of this study, only the most commonly deployed offshore wind turbines are studied since, as seen above, relatively few turbines account for most of the installed capacity. Nonetheless, the installed capacity itself is a useful quantification when considering energy supply impacts of decommissioning, but more important for this analysis is the number of installed turbines and the nominal capacities, as shown in Figures 3 and 4 below. In Europe, nearly 5200 turbines have been installed or are under installation, where the three preferred models have been from Siemens Wind Power and correspond to the SWT-3.6-120 with 953 turbines (18%), SWT-3.6-107 with 591 (11%) and SWT-7.0-154 with 540 (10%).

In Figure 4, the market is distributed by turbine size or rated power, showing that turbines of 3.6MW have been the leaders with 1551 turbines, followed by the 3MW with 609 turbines, and closely by the 6MW with 547 less. This is changing with time as wind turbines are continuously increasing in size and nominal power, being around 4.3 MW the calculated European average rated power at the moment.

Figure 3: Total number of offshore wind turbines being installed in Europe.

Figure 4: Total number of offshore wind turbines being installed in Europe considering rated power.

When assessing the amount of material used per turbine, another important element to analyse is the foundation type, since there is a significant amount of recoverable materials there too. Foundations are the structures that connect the turbine to the ground [26]. In Figure 5, it is shown that monopiles are the most frequently implemented structure typology and is because of its good adaptability to diverse seabed conditions, ease in fabrication and cost competitiveness up to water depths of 50m [27]. Other common types are jackets, tripods, suction buckets, gravity bases and floating. All foundation structures are primarily fabricated in steel. This is mainly due to the material's strength, flexibility and resistance to marine environments, while being 100% recyclable, making it a fundamental part of the circular economy.

In total, it is calculated that more than 4044 monopiles from 70 projects have been installed or are being currently deployed. There is in fact, even more available for recovery if meteorological mast foundations, substations or projects that choose to have different types of foundations in the same array are included.

Figure 5: Foundations being installed in the European offshore wind energy sector.

To achieve a reduction in the levelised cost of energy (LCOE), projects are moving into deeper waters to enable the exploitation of more energetic and consistent wind energy resource [27]. In the following table, the average characteristics of the European offshore wind energy projects are represented, considering the number of installed turbines.

Table 1: Average characteristics of European offshore wind energy projects.

Another well-known trend is the increase in the nominal rated power of offshore wind turbines, since more energy can be generated as a result of larger rotors, swept area and associated drivelines [28]. This involves the use of more materials due to having to fabricate longer blades, bigger generators, larger towers, etc., making the whole structure heavier. Figure 6, performed with the data collected, confirms that as the size of offshore wind turbines increase (bubbles), so do the blades, making them heavier.

Figure 6: Change in blade length and weight as turbine's nominal power increases (bubbles).

From the specifications of the 22 different turbine models that comprise the 99% of the European installed capacity, it is observed that the blade materials are changing to optimise the weight. In general, as described in Figure 7, glass fibre reinforced epoxy (GRE) has been the most applied (in blue), followed by glass fibre reinforced plastics (GFRP) in green, and carbon fibre reinforced epoxy (CFRE) in red. It must be highlighted that blades are one of the wind turbine elements found to be very difficult to reuse/recycle due to its material composition, and there is significant ongoing research to solve this challenge [29]. They are also the most voluminous part of the wind turbine and makes them difficult to handle. They are currently being shredded and incinerated or sent to landfill for disposal [30].

Figure 7: Comparison between blade length and weight considering the materials (GRE: blue, GFRP: green, CFRE: red).

As nominal power of offshore turbines is increasing, and projects are being placed at deeper waters, monopile foundation designs need to meet this requirement too. The forces on higher power turbine foundations increase due to higher top head mass, thrust and wave loading [31]. Consequently, monopiles are becoming bigger in diameter, with thicker plates and thus, heavier [32]. Therefore, if the dimensions of monopiles are studied considering characteristics such as weight, length and diameter, it can be noted that the strongest relationship is between weight and length, as represented in Figure 8, where the bubbles indicate the rated power of the turbines that the monopile support.

Figure 8: Monopile change in weight and length as the rated power of offshore wind turbines (bubbles) increases.

Furthermore, offshore wind turbines can be categorised into geared turbines and direct-drive (no gearbox), where the current preference in the market is towards geared [33]. This comprises 67% of the total European installed capacity, but 76% if the number of installed turbines is used instead, with 18 different turbine models.

The calculated average specifications of these turbines can be observed in the subsequent table, where the number of turbines installed is also taken into account, reducing the previous calculated averages. This is because the new bigger offshore wind turbines appearing in the market are direct drive (no gearbox) and imply higher rated powers, with a current average of 6MW. These gearless offshore wind turbines benefit from a weight reduction on the nacelle, as gearboxes are one of the heaviest elements found in the nacelle. It also decreases the amount of technical failures as there are fewer moving parts, and this translates into a decrease in the costs of operation and maintenance [34]. However, these machines are currently a minority of the sector with a 32% installed capacity and a 22% regarding number of installed turbines.

From Table 2 it can be observed that as a significant number of Siemens direct-drive 154m bladed turbines for both the 6MW and the 7MW models have been installed, the averages tend to converge to these specifications. Besides, this table also reflects

the challenges of gathering public data, which is the main reason for it to have incomplete cells to date. Curiously, the majority of these refer to the specifications of direct drive turbines, not enabling its further analysis.

Table 2: Average specifications of geared offshore wind turbines installed in Europe.

5. RECOVERABLE MATERIAL QUANTITIES

An investigation of the material proportions used for manufacturing offshore wind turbines was also performed. Wind turbines are mainly composed of steel and iron, whilst the blades are usually made of other materials such as carbon fibre or alloys, and are held in place as they turn by means of a cast iron rotor hub [35].

For this part of the analysis, the direct drive offshore wind turbines were excluded due to being a current minority in the market and not having enough relevant data, as well as requiring different fabrication materials. Nonetheless, this is definitely an area of future research that will enable the understanding of material use convergence as more of these turbines are being installed and rated power keeps increasing.

The analysis was carried out by means of identifying the different characteristics and resources used for manufacturing offshore wind turbines, including the tower, the nacelle and its contents (generator, gearbox etc.), the hub and the blades. This data was combined with the results of a NREL Study [36] in order to estimate the main material resource proportions.

The outcome indicates that offshore wind turbines are mainly comprised of steel (~83%), followed by cast iron (~11%), and a minority of copper (~1%) and other components (~5%). The figures in terms of weight are then standardised into quantities per MW in order to allow a more general application, being numerically described in Table 3 and graphically represented in Figures 9, 10 and 11.

Table 3: Estimation of the main resources used in offshore wind turbines.

Figure 9: Steel weight used in different offshore wind turbine models.

Figure 10: Cast iron weight used in different offshore wind turbine models.

Figure 11: Copper weight used in different offshore wind turbine models.

It is also important to understand how the material requirements change as the size of offshore wind turbines increase, since this will allow the results presented here to be extrapolated for larger turbines for which there is currently no available data. In order to do this, the material proportions for two turbines of rated power x MW are compared with the materials implemented in a single turbine of double its rated power ($2x$ MW). This was done for two cases:

- Two 2MW Vestas V80 offshore wind turbines versus two different models of the 4MW Siemens turbine,

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2 - Two 4MW Siemens offshore wind turbines versus the Vestas 8MW V164 turbine.
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4 The results conclude that in both cases, a single larger turbine requires more resources than two smaller turbines, making the
5 second case more environmentally friendly according to the material use requirements. This is an important outcome as if the
6 trend of turbines increasing in capacity continues, then the need for good recycling measures becomes even more important as
7 larger amounts of resources will be required.
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12 Figure 12: Comparison of resource use for 2x2MW offshore wind turbines and two different models of 4MW turbines.
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15 Figure 13: Comparison of resource use for 2x4MW offshore wind turbines and an 8MW turbine.
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18 Regarding foundations, it is noted that data for monopiles such as length, diameter and weight were generally available within
19 the project's descriptions. As the weight and the length of monopiles can vary, averages were calculated. With this data, and
20 knowing the location of the project, an estimation of how much steel is currently in the sea could be performed, as represented in
21 Figure 14. In total, around 2Mt of steel has been used for the installation of monopiles, where the majority is encountered in the
22 United Kingdom (~1Mt), followed by Germany (~0.6Mt) and the Netherlands (~0.2Mt).
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25 This analysis was only performed for monopiles as they are the present predominant foundation and because there was not
26 enough data to study other typologies. Transition pieces were also considered, but again, a lot of missing data made the analysis
27 difficult.
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32 Figure 14: Amount of steel found in monopiles from already installed European offshore wind farms.
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40 6. DECOMMISSIONING COSTS 41

42 On the topic of costs, and having already estimated the amounts of steel, cast iron and copper available in offshore wind turbines,
43 the money which can be recovered from its scrap value [37] can be calculated, as shown in Table 4. This was performed by
44 multiplying the actual scrap value of each resource (£/t) against the previously calculated averages (t/MW).
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47 It has to be highlighted that the costs have been estimated by optimistically assuming that all the materials can be recuperated
48 and eventually recycled, but it is noticeably understood that some components of wind turbines are very difficult to disassemble
49 into its different constituents, especially the ones from the "other" materials column, which are a mixture of remaining resources
50 and mainly refer to the composition of blades.
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53 Blades are mainly composed either from carbon fibre or fibre glass, and are currently very difficult to recycle. Due to this, they
54 are just being shredded and/or incinerated and landfilled [38]. Nevertheless, this will become a near future problem as landfilling
55 is becoming prohibited in some countries such as in Germany, where other options are being studied [39].
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Table 4: Estimation on the recoverable costs from the main resources used in offshore wind turbines.

Regarding monopile foundations, these depend on the turbine size and the characteristics of the location [36]. It has been estimated that a total amount of around 2Mt of steel has already been deployed in the European sea, but this will not be the total amount to be recycled. For the removal and dismantling of these embedded foundations, these are cut a minimum of a meter into the seabed to minimise environmental impacts and avoid extreme costs [7]. In consequence, the removed length and weight of the monopiles need to be calculated, being the removed length of the monopile equal to the water depth plus the 2 meters required by excavation, and the weight, a proportion of these lengths.

Table 5: Monopile average specifications.

If all this material was recovered and properly recycled, it could lead to a value of £109 million in a best-case scenario, where an average of £31,400 could be recovered from steel just from a single monopile. If these figures are now standardised by dividing by the average rated power of the offshore wind turbines that are held by these monopiles (~3.9MW), this results in a recovering value of nearly £8,000/MW, as stated in Table 6. This analysis could not be performed for other types of foundations due to the lack of available data.

Table 6: Estimation on the recoverable costs from monopiles.

Moreover, taking into account the figures from a previous study which estimated the total decommissioning costs in around £200,000/MW [7], Table 7 is achieved, where nearly 9% of the decommissioning costs could be paid just by recycling offshore wind turbines materials. If monopile foundations are also included, then the value rises to 13%.

Table 7: The impact of recycling on decommissioning costs.

It is important to understand the high volatility of scrap metal prices, as represented in Figure 15. These historically fluctuate with the existing market conditions and can vary greatly on a daily, weekly and yearly timescales, depending on the economic conditions at the time. In consequence, the recoverable amount will depend on these prices and hence, the cost reduction on the decommissioning costs.

Figure 15: 10-year E3 scrap steel price variation in €/t. Source: The European Steel Association (EUROFER) [40].

Due to this, and as the amount of steel encountered in an offshore wind farm with monopile foundations accounts for 88% of the total material, it seemed interesting to investigate variations in the scrap prices. For this analysis, three different values were

considered: the current scrap price for steel, an average (of 2017, Figure 16), and a maximum (of 2017, Figure 16), while maintaining the scrap values for cast iron and copper constant as are a minority within the total material and thus, less influenceable towards cost reductions. The steel was considered to be old scrap E3 grade due to its characteristics [41] and only 2017 values were involved as these were the most current ones found and it was difficult to encounter more trends. The currencies were changed to the current value of pounds for enable comparison, but this factor also increases a degree in the uncertainty of prices.

Figure 16: E3 scrap steel prices for 2017 in €/t. Source: Bureau of International Recycling [42].

The results included in Table 8, confirm that as the scrap value of steel increases, so does the recoverable value, and in consequence, the cost reduction on the decommissioning costs. Therefore, if the average value is used, the recoverable value obtained from recycling could pay for 18% of the decommissioning costs (where the recoverable amount of the turbine alone would be nearly 12%), whereas if a higher price is used, then the cost reduction rises to 20% (where the turbine itself is more than 13%).

Lastly, this reveals that decommissioning should be thus targeted when scrap metal values are high, especially for steel as this is the principal material encountered in offshore wind projects. This would increase the recoverable value from recycling while reducing the decommissioning costs.

Table 8: The impact of scrap price fluctuation on decommissioning costs.

7. DISCUSSION

The offshore wind energy sector has grown rapidly since its inception in 1991 with the Vindeby project in Denmark. More than 42 different turbine models have now been installed, with 22 of these models making up 99% of the European installed capacity, and 18 (67% of the installed capacity) correspond to geared turbines, being the predominant technology. Of these, Siemens and Vestas are the two leading manufacturers with 90% of the market share. They have gained sector experience from acquiring smaller companies (like Bonus in the case of Siemens and Neg Micon with Vestas) as well as providing access to greater corporate resources.

Siemens alone comprises 69% of the market and has the four most frequently installed turbine models in the European market. The SWT-3.6-120 model has been the most frequently installed (953, 18%). It is important to recognise this as manufacturers can use different proportions of resources which will need an eventual sustainable treatment. Moreover, the tendency is to

change to larger direct drive turbines as these do not require gearboxes, reducing failure rates and consequently, the operation and maintenance costs.

Regarding the foundations within the European market, monopiles have been predominantly installed as a consequence of being cost competitive while versatile in seabed conditions. Moreover, arrays are developing into more energetic resources, moving into deeper waters while offshore wind turbines keep on increasing in rated power and thus, the dimensions. Due to this, monopiles increase in consequence, becoming wider and heavier to withstand the bigger turbines, and larger, as waters get deeper.

Steel is the resource mostly used in the fabrication of offshore wind turbines, and it is mainly due to its application in the tower structure. Besides, it has been noted that two smaller turbines require less materials than a single more powerful one of the same capacity, which is the current tendency. As the turbine's rated power increases, it becomes more cost-of-energy competitive and this is the main reason for developing larger machines which are less environmentally friendly in terms of resource usage. This trend may well make recycling of materials at end of life a more lucrative and attractive option.

As offshore wind turbines keep increasing in size, they are also becoming heavier and this has led manufacturers to investigate on the search for lighter materials (for blades for example), as there could eventually be weight constraints due to heavy lifting operations. Moreover, the volatility of the scrap price makes the recoverable amounts from recycling uncertain and impact directly on the decommissioning costs, therefore it would be ideal to proceed when scrap values are high.

8. CONCLUSION AND POLICY IMPLICATIONS

Wind farms are starting to reach the end of life phase but there is still too much uncertainty on how to proceed with the decommissioning, as regulations are yet being formulated and are subject to review in some cases. Sustainability and environmental impacts are important considerations alongside costs. Materials should be reused/recycled instead of being landfilled, which should be the last option and only if none of the previous are possible [7]. It has been estimated that between 80-90% of the weight of a wind turbine could be recycled, and mainly corresponds to construction materials and metals. On the other hand, rotor blades which are the most voluminous part cannot be currently recycled according to modern eco-design standards and are merely disposed of. These can be either shredded and incinerated or added to concrete. Landfill is becoming prohibited in some countries, such as in Germany, where other options are being investigated.

The disassembling of wind turbine components into the different materials can be a difficult task, making complete recycling a challenge. It has been estimated that as a best-case scenario, nearly 20% of the total decommissioning costs could be paid for by recycling offshore wind turbines on projects with monopile foundations, being the turbine itself nearly. Although this figure is

known to be overly optimistic, it is high enough that recycling of components remains an attractive possibility even if the possible cost reductions are less than those seen here. In addition, as the volatility of scrap metal prices have significant impacts on the decommissioning costs, these could help define when it would be best to proceed by targeting at high scrap values. This is definitely a future research area.

Monopiles were identified to be the most implemented foundation type, being implemented in 80% of projects. In addition, offshore wind farms with this type of foundations were seen to be comprised by 88% of steel. On the other hand, other types of foundations could not be contemplated on this analysis as the available data was not detailed enough. This will be attempted in upcoming work. The size of the offshore wind turbine is related to its rated power and hence the larger the machine, the bigger the pile diameter and the greater the seabed penetration will tend to be.

To finalise, it was estimated that in total, more than 3.4Mt of steel is currently at the sea coming from geared offshore wind turbines and monopiles, 192,393t of cast iron and nearly 12,710t of copper. All these will eventually require an appropriate treatment and thus, the project's respective decommissioning programmes will need to have clear instructions on how to deal with them sustainably by means of more specific regulations.

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Table 1

Calculated Average Characteristics	
Water Depth (m)	22
Rated Power of Turbines (MW)	4.3
N° of Turbines per Project	45
Hub Height (m)	81.5
Rotor Diameter (m)	118
Blade Length (m)	58
Blade Weight (t)	18

Table 2

Calculated Average Specifications	Geared Turbines	Direct Drive
Rated Power (MW)	3.8	6
Blade Length (m)	55	74
Rotor Diameter (m)	113	152
Hub Weight (t)	49	-
Blade Weight (t)	16.5	25
Rotor Weight (t)	99	-
Nacelle Weight (t)	149	-
Tower Weight (t)	453	-

Table 3

Resource in Wind Turbine	Steel	Cast Iron	Copper	Other
Total Composition (%)	83	11	1	5
Range (t/MW)	55.27-138.15	9-17.20	0.51-1.25	0.20-0.36
Average (t/MW)	94 ± 22.53	12.78 ± 1.79	0.89 ± 0.23	0.28 ± 0.05

Table 4

Material	Steel	Cast Iron	Copper	Other
Scrap Price (£/t)	140	116	4000	-
Estimated Available Total Amount (t)	1,375,137	192,393	12,711	85,699
Estimated Value from Recycling (£)	192,519,177	23,087,208	49,825,105	-
Average per Material (£/MW)	12,816	1,486	3,385	-
Estimated Total from Recycling (£/MW)	17,690			-

Table 5

Monopile Specification	Weight (t)	Length (m)	Diameter (m)	Length to be removed (m)
Average	577.3	58.8	5.6	22.3

Table 6

Recycling Monopiles	Methodology	Value
Total Available Steel (t)	Weight of Removed Monopile x Total N° of Monopiles	782,795
Estimated Value from Recycling Steel (£)	Total Amount of Steel x Scrap Value	109,591,247
Estimated Total (£/Monopile)	(Total Amount of Steel x Scrap Value) / Total N° of Monopiles	31,402
Estimated Total (£/MW)	Estimated Total / Average Rated Power	8,010

Table 7

	Costs (£/MW)	% Cost Reduction
Estimated Decommissioning Costs [7]	200,000	-
Estimated Value from Recycling Offshore Wind Turbines	17,690	9%
Estimated Value from Recycling Monopiles	8,010	4%
Estimated Total from Recycling	25,700	13%

Table 8

Steel Scrap Value (£)	Recoverable Value from Turbines (£/MW)	Recoverable Value from Turbines (£/MW)	% Cost Reduction	Average Value from Monopile + Offshore Wind Turbine (£)
Actual: 140	8,010	17,670	13%	49,090
Average: 205	11,730	23,640	18%	69,620
Maximum: 236	13,500	26,475	20%	79,410

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

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Figure 16