Waste Management xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Wind turbine blade waste in 2050

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ARTICLE INFO

Article history:
Received 4 July 2016
Revised 23 January 2017
Accepted 4 February 2017
Available online xxxx

Keywords:
Composites waste
Decommissioning
End-of-life
Wind turbine blade waste

ABSTRACT

Wind energy has developed rapidly over the last two decades to become one of the most promising and economically viable sources of renewable energy. Although wind energy is claimed to provide clean renewable energy without any emissions during operation, but it is only one side of the coin. The blades, one of the most important components in the wind turbines, made with composite, are currently regarded as unrecyclable. With the first wave of early commercial wind turbine installations now approaching their end of life, the problem of blade disposal is just beginning to emerge as a significant factor for the future. This paper is aimed at discovering the magnitude of the wind turbine blade waste problem, looking not only at disposal but at all stages of a blade's lifecycle. The first stage of the research, the subject of this paper, is to accurately estimate present and future wind turbine blade waste inventory using the most recent and most accurate data available. The result will provide a solid reference point to help the industry and policy makers to understand the size of potential environmental problem and to help to manage it better. This study starts by estimating the annual blade material usage with wind energy installed capacity and average blade weight. The effect of other waste contributing factors in the full lifecycle of wind turbine blades is then included, using industrial data from the manufacturing, testing and in-service stages. The research indicates that there will be 43 million tonnes of blade waste worldwide by 2050 with China possessing 40% of the waste, Europe 25%, the United States 16% and the rest of the world 19%.

1. Introduction

Wind energy has become one of the most promising renewable energy sources over the last two decades with the installed capacity increasing from 7600 MW in 1998 to 364,270 MW in 2014 (GWEC, 2015). The capacity is expected to continue to increase, although rates may vary in different geographical areas. The Global Wind Energy Council (GWEC) predicts that the global annual growth rate of wind power will exceed 12% between 2013 and 2018 (GWEC, 2014b). The European Wind Energy Association (EWEA) predicts that by 2020 there will be 192 GW of wind capacity supplying 14.9% of global electricity in 2020 (EWEA, 2014). The International Energy Association (IEA) estimates that 15–18% of global electricity will be produced from wind energy in 2050 (IEA, 2011). Despite these disparities, all the predictions indicate that wind energy will continue to develop rapidly over the next decade.

Although wind energy is often claimed to provide clean renewable energy without any emissions during operation (U.S. Department of Energy, 2015), a detailed ecological study may indicate otherwise even for this stage. The manufacture stage is energy-intensive and is associated with a range of chemical usage (Song et al., 2009). Disposal at end-of-life must also be considered (Ortegon et al., 2012; Pickering, 2013; Job, 2014). A typical wind turbine (WT) has a foundation, a tower, a nacelle and three blades. The foundation is made from concrete; the tower is made from steel or concrete; the nacelle is made mainly from steel and copper; the blades are made from composite materials (Vestas, 2006; Tremeac and Meunier, 2009; Guezuraga et al., 2012). Considering these materials only, concrete and composites are the most environmentally problematic at end-of-life, since there are currently no established industrial recycling routes for them (Pimenta and Pinho, 2011; Job, 2013). Composite materials are energy intensive to manufacture and some of the material has high

Abbreviations: AWEA, American Wind Energy Association; BoM, bill of materials; CWEA, Chinese Wind Energy Association; EoL, end-of-life; EWEA, European Wind Energy Association; GWEC, Global Wind Energy Council; IEA, International Energy Association; kt, kilo tonnes; Mt, million tonnes; MW, mega watts; NREL, United States National Renewable Energy Laboratory; O&M, operation and maintenance; PTC, Production Tax Credit for Renewable Energy; WT, wind turbine; WTB, wind turbine blade.

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http://dx.doi.org/10.1016/j.wasman.2017.02.007
0956-053X/

value, which means they have strong recycling potential in terms of both environmental and economic prospects (Shuaib et al., 2015). This study focuses on the composite component of wind turbine blades, looking at the waste inventory of all stages of their lifecycle. Composites account for more than 90% of the weight of WT blades (Liu and Barlow, 2016b). At present, most of the blades are made from polymer composite reinforced with mainly glass fibre, some carbon fibre and the hybrid combination of glass fibre and carbon fibre (Collier and Ashwill, 2011). High-grade epoxy and polyester are the mainstream resins used. Commonly adopted manufacturing processes use Pre-impregnated fabric (Prepreg) and Vacuum assisted resin transfer molding (VARTM) (Gurit Composites, 2009). It is recognised that the materials and manufacturing techniques will evolve over time, but predictions vary. Some predict that the proportion of carbon fibre will increase (NEEDS, 2008; McKenna et al., 2016) and will lead to more serious environmental impact from blade (Liu and Barlow, 2016a). However, current trends have provided no clear support for this trajectory, so it may be that manufacturers are impeded by the high cost of carbon fibre (Liu, 2016).

A few studies have been carried out on different aspects of the ecology of wind energy. For the blade waste volume, Red estimates there will be 260,000 tonnes material used to manufacture wind turbine blades in 2008 and this number will increase to 1.18 million tonnes in 2017 (Red, 2006). Albers notes that every one-kilowatt of wind power needs ten kilograms of WT blade materials (10 kg/kW or 10 t/MW), predicts that there will be nearly 50,000 tonnes of blade waste in 2020 and that this number will exceed 200,000 tonnes in 2034 (Albers, 2009). Andersen adopts Albers' blade material demand figure of 10 t/MW and predicts that the amount of blade material that will need to be recycled annually is 400,000 tonnes between 2029 and 2033. It will increase to 800,000 tonnes per year by 2050 (Andersen et al., 2014). It is clear that there will be a significant number of end-of-life WT blades needing to be decommissioned over the next two decades. It should be noted that the wind power industry has developed rapidly in both scope and technology in this period (Sieros and Chaviaropoulos, 2012; Siemens AG, 2014), which is not taken into account by these previous studies. Liu and Barlow attempt to tackle this issue but only provide general information about the blade size increasing and lifecycle contributing factors (Liu and Barlow, 2015). The more detailed analysis of the present study includes such significant factors as the effect of increased turbine size on blade masses, the variation between different geographical regions, and consideration of waste generation over the whole life cycle.

Presently, most WT blade waste is sent to landfill, but this is not an environmentally benign solution, and indeed many European Union countries have forbidden the landfilling of composite waste (Pickering, 2006). Awareness of this issue is rising and has been highlighted in recent wind power studies. Hayman raises the recyclability problem of wind turbine blades and Larsen summarises a few possible recycling options for WT blades (Hayman et al., 2008; Larsen, 2009). Both of them point out that the relatively short history of the WT industry and low production volumes lead to there being no successful industrial scale WT blades recycling processes that have yet been well-defined and established. Other studies also explore possibilities for reusing the composite WT blades including remanufacture and reuse as structural components in buildings, bridges or artificial reefs (Asmatulu et al., 2013; Falavarjani, 2012). A few ideas have been proposed and have been trialed in laboratories, but none of these has emerged as the industrial path of choice for end-of-life WT blades either because of technical or economical problems. At the moment, wind turbine blade manufacturers and governments lack detailed information about this potential blade waste problem. They are aware that end-of-life materials management needs to be addressed, and are keen to know how serious a problem it will be and what options will be available. A comprehensive answer is needed for this question, including how much waste will be generated in the future, its environmental impact, and the range of possible options for dealing with the waste.

1.1. Research objective

This study aims answer the first part of the question above which is trying to quantitatively and comprehensively understand the life cycle waste inventory of WT blades using accurate and state-of-art data. This paper provides a full evaluation of the material flows associated with all stages of the lifecycle of WT blades, estimated over a timeframe extending to 2050. Material is used in the manufacture of the WT blades and during their service life, to repair damage for example. At the end of their service life, the blades are decommissioned and become end-of-life waste material. The magnitudes of all these material usage and waste streams are estimated using current global data and growth predictions under different scenarios.

1.2. Paper structure

Research methodology and the logic behind the calculations are introduced in Section 2. The blade material required per unit rated power is analysed in Section 3.1 followed by the estimation of total blade material usage presented in Section 3.2. Then the lifecycle waste contributing factors from manufacture to end-of-life are discussed in Section 3.3. The waste inventory and model limitations are presented in Sections 3.4 and 3.5 respectively. Finally, conclusions are presented in Section 4.

2. Methods

The calculation starts from the manufacture stage. An estimation of the amount of material used for WT blades globally requires a statistical method with input from many different sources. We need to know the amount of blade material required per unit wind power, and to quantify how this changes over time with the evolution of turbine design and especially size.

The blade material usage is related to blade size and the blade size is normally determined by its rated power. Generally, a high rated power wind turbine needs large blades and this goes with high blade material usage. Nevertheless, the relation between blade size and rated power is only roughly proportional, not directly proportional. In order to analyse the relation between blade rated power and blade weight, we collect blade weight data for 56 models produced by 14 wind turbine blade manufacturers and divide them into five classes. In each class, the blade masses are summed then divided by the sum of the turbine rated power to obtain the average blade material required per unit rated power (tonnes/MW) (Section 3.1).

The size of the wind power generation capability is then estimated. Data on the current annual wind power installed capacity and average rated power of new installed turbines is provided by wind power associations, together with some predictions for the future growth of the industry. These are used with the blade material per unit rated power to calculate the total blade material usage. For each specific year and region, we use the average rated power in this region at this year to find the matched blade material required per unit installed capacity (t/MW). We then use the unit material requirement multiplied by the installed capacity (MW) to get the total blade material usage (t) for this region during this