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ARTICLE

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Solutions for recycling emerging wind turbine blade waste in China are not yet effective

Juhua Yang[1,2,10], Fanran Meng[3,10✉], Lixiao Zhang[1✉], Jon McKechnie[4], Yuan Chang[5], Bingran Ma[1], Yan Hao[1], Xiang Li[6], Kyle Pender[7], Liu Yang[7], Gary A. Leeke[8] & Jonathan M. Cullen[9✉]

Wind power supply chains are evolving as markets expand to reach climate goals. With the largest installed wind power capacity globally, China must deal with increasing composite turbine waste and anticipate its associated costs. Here we predict the quantity and composition of wind turbine blade waste based on historic deployment. A high-resolution database containing 14 turbine capacities (150–5500 kilowatts) was compiled based on 104 turbine models. The environmental and financial costs of waste treatment options were evaluated using a bottom-up approach. Based on current installations and future projections, 7.7 to 23.1 million tonnes of blade waste will be generated in China by 2050. Technologies exist to recycle glass fibre from blade waste, but these solutions vary in level of maturity and are not always commercially available, cost-competitive, or environmentally sustainable. Our findings can inform decision-makers in governments and industry on the pathways to carbon neutrality.

[1] State Key Joint Laboratory of Environmental Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing, China. [2] Strategic Planning Department, China Huadian Corporation, Beijing, China. [3] Department of Chemical and Biological Engineering, Faculty of Engineering, University of Sheffield, Sheffield, UK. [4] Department of Mechanical, Materials and Manufacturing Engineering, Faculty of Engineering, University of Nottingham, Nottingham, UK. [5] School of Management Science and Engineering, Central University of Finance and Economics, Beijing, China. [6] Research Institute, By-Health Corp, Ltd, Guangzhou, China. [7] Department of Mechanical and Aerospace Engineering, University of Strathclyde, Glasgow, UK. [8] School of Chemical Engineering, University of Birmingham, Birmingham, UK. [9] Department of Engineering, University of Cambridge, Cambridge, UK. [10] These authors contributed equally: Juhua Yang, Fanran Meng. ✉email: f.meng@sheffield.ac.uk; zhanglixiao@bnu.edu.cn; jmc99@cam.ac.uk

The urgent global deployment of renewable energy to mitigate climate challenges has led to an escalating commitment among nations to achieve carbon neutrality. A key facet of this endeavour is the escalating emphasis on renewable energy sources, projected to account for around two-thirds of the world's energy supply by 2050[1], up from a mere 15% in 2015 according to the IRENA scenario[2].

In this transformative landscape, wind power emerges as an important player, being a relatively mature low-carbon technology with a proven track record[3]. Its significance is underscored by the fact that wind power contributed over 6% of the global electricity demand in 2019[4], through an installed capacity of 651 GW, a figure projected to rise to 4000 GW by 2050. However, the promising trajectory of wind power adoption brings forth a consequential challenge—the mounting waste generated by composite wind turbine blades arising from both manufacturing and end-of-life processes.

Efforts to achieve cumulative installed capacity necessitate rapid wind farm development, larger turbines, and the phased replacement of ageing components[5]. This surge in demand for turbines is poised to escalate resource inflows for construction and waste outflows as decommissioned units reach the end of their approximately 20-year lifetime[6]. While recyclability is feasible for some turbine components[7], such as metals and rare earth elements, other components such as wind turbine blades composed of composite materials are bulky, difficult to separate by material and expensive to recycle. Wind turbine blades, therefore, pose a potential waste treatment burden[5].

Conventional waste management approaches, including landfill and incineration, while technically feasible, occupy valuable land resources, fail to recover material value (particularly the fibres), emit greenhouse gases, and are restricted in some jurisdictions. Several countries such as Germany, the United Kingdom and China have responded with regulations and financial incentives (i.e., China Solid Waste Law[8], Guiding Opinions on Comprehensive Utilisation of Bulk Solid Waste during the Fourteenth Five-Year Plan[9]) and high gate fees (i.e., the UK landfill tax[10]). Current waste handling and recycling methods vary from cement kiln co-processing, and mechanical recycling to thermal recycling such as pyrolysis and fluidised bed process as well as chemical recycling[11–15]. These techniques are available at different levels of maturity and not all of them are available at an industrial scale. Also, the processing methods vary in their impacts on the fibre quality such as length, strength, and stiffness properties which subsequently affects how the recycled fibres can be applied. The reported regulations are an important driver of novel disposal alternatives for treating turbine blade waste, including recycling initiatives for glass fibres and resins in which environmental impacts associated with primary production can be avoided via replacement.

China currently has the largest wind power capacity of any country, making up 37% of the total global installed capacity or 210 GW accumulated capacity in 2018. This has been accompanied by periodic increases in wind turbine sizes during 1989-2018, from 0.85 MW to 2MW[16]. However, due to the vast territory of China, there are significant differences in the endowment of wind energy resources, the layout of wind farms, and the spatial distribution of wind turbine blade manufacturing plants (Figure S1). China's ambitious targets to reach peak emissions before 2030 and carbon neutrality by 2060 will require clean energy paths to be developed at the national and provincial levels[17]. The resulting variation in manufacturing, installation, and waste treatment profiles for wind power across China will have impacts on the spatial and temporal distribution of blade waste but underexplored.

While existing studies have only presented a cursory estimation of the global and national blade waste generation[7,18–20], they have not considered the impact of periodic increases in wind turbine capacity[21], and have lacked resolution in the inventory models when considering waste management strategies[22]. Moreover, to our best knowledge, the waste material flow with high-resolution and multi-spatial dimensionality remains underexplored for the Chinese wind turbine market. Our location-specific analysis provides estimates of wind turbine blade waste in each China province, identifying potential hotspots for the issues of material availability and waste arisings in the future. The blade waste mapping is critical for strategic decisions regarding waste recycling plant locations, capacity planning and related technical reserves.

Increasing life cycle assessment studies have arisen for composite waste recycling in the wind power sectors[5]. However, previous studies estimating the energy consumption to composite manufacture and recycling[23,24] only consider static impacts and limited waste treatment options (e.g., landfill[21], cement coprocessing[25,26]), and lack the location-specific background of energy systems with a dynamic cost impact analysis. Environmental impacts of waste management can be highly sensitive to the local background energy systems as the electricity emission intensity has geographical variance affecting the primary production, recycling processes and electricity credits. Therefore, accurately quantifying the environmental and economic cost associated with blade waste treatment, with consideration of national and regional variability in energy provision, provides essential insights for the formulation of government/industrial policies to achieve carbon-neutral targets.

In this study, we comprehensively quantify waste generation across manufacturing, operation & maintenance, and end-of-life phases by considering a markedly higher geographical resolution at the national and provincial levels in China. This is based on historic wind power deployment by field surveys and robust modelling for the years 1989 to 2018 and projected wind power deployment until 2050. We rigorously evaluate the environmental and financial cost implications of waste treatment options for blade waste including conventional treatment routes (landfill, incineration) and current handling/recycling technologies based on the best available data. This comprehensive model framework, enriched by consideration of energy system dynamics, can inform policymakers and industries to develop effective strategies to achieve carbon-neutral targets, efficiently manage blade waste, and sustain the upward trajectory of wind power. The model framework can be extended explicitly to other countries evaluating the role of wind power in decarbonisation and dealing with the blade waste challenges.

Results

In this study, we develop multi-dimensional models to predict wind turbine blade waste quantity, composition, and associated environmental impacts and costs in China up to 2050. This is achieved by utilising historical wind turbine deployment data and projected uptake. A comprehensive wind turbine blade database is constructed, encompassing various capacities and models. Size-specific quantities of waste generation across manufacturing, operation, maintenance, and end-of-life stages is calculated based on installed nominal capacities and age, allowing for national, regional, and provincial waste estimations. Additionally, we evaluate life cycle environmental and cost impacts for different waste management options, including recycling and conventional disposal methods. The model also considers dynamic environmental and cost variations at national and provincial levels based on evolving electricity sources. The following results are

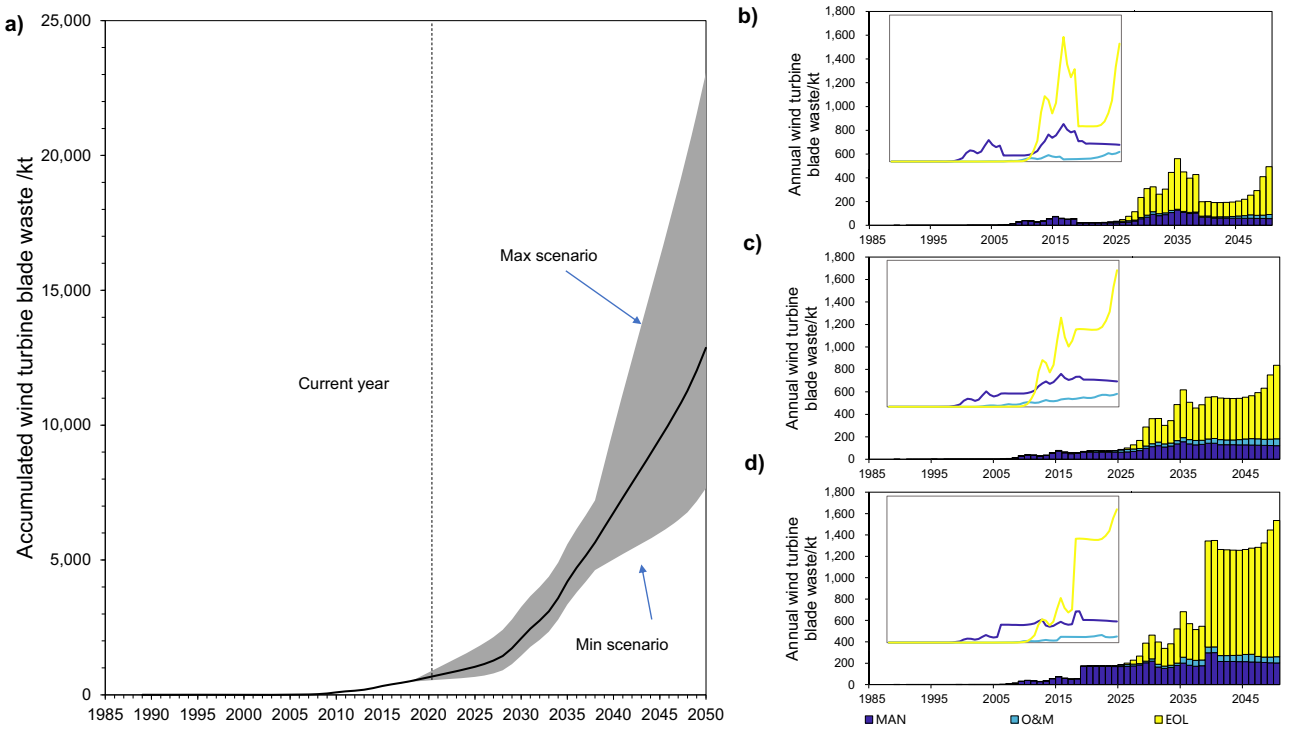

Fig. 1 National wind turbine blade waste generation in China until 2050. a accumulated wind turbine blade waste in kt, with a grey shaded area showing the range between the minimum and maximum scenario, the vertical dashed line indicates the current study year of 2018; annual wind turbine blade waste by waste types (MAN waste manufacturing waste, O&M waste operation & maintenance waste, EOL waste end of life waste) for **b** minimum scenario, **c** base scenario, and **d** maximum scenario. The numerical data for these figures are provided in Supplementary Data 1 (SS1-3).

generated using this multi-dimensional dynamic modelling approach which considers the future deployment of wind turbines in China, technology developments, changing impacts and recycling pathways. The results are organised by national, regional, and provincial waste levels.

National wind turbine blade waste accumulates significantly and EOL waste becomes dominant overtaking manufacturing waste. Figure 1 presents the anticipated wind turbine blade waste in China and shows a 20-fold increase from 2018 (507 thousand tonnes) to 2050 in the base case scenario, resulting in a cumulative 12.9 Mt (million tonnes) over the next 30 years. This can be broken down into 3.9 Mt of manufacturing waste, 7.8 Mt of end of life (EOL) waste and 1.1 Mt of operation & maintenance waste (Fig. 1a, c) in 2050. In the maximum scenario, blade waste rises to 23.1 Mt by 2050, compared with 7.7 Mt in the minimum scenario (Fig. 1b, d) (Figure S25). Previous estimates by Liu and Barlow (2017)[7] of national blade waste increases, at 17.2 Mt waste from 2018 to 2050, sit within this range.

The volumes of waste change considerably over time: production waste evolves with changes in the expansion of wind power generating capacity; EOL waste lags, due to the average lifetime of wind turbine blades in service; operation & maintenance waste scales directly with the installed capacity of wind power. The generation of blade waste has increased dramatically with the large-scale deployment of wind power since 2007. Before 2025, most blade waste will result from manufacturing waste, at 50–60 kt/y (kilotonnes per year), as generating capacity expands but demand for replacement turbines has not yet caught up.

From 2025 to 2040, the amount of total waste increases considerably from 88 kt/y to 557 kt/y, reaching a first peak at 618 kt/y in 2035. EOL waste begins to dominate, increasing from 5% of the total in 2025 to 67% in 2040. This results directly from the decommissioning of large numbers of wind turbines as they reach the end of their life, after about 20 years. Moreover, waste arises from the manufacture of replacements for the retiring wind turbines. After 2025, total manufacturing blade waste arising is about 120 kt/y and is greatly affected by the development scenario, with a range from 70 to 200 kt/y.

In 2040–2050, production waste will remain at a stable level, but EOL waste will continue to grow, due to the accumulation of stock in wind farms and the considerable scale of waste generated from operation & maintenance during the operation phase.

Waste compositions differ in each province and regional differences become larger over the years. There are significant differences in wind resource distribution, development progress, and power policy for wind power, across regions in China. These disparities result in variability in the growth patterns for wind power, resource inflows, and turbine blade waste arisings across China. Nearly half of the total 58 wind turbine manufacturing facilities are concentrated in a few provinces, such as Jiangsu (11), Inner Mongolia (8), and Hebei Province (7) (Fig. 2), with the distribution affected primarily by the wind resources available and local policies. Since the blades are the largest components of a wind turbine, the wind turbine blade manufacturing facilities are typically located close to wind resource-rich areas, where many wind turbines can be deployed with reduced transportation costs. Where a favourable policy is provided by local governments, this promotes the local development and concentration of the industry. In this study, the locations of turbine blade manufacturing facilities are assumed to be constant, allowing the spatial and temporal distribution of future waste arisings to be modelled.

The results show that the volume and composition of waste changes considerably for each decade from 2018 through to 2050 (a. 2018, b. 2030, c. 2040 and d. 2050) (see Fig. 2,

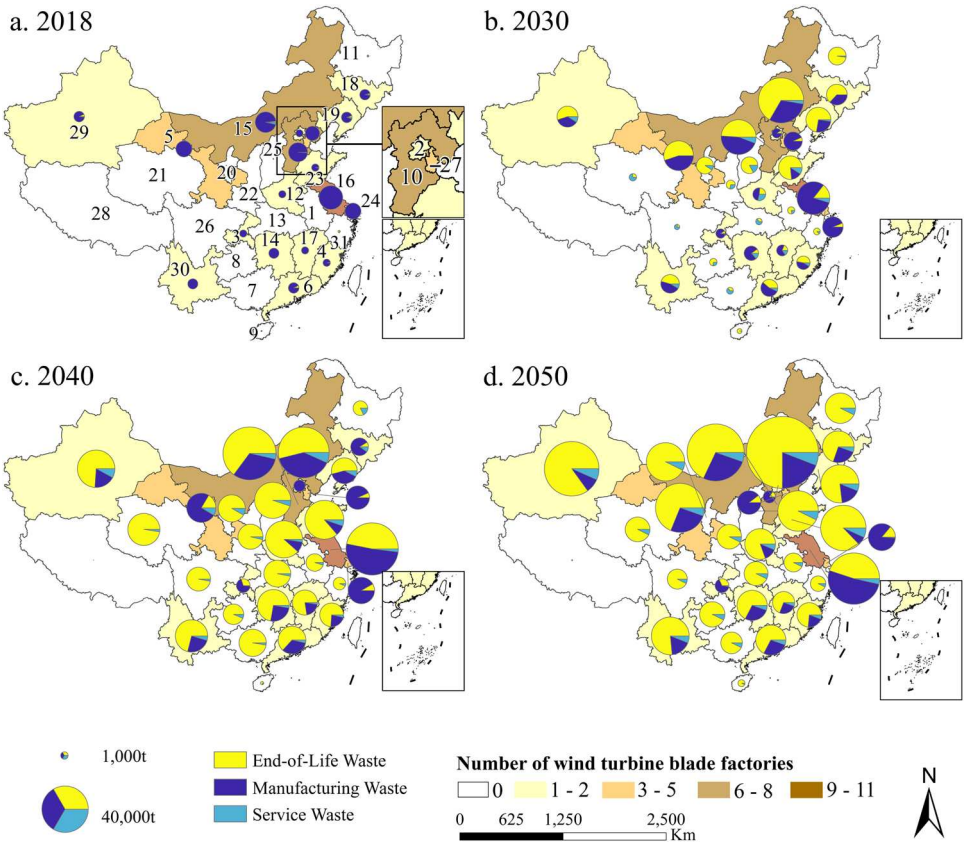

Fig. 2 Annual wind turbine blade waste generation in each province of China in 2018, 2030, 2040 and 2050. The number of wind turbine blade manufacturing factories (existing and planning to build) in each province is shown as the background colour of the map. The numerical data for these figures are provided in Supplementary Data 1 (SS6). Map data were sourced from the Resource and Environmental Science and Data Centre of the Chinese Academy of Sciences (https://www.resdc.cn/). ArcGIS 10.4 was employed as the mapping software for the data analysis. Number codes for provinces: 1-Anhui, 2-Beijing, 3-Chongqing, 4-Fujian, 5-Gansu, 6-Guangdong, 7-Guangxi, 8-Guizhou, 9-Hainan, 10-Hebei, 11-Heilongjiang, 12-Henan, 13-Hubei, 14-Hunan, 15-Inner Mongolia, 16-Jiangsu, 17-Jiangxi, 18-Jilin, 19-Liaoning, 20-Ningxia, 21-Qinghai, 22-Shaanxi, 23-Shandong, 24-Shanghai, 25-Shanxi, 26-Sichuan, 27-Tianjin, 28-Tibet, 29-Xinjiang, 30-Yunnan, 31-Zhejiang.

Figure S27-28 and Supplementary Data 1 (SS6)). In 2018, the composition of the waste is primarily from manufacturing and is located in provinces where manufacturing facilities are concentrated, such as Jiangsu (10.6 kt), Inner Mongolia (9.2 kt), Hebei (7.0 kt), Shanghai (4.7 kt) and Gansu (4.7 kt). Meanwhile, the operation & maintenance waste is estimated to be 0.8 kt (1.5 % of the total waste) and the EOL waste is 0.8 kt (1.4 %). The manufacturing waste generated is typically small, from cutting and milling machines, and concentrated at the facilities, making it much simpler to collect and process centrally.

From 2030 the total amount of waste in all provinces starts to increase, with 90% of the total waste concentrated in the top eight provinces where manufacturing waste still dominates. For example, manufacturing waste accounts for over 60% of the total waste in Jiangsu, Shanghai and Tianjin, which are traditional blade manufacturing bases. Due to the increase in new installed capacity and the replacement of old turbines, the production capacity of blade manufacturing plants increases, and the amount of manufacturing waste is increased. Meanwhile, decommissioned waste generated by the replacement of wind turbines is generated in larger proportions, from 50–75%, in the remaining five provinces, including Inner Mongolia, Gansu, and Hebei. Due to the 2020 Wind Power Investment Monitoring and Early Warning Results by National Energy Commission[27], new installed capacities in the northern provinces shrink significantly while at the same time, increases are seen in the southern provinces. This makes the distribution of installed capacity in each province in 2020 more even. Ultimately it narrows the spatial difference of decommissioned end-of-life waste across the country in 2040.

In 2040, the amount of annual waste in the top five provinces is: Hebei (53.6 kt), Jiangsu (51.5 kt) Inner Mongolia (50.4 kt), Shandong (29.1 kt), Xinjiang (26.1 kt), accounting for 41.4% of the total waste in China. EOL waste from decommissioned waste will dominate in most provinces, often exceeding 75%, except for the provinces of Jiangsu, Shanghai, and Tianjin where manufacturing waste still dominates (55–90%) due to additional production of new blades to replace decommissioned blades. Compared with 2030, the southern provinces shift from a small volume of waste dominated by manufacturing waste to large volumes of waste from decommissioned waste.

In 2050, large amounts of EOL waste will be generated, increasing the total amount of blade waste and the fraction of EOL waste for all provinces across the country. The top five waste generating provinces (i.e., Inner Mongolia, Hebei, Xinjiang, Jiangsu, and Gansu) account for approximately 50% of the total country's waste. Previous estimates by Chen et al.[22] of cumulative blade waste in Guangdong province, at 169–340 kt waste from 2018 to 2050, sit within our range (132–430 kt) (manufacturing waste has been excluded to match their assumption for comparison purpose here). Offshore wind turbine blades are not considered in this research, which would produce even more manufacturing waste in Jiangsu. In addition, the longer service time (25 years) of offshore wind turbines serves to delay the generation of operation & maintenance and EOL waste associated with offshore wind power.

Table 1 Annual wind turbine blade waste in each region of China in selected years (2018, 2030, 2040, and 2050).

Region	Type	2018	2030	2040	2050
Northeast	Blade weight	10.1	20.2	25.9	21.9
	Annual O&M	0.2	0.8	1.3	1.9
	Annual EOL waste	0.1	38.0	11.5	20.2
	Annual MAN	3.74	7.74	9.92	8.38
North	Blade weight	81.2	162.3	207.9	175.7
	Annual O&M	1.2	6.6	10.3	15.3
	Annual EOL waste	0.1	88.7	92.3	162.3
	Annual MAN	18.71	38.72	49.60	41.92
Northwest	Blade weight	44.8	124.8	159.9	135.1
	Annual O&M	0.7	5.1	7.9	11.8
	Annual EOL waste	0.0	56.6	71.0	124.8
	Annual MAN	6.55	13.55	17.36	14.67
Southwest	Blade weight	17.5	62.8	80.4	67.9
	Annual O&M	0.3	2.6	4.0	5.9
	Annual EOL waste	0.0	4.5	35.7	62.8
	Annual MAN	2.81	5.81	7.44	6.29
Central	Blade weight	60.9	95.5	122.3	103.4
	Annual O&M	0.9	3.9	6.1	9.0
	Annual EOL waste	0.0	2.5	54.3	95.5
	Annual MAN	2.81	5.81	7.44	6.29
East	Blade weight	72.5	143.5	183.8	155.3
	Annual O&M	1.1	5.9	9.1	13.6
	Annual EOL waste	0.2	28.2	81.6	143.5
	Annual MAN	17.77	36.79	47.12	39.83
South	Blade weight	28.4	43.9	56.2	47.5
	Annual O&M	0.4	1.8	2.8	4.1
	Annual EOL waste	0.3	4.5	25.0	43.9
	Annual MAN	1.87	3.87	4.96	4.19

Detailed data can be found in Supplementary Data 1 (SS5). *MAN waste* manufacturing waste, *O&M waste* operation & maintenance waste, *EOL waste* end of life waste.

The growth patterns for the seven regions modelled—East, North, Northwest, Central, Southwest, South, and Northeast (see Table 1, Supplementary Fig. S26 and Supplementary Data 1 (SS5))—can be grouped into four modes: exponential growth, logarithmic growth (first increase and then staying flat), Kuznet growth (first increase and then decrease) and slow growth. The underlying reasons for the variance in growth patterns are discussed in Section 2.3 in SI.

Options to reduce wind turbine blade waste during manufacture include more accurately controlling the curing processes and incorporating automatised manufacturing processes, to minimise the generation of manufacturing waste while maintaining high conversion efficiency. Notably, waste generated during blade manufacture is mainly from the blade production plant, which makes the collection of the manufacturing waste much easier than the service and EOL waste. Many manufacturers are located in areas with developed chemical industries, such as Jiangsu, Shanghai, and Tianjin, facilitating the deployment of emerging recycling and production technologies. Moreover, the co-location of industrial facilities in eco-parks allows for the implementation of industrial symbiosis strategies, where manufacturing wastes from wind turbine blade production, such as glass fibre and filler, can provide a valuable feedstock for sheet moulding compound production in other plants and economically feasible and environmentally friendly solution to the waste treatment and utilisations.

Recycling blade waste reduces GHG emission relative to conventional landfill and incineration options, in all cases except for pyrolysis. The national environmental impacts of wind turbine blade waste are determined by both the waste quantity and the environmental impact intensity of each treatment route, which is sensitive to energy mix changes. The changes in the environmental impact intensity of electricity generation by fuel can be found in Section 1.7 in SI. Taking such dynamics into consideration, the primary energy demand (PED) and GHG emission of wind turbine blade waste treatment from 2018 to 2050 are estimated in Fig. 3 and Figure S30.

Figure 3a, b shows the projected PED and GHG emissions per unit of blade waste, indicating changes in waste treatment options over time. This shows that recycling blade waste reduces GHG emissions relative to conventional landfill and incineration options, in all cases except for pyrolysis, with mechanical recycling (an existing mature technology) achieving the largest GHG emission reduction. However, the relative benefits of treatment options do change over time.

Pyrolysis recycling releases the most GHG emissions of any process (positive value) due to the use of electricity to power the process. But it is noted that in this study no chemical vapour is assumed to be condensed during pyrolysis recycling, which may reduce the GHG emission further (Section 1.6 in SI). This can be the focus of future research when they reach commercial status. Fluidised bed and mechanical recycling (with either landfill or incineration of residual materials) achieve the lowest GHG emissions (negative value). However, mechanical recycling with a landfill of residual materials is no longer viable as landfill of this solid waste is banned in China[8].

Conversely, the fluidised bed process generates electricity which offsets GHG emissions from electricity generation, so the decarbonisation of electricity has the opposite effect, increasing the net emissions intensity with time (Fig. 3b), albeit marginally. However, the overall negative emission intensity of the fluidised bed means the net annual scaled GHG emission continues to decrease, by 10.6 times, from −0.04 to −0.39 $MtCO_2eq$/year.

Cement kiln coprocessing achieves close to net zero emissions by converting waste into energy which avoids the use of coal and

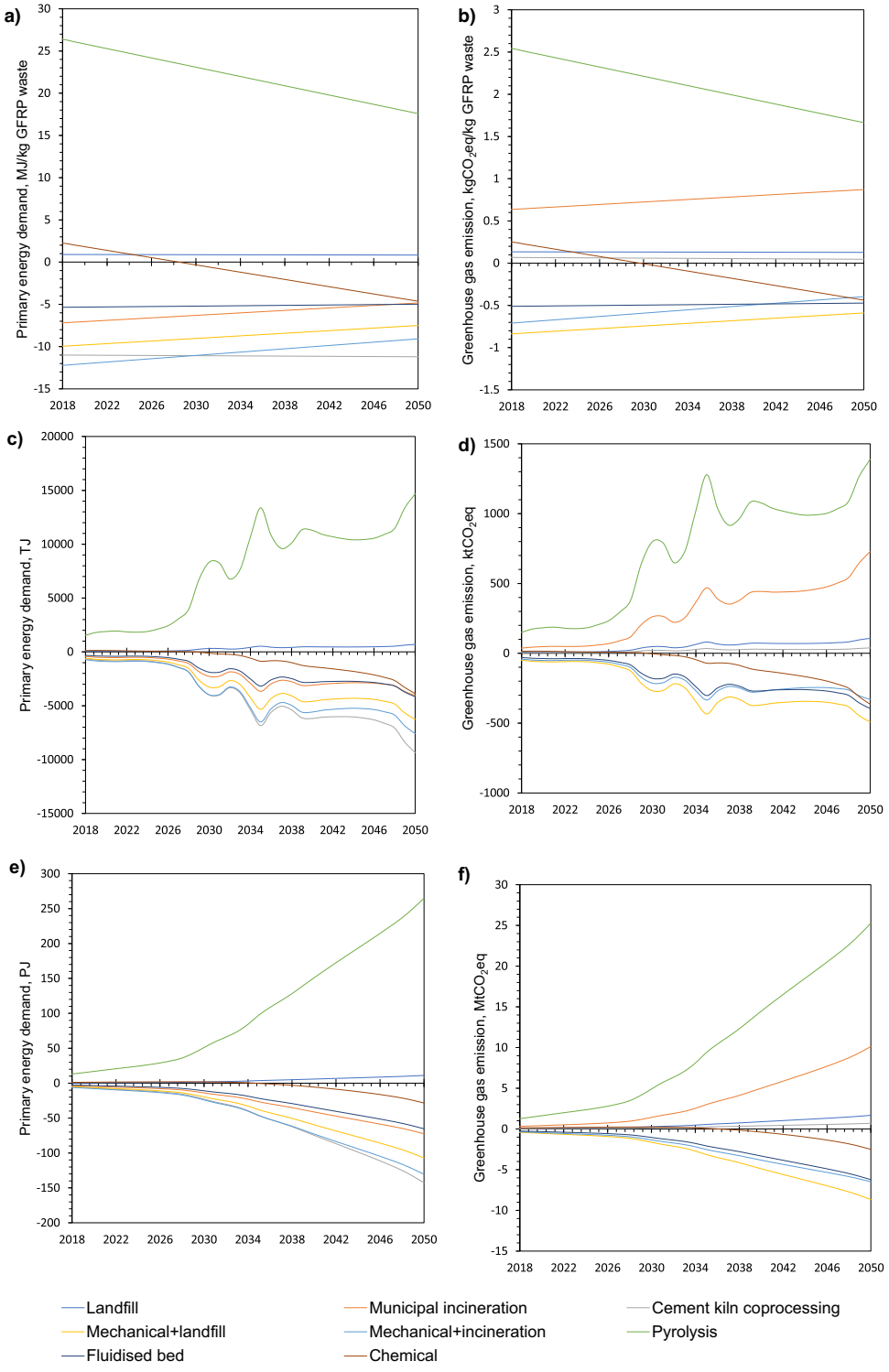

Fig. 3 National energy and greenhouse gas emission of wind turbine blade waste treatment from 2018 to 2050. a Per-unit PED (MJ/kg GFRP); **b** Per-unit GHG emissions ($kgCO_2eq$/kg GFRP); **c** scaled PED (TJ) and **d** scaled GHG emissions ($ktCO_2eq$) per annum and **e** cumulative PED (PJ) and **f** cumulative GHG emissions ($MtCO_2eq$) of different methods to handle the turbine blade waste. The numerical data for these figures are provided in Supplementary Data 1 (SS8-9). Per unit PED and GHG emissions of recycling solutions in processing 1 kg of GFRP waste may be improving over time primarily due to the decarbonising electricity generation (see **a**) and **b**. However, driven by the increasing amount of waste generated over the years, the scaled PED and GHG emissions per year increase significantly and this increase accentuates the difference between various treatment methods (see **c**, **d**). Cumulative PED and GHG emissions until 2050 present the possibility of achieving negative impacts of waste management (see **e**, **f**), e.g., the cumulative GHG emissions range from +25.3 $MtCO_2eq$ to -8.7 $MtCO_2eq$ (for comparison, China emits 9.8 $GtCO_2eq$ totally in 2020) The numerical data for these figures are provided in Supplementary Data 1 (SS10).

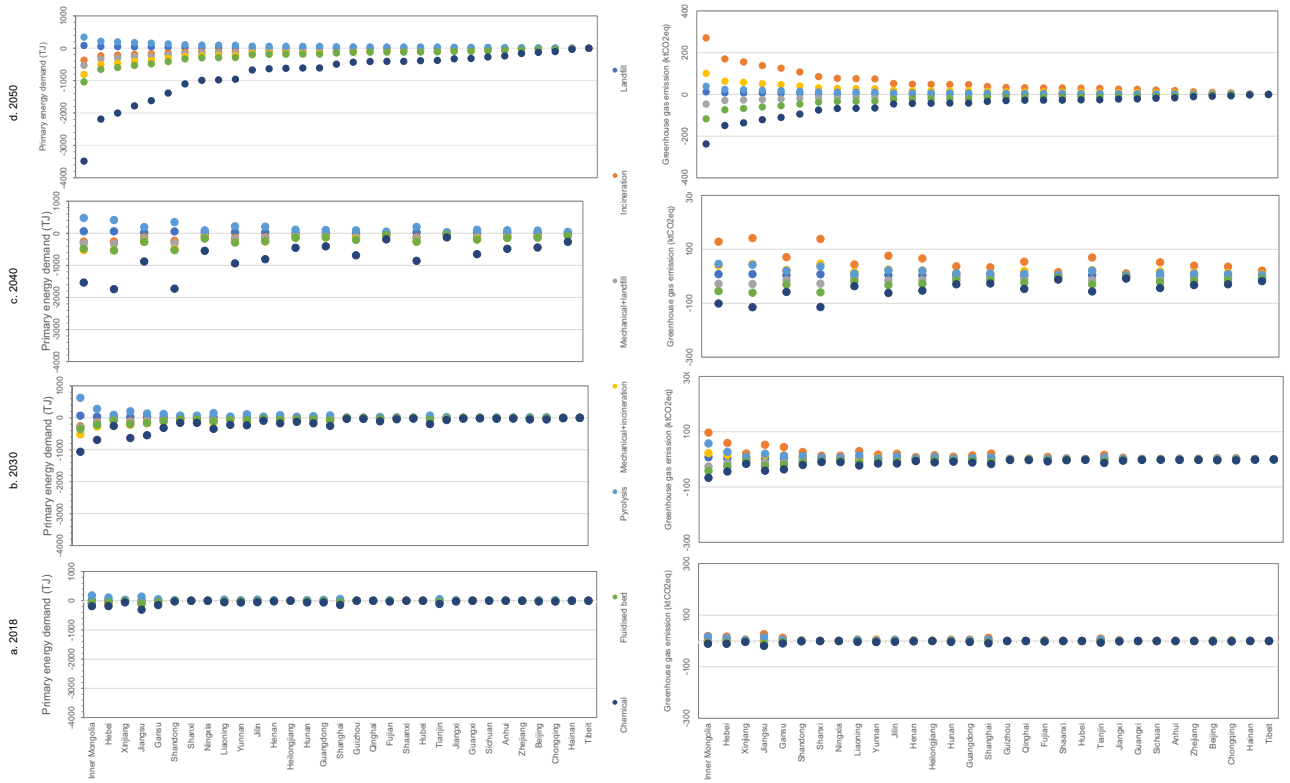

Fig. 4 Energy and GHG emissions of wind turbine blade waste at the provincial level from 2018 to 2050. The numerical data for these figures are provided in Supplementary Data 1 (SS8-9).

raw materials for cement production. This is only the case if we assume that coal would continue to be used as the cement plant releases significant fossil CO_2. Moreover, the net zero GHG emission is achieved by replacing one form of fossil carbon from coal with another from a polymer matrix. Therefore, it looks close to zero because of how emissions are accounted not because the emission to the atmosphere is close to zero. If we want to achieve near zero life cycle emissions with this route, we will need carbon capture and storage at a cement facility or if in the future the plastic waste is made from bio-sources. The significant GHG emission reduction was also reported in previous studies that coprocessing of Irish blade waste in a cement kiln was found to be six to ten times better environmentally than depositing waste in an Irish landfill[25].

Figure 3c, d show the annual projected PED and GHG emissions, revealing the impact of treatment options at scale, while Fig. 3e, f shows the cumulative PED and GHG emissions, from today until 2050 as a result of treatment options. Scaled PED and GHG emissions for each waste treatment option experience significant growth after 2025, corresponding to increases in waste generation, and this increase accentuates the difference between various treatment methods. The primary energy demand (PED) impact presents similar trends to the GHG emission trend. Pyrolysis recycling has the largest scaled energy consumption, up to 14.68 PJ/year by 2050, about eight times larger than that in 2020. Cement kiln coprocessing can achieve the largest PED reductions with a net PED of −9.35 PJ/year in 2050. During the period, the decarbonised energy mix will reduce the environmental impact intensity of both waste disposal options and virgin glass fibre/resin production. During 2035-2045 the significant decrease in PED intensity decouples the environmental impact of the pyrolysis and the quantity of waste generation, resulting in a decreased PED with increasing waste generation.

The future trend for decarbonising electricity generation decreases the unit emission intensity of pyrolysis recycling with time by 12%, from 2025 to 2035 (Fig. 3b). However, over the same period the amount of waste increases by 7 times, meaning the net annual scaled GHG emissions of pyrolysis recycling continues to rise (Fig. 3d), by 6.3 times from 0.20 to 1.28 $MtCO_2eq$/year.

From 2035 to 2045, total waste continues to grow, but the annual growth rate slows, falling to −1%. Assuming the emission intensity continues to decline at the same rate, the unit GHG emission intensity decreases by 13% for pyrolysis and 188% for chemical recycling, respectively. However, the fluidised bed annual scaled GHG emissions increase by 13% (from −0.30 to −0.26 $MtCO_2eq$/year in Fig. 3d) because the net GHG emission savings is reduced as electricity generation is decarbonised. This demonstrates that the waste management methods which rely heavily on electricity are more affected by the electricity grid decarbonisation compared to less energy-intensive approaches, such as the landfill and cement kiln coprocessing, and processes which generate electricity, such as fluidised bed.

Ten provinces concentrate the majority of the environmental impacts with variations due to waste quantities and electricity GHG intensities. Life cycle environmental impacts associated with managing wind turbine blade wastes vary significantly by province, due to spatial variations in the quantity of waste generated (discussed previously in Section 2.3) and varying GHG intensities of provincial electricity supplies. The overall findings reveal that environmental impacts are concentrated in the top 10 provinces (Jiangsu, Inner Mongolia, Hebei, Gansu, Shanghai, Tianjin, Liaoning, Jilin, Xinjiang, Guangdong) due to their large share of current and projected wind turbine installations (Fig. 4, Figures S31-40). In 2018, the top 10 provinces accounted for 79%

to 93% of the GHG emissions impact across all waste management options. In 2050, this GHG emission contribution is projected to fall to between 58% and 59% in the top 10 provinces, with waste generation distributed more evenly across all provinces. R&D investment should be prioritised in the key provinces and supply chain cooperation enhanced across manufacturers, transportation, recycling companies, and local governments to find solutions to the waste challenges. The recycling framework needs to prioritise recycling methods which reduce the overall environmental impact and cost for each province. Pilot projects in the top 10 provinces can act as good practice demonstrators, which can translate technical knowledge and manager experience to other provinces with lagging practices.

The ranking of the top 10 provinces by environmental impact differs from the ranking for wind turbine blade waste, due to the variance seen in electricity grid emissions intensity across provinces. For example, for annual GHG emissions, Jiangsu moves from first/second in 2018, to third in 2030 and 2040 and to fourth/fifth in 2050, while for waste generation Jiangsu ranks first in 2018, third in 2030, second in 2040 and third in 2050. In 2018, manufacturing waste dominated the total waste of wind turbine blades and was mainly concentrated in the Jiangsu and Inner Mongolia provinces, making them the largest two waste producers (overall 10.6 kt/y and 9.2 kt/y respectively). Inner Mongolia is the largest coal producing province in China, so electricity generation is mainly from coal-fired power plants with high emission intensities (1.55 $kgCO_2eq/kWh$, compared to 1.01 $kgCO_2eq/kWh$ in Jiangsu, in 2018), which affects the relative environmental impacts of the turbine blade waste treatment options. For example, municipal incineration recovers the blade waste energy content and displaces high emission intensity generation from fossil fuels, leading to a greater net emission gain in the Inner Mongolia province. The impacts of municipal incineration thus differ between these two provinces: 3.26 $ktCO_2eq/yr$ for Inner Mongolia and 6.27 $ktCO_2eq/yr$ for Jiangsu. In comparison, Yunnan province is endowed with plentiful hydropower resources, and a low grid emissions intensity of 0.456 $kgCO_2eq/kWh$[28,29]. The power structure in Yunnan changes little over time, and therefore the grid intensity has a smaller effect on the overall environmental impact, with changes dependent mostly on the amount of waste generated. The different patterns observed for different provinces, in the predicted waste quantities and net environmental impacts, indicate the importance of considering local energy systems to reduce uncertainty in estimating the net impacts of waste management systems.

Moreover, in the process of waste treatment, if more "decarbonised electricity" can be used to dispose of waste, it will further reduce the carbon emissions of the wind power industry in its entire life cycle. However, it should also be noted that other aspects cannot be ignored for the "decarbonising" of a single process, such as the decommissioning, transportation, and landfill of residual materials, which may cause differences in China's carbon peak and carbon neutrality practice.

Recycling options have a lower cost to treat blade waste except pyrolysis process. Figure 5 and Figures S41-44 present the total recycling costs and recyclate values for each glass fibre (GF) EOL option, by (a, b) per-unit level (per tonne), (c) scaled level (per year) and (d) cumulative level. All costs are presented in US$ for 2018. For conventional waste treatment processes, the costs of landfill can be lower than other recycling options, while mechanical recycling is estimated to have the lowest cost of the advanced recycling options. The cost is relatively low compared to other recycling processes as this process is less energy-intensive and recovers the GF with good mechanical properties (78% retention of primary property[30]). The thermal pyrolysis process is more energy-intensive and the credits from recycled GF are not sufficient to balance the processing costs. Furthermore, the yield and performance of the fibrous product recovered from the pyrolysis and chemical recycling processes[31–34] are lower than for mechanical recycling. Therefore, chemical recycling and pyrolysis are unlikely to be commercially viable for recycling GF blade waste, with a deficit of about US$204 per tonne. If these technologies are used to recycle glass fibre blade waste, technological improvement is required to reduce energy consumption and improve recycled fibre mechanical properties, with policy support.

The increase in turbine blade waste generation after 2025 will require large investments in EOL waste facilities and increased annual costs. The annual cost of processing options will increase over the period 2018 to 2050, from US$8.5 million/year to US $226.3 million/year for municipal incineration, and US$12.1 million/year to US$320.6 million/year for pyrolysis. The cumulative costs over this period of conventional landfill of GFRP waste are as high as 3.2 billion USD (see Fig. 5d), while in comparison, mechanical recycling can generate an income of US $1.86 billion to US$1.91 billion. However, the newly implemented China Solid Waste Law, banning the landfill of composite waste, prohibits the landfill of residuals. Fluidised bed, which has good retention of GF mechanical properties with less energy consumption, will achieve a relatively low cost by 2050 with an annual cost of US$176 million/year and a cumulative cost of US $2.19 billion. On the contrary, pyrolysis and chemical recycling are even more expensive than landfill disposal, and while cement kiln achieves reductions in primary energy demand and GHG emission, the process is not financially viable for treating GFRP waste (a cumulative cost of US$4.1 billion).

Displacing virgin glass fibre with recycled glass fibre reduces environmental and cost impacts. Displacing virgin GF with recycled GF reduces the energy consumption, GHG emissions and costs associated with the virgin GF production process. The fraction of virgin material displaced by recycled is defined as the displacement factor. The energy, GHG and cost mitigation potentials directly depend on the substitution rate of virgin GF with recycled GF, as shown in Supplementary Fig. S45. The net PED, GHG emissions and cost associated with waste recycling options where recycled GF is used to displace virgin GF and residual materials are disposed of in a landfill or by incineration. Due to the high GHG-intensity of virgin GF manufacture, a net reduction in GHG could be achieved at high displacement factors (> 70%) for chemical recycling. In terms of PED, a lower displacement factor of 40% is sufficient to achieve net zero PED for fluidised bed processing compared to 65% for chemical recycling. Mechanical recycling + landfill reveals that even at lower displacement ratios of 8%, recycling can achieve net reductions in PED and GHG emissions. While we do not suggest that such performance is feasible with mechanical recycling, this analysis indicates the potential benefits that could be achieved with more advanced recycling processes, such as fluidised bed recycling, as it leads to the recovery of higher-quality fibre products.

In 2019, glass fibre production in China reached 5.3 Mt, accounting for more than half of the world's total output. We estimate current emissions from glass fibre production in China are 3.04 tCO_2eq/t GF. GHG emissions of recycled GF based on mass allocation for environmental impacts estimations range from +30% to −95% (see Supplementary Table S11). Providing glass fibre via recycling could be an important contribution to the transition towards net zero for the glass fibre sector. Based on the cumulative 12.9 Mt of wind blade waste (~ 60% GF) by 2050, we

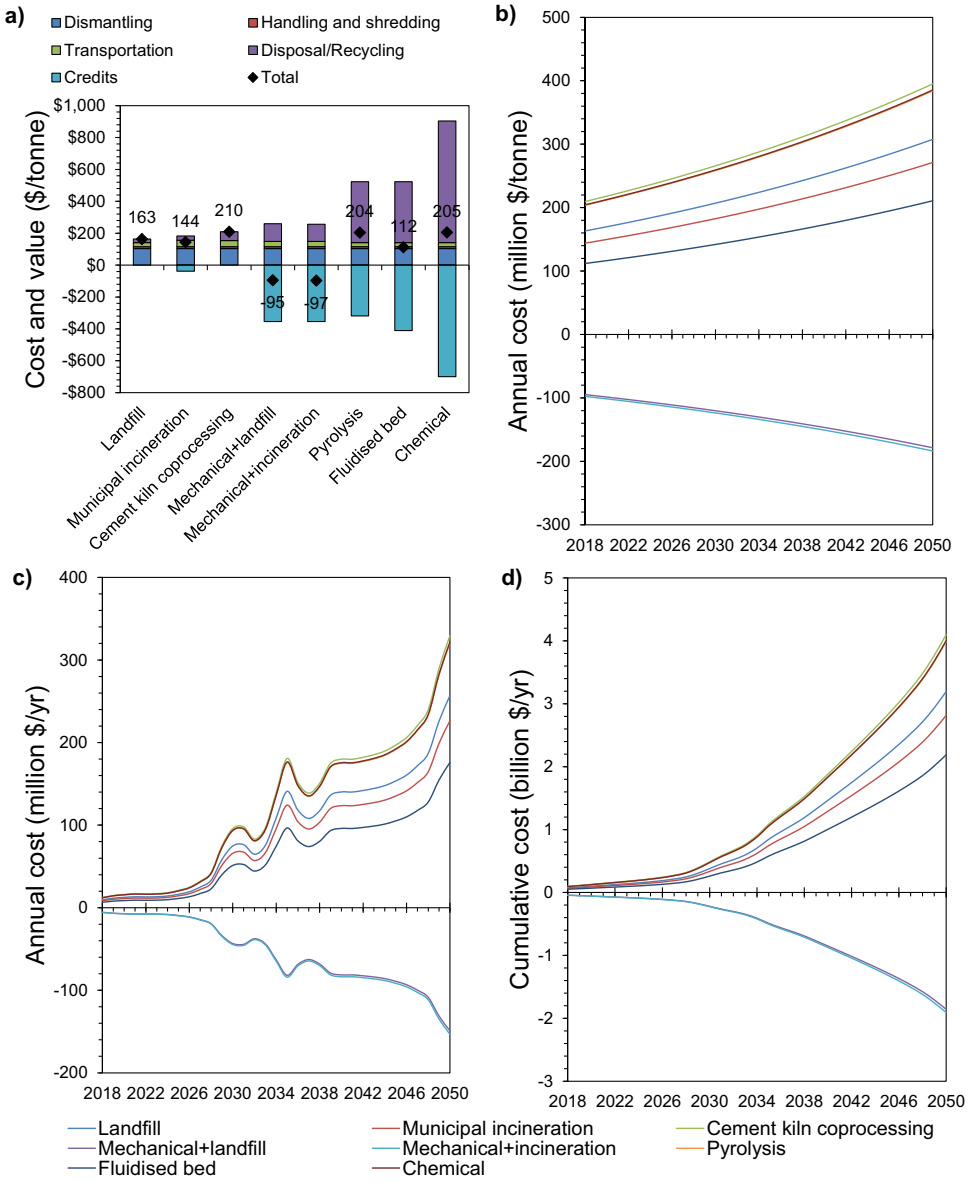

Fig. 5 National cost of wind turbine blade waste treatment from 2018 to 2050. a Per-unit cost breakdown cost (US$/tonne) in 2018; **b** annual unit cost until 2050 (US$/tonne); **c** annual cost impacts (million US$/y); **d** cumulative cost impacts (billion US$) of different waste treatment methods to handle the turbine blade waste. The numerical data for these figures are provided in Supplementary Tables S5-10 and Supplementary Data 1 (SS12).

can estimate GHG emission savings from using recycled glass fibre to be ~23.5 $MtCO_2eq$.

Discussion

Our modelling shows that, based on current installations and future projections, approximately 12.9 Mt of wind turbine blade waste (base case) will be generated in China between 2018 and 2050, with a possible range of 7.7 to 23.1 Mt under different development scenarios. For comparison, China consumed 3 Mt GF in 2019[35] and recycled 5.5 Mt aluminium in 2018[36]. The annual volumes of blade waste are small (507 kt in 2018) when compared to annual levels of municipal solid waste in China (228 Mt in 2018)[37]. Yet turbine blades are made from valuable materials, presenting an economic opportunity for recovery, and China's current capacity for treating blade waste is underdeveloped.

As demand for wind power grows over the next 30 years, significant quantities of turbine blade waste will be generated, requiring effective management, supporting policies, systems, and technical reserves. We use wind development outlook data which is specific to the situations in China. The environmental and cost impacts of waste treatment quantified using highly spatial geographic data and annual electricity mix data provide a comparison of current waste management options with improved accuracy compared to previous studies. These results are useful for decision-makers in planning wind power development and waste management strategies, where there is a current lack of policies that focus on the decommissioning of wind turbines, to maximize the net benefit of exploiting wind power as a renewable resource. The research methods and models developed in this study can be carried out in different countries, which is conducive to the construction of a global wind turbine blade material flow network. It provides an analytical and predictive basis for the global processing of wind turbine blade waste in the future. Reducing the panic caused by the sudden global policy of waste

trade, wind turbine blade waste can be handled in a reasonable division of labour on a national and global scale.

Circular strategies will be required to reduce the wind turbine blade waste from production, operation, and EOL phases[38]. Modular blade designs could facilitate component reuse, reducing end-of-life waste. Upgrading production processes with extended producer responsibility can minimise scrap during manufacturing (particularly for those blade manufacturing provinces such as Jiangsu, Inner Mongolia, and Hebei Province). In the operational phase, turbine blade monitoring using advanced sensors and monitoring can provide the data needed for timely and efficient repair and maintenance, potentially extending facility lifetimes. Options to reduce impacts at the EOL include finding secondary uses for turbine components that are higher on the waste hierarchy, generally in lower demand applications (e.g., pedestrian bridges and transmission towers[39–41]). However, there will be a limited market for repurposing wind turbine blades compared to the future availability of these. Therefore, developing a comprehensive recycling framework to extract value from blades which have reached their end-of-life is needed although this is lower down the waste hierarchy.

Viable, large-scale recycling solutions are thus urgently needed to accelerate the transition to a circular economy for wind turbine blades and composite materials. However, our results for the potential environmental and cost impacts of different treatment strategies indicate that there are no simple solutions for managing wind turbine blade waste that is favourable across all criteria. At present, various technologies exist to recycle glass fibre waste from wind turbine blades, but the level of maturity of these solutions varies greatly, and none are yet commercially available, environmental- and cost-competitive. The commercial viability depends on the market demand for these recyclates (e.g., recycled GF filler materials versus the low cost of conventional fillers such as calcium carbonate) and the rCF displacement factor (see Section 2.6), which can be the focus of future work. Mechanical recycling, an existing technology (TRL 7-8), combined with landfill or incineration of residual materials, achieves the lowest GHG emission impact (a cumulative of −8.7 to −6.5 $MtCO_2eq$ relative to 1.7 $MtCO_2eq$ by landfill by 2050) and the lowest cumulative cost impacts (-US$1.86 billion to -US$1.91 billion compared to US$3.19 billion if disposed of in landfill by 2050). However, mechanical recycling followed by a landfill of residual materials is not viable as the landfill of this solid waste is currently banned in China (residual materials are still classified as general solid waste). This route achieves reduced landfill amounts and already shows the potential to address the waste challenge. Therefore, this current policy of banning solid turbine waste prevents China from pursuing the lowest environmental impact option for turbine blade waste and should be reviewed. The review should look beyond waste disposal and consider revising relevant laws and regulations to increase producer responsibility, improve emission control in production and enable strategic plans for the wind power industry to take a systems view. Mechanical recycling with incineration of residual materials can achieve lower costs but emissions associated with polymer combustion negate the overall benefits achieved by glass fibre and energy recovery (a cumulative −6.5 $MtCO_2eq$). Cement kiln co-processing (TRL6) achieves GHG emissions levels which are just above zero (0.7 $MtCO_2eq$), whereas fluidised bed treatment, an emerging technology (TRL 5), potentially offers an effective and sustainable way to lessen the environmental impact of wind turbine blade waste (a cumulative −8.7 $MtCO_2eq$ and US$2.2 billion by 2050). Chemical recycling, (TRL3-4) (a cumulative −2.5 $MtCO_2eq$ and US$4.0 billion cost) is also worth evaluation as an alternative waste disposal option if the process can be further optimised for energy efficiency. Pyrolysis recycling, a widely reported thermal solution (TRL 5), is not economically viable (costing a cumulative US$4.0 billion by 2050) due to the high energy intensity of the process, which outweighs any credit from the recovered GF.

It can be concluded from the recycling solutions studied here that the industry and policymakers should promote recycling technologies such as mechanical recycling and thermal/chemical recycling which reclaim the value of the fibres at a low cost, especially for applications where fibre content is high. In this paper, we use best available data and assumptions to estimate process costs, using China-specific data, where available, combined with generic global data related to the technologies (see Section 4.7 and Section 1.8 in SI). This presents initial comparison of different composite recycling technologies. Developing future investment cases for wind turbine blade recycling in China requires more rigorous modelling of the most promising technologies based on more detailed, regionally specific, transparent, and trustworthy cost data, which can be a focus for future research.

Furthermore, measuring circularity and environmental impacts, and optimising the circular strategies, could help to achieve improved environmental and cost impacts for the wind industry. For instance, as there are different types of waste (i.e., manufacturing, service, and EOL waste) so future research should examine how the effect of plant capacity, waste collection, transportation, location, and regional factors on environmental and cost impacts. The recycling framework needs to prioritise recycling methods which reduce the overall environmental impact and cost for each province, especially in the top 10 provinces. For example, Inner Mongolia is the largest coal producing province in China with electricity generation mainly from coal-fired power plants. They can prioritise cement co-processing /mechanical recycling + incineration methods to help decarbonise the electricity generation together. In comparison, Gansu and Shanghai already have relatively low grid emissions intensity thus the decarbonisation of the grid strategy has a smaller effect on the overall environmental impact. Therefore, China should focus on several solutions following the circularity pyramid depending on location and resources; firstly reducing the amount of waste generated, then re-permitting, reuse, repurposing, and recycling via more advanced recycling processes before final disposal.

Lastly, composite waste treatment is a cross-sector challenge which extends beyond just the challenges seen in the wind industry. All the composite-using sectors and sustainability practitioners must work together to find environmentally friendly and cost-effective solutions for composite waste streams and develop new value chains for the increasingly large volumes of blade waste to close the material loop. Technical and logistical advances would be required before a business model to support this could be proven. There is currently significant activity in the wind industry to develop and commercialise viable, sustainable, and cost-efficient solutions for recycling wind turbine blades. For example the 'ZEBRA (Zero wastE Blade ReseArch) project (18.5 M€)[42], launched by IRT JULES VERNE in September 2020, aims to develop 100% recyclable composite wind turbine blades with industrial partners; the 'DecomBlades' project[43] launched in January 2021 seeks to explore the commercial viability of sustainable techniques for recycling wind turbine blades; the UK's first wind turbine blade recycling project gets go-ahead[44] aiming to commercialise a revolutionary method developed by the University of Strathclyde to separate the GF and resin components in composites and recover the GF component which can then be reprocessed, moulded, and reused in other industries, such as the automotive sector and the construction industry. However, the current economics of recovering composite waste, which has

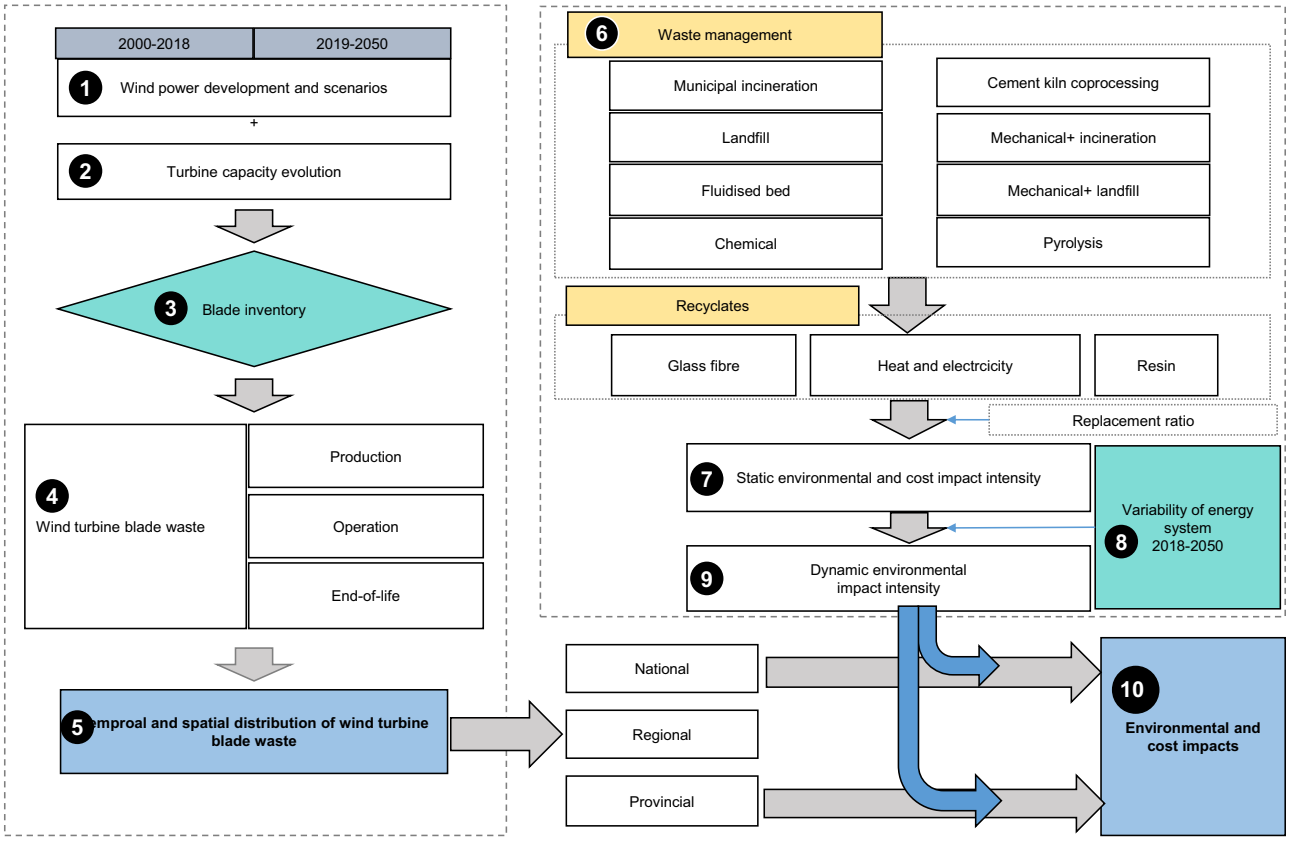

Fig. 6 Research framework of this study. The numbered nodes represent the modelling steps. First, an dynamic material flow framework is built to predict the waste generation (steps 1–5). Second, process-level life cycle assessment is applied to evaluate the environmental and cost impacts of blade waste management (steps 6–9). Finally, the dynamic material flow framework and life cycle assessment are integrated to assess the scaled environmental and cost impacts (step 10).

limited financial viability due to the low value of glass fibre, provides little motivation for recycling[45,46]. Therefore, current recycling methods are likely to require policy support—to encourage the collection of composite waste for recycling and producer responsibility (EPR) to treat this waste for minimal cost. Further complications exist for offshore wind turbines, which are not included in this study, due to the difficulties and expense of recovering blade waste from offshore locations.

Methods

Modelling framework. In this study, we develop multi-dimensional models to (1) predict the quantity and composition of wind turbine blade waste to 2050, on a provincial basis within China; (2) quantify the life cycle environmental and cost impacts of alternative waste management options (Fig. 6). Wind turbine blade waste prediction is determined based on the historic deployment of wind turbines and predicted uptake to 2050, using on-site data collected from wind turbine manufacturers and customers. A high-resolution wind turbine blade database that contains 14 wind turbine capacities ranging from 150 kW to 5500 kW was compiled for this study based on 104 wind turbine models. According to this database, we calculated the size-specific quantities of the wind turbine blade waste generated from the manufacturing processes, operation & maintenance, and end of life based on installed nominal capacities and age (date of decommissioning). Waste quantities are estimated at national, regional, and provincial levels to investigate the overall trends, growth patterns, and temporal and spatial distribution, respectively.

Life cycle environmental and cost impacts are considered for a set of waste management scenarios based on comprehensive process models of pilot plant or commercial scale processes, including conventional disposal (with landfill and municipal incineration options) and potential recycling technologies. Assumptions are made on technical parameters such as transportation distances and processing methods. The recovered product obtained from the treatment will partially replace the production of the primary material, thereby creating a static impact intensity. According to the evolution scenario of the electricity sources (Figure S21), the dynamic changes in the environmental and cost impact of waste treatment and disposal are simulated from the national and provincial scales. The whole model framework can be extended explicitly to other countries evaluating the role of wind power in decarbonisation and dealing with the blade waste challenges.

Wind power development and scenarios (step 1). The rapid development of wind power in China began at the start of this century. Therefore, we have traced the development process of wind power from 2000 to 2018. The historical data on wind power development comes from the report issued by the China Wind Energy Association (CWEA)[47]. The wind turbine blade waste prediction model accounts for historic deployment of wind turbines and projections of future installations to 2050. For the blade manufacturing sites, the future capacity layout is developed on the existing layout.

Future scenarios of wind power capacity in China by 2050 are used: two scenarios from the International Energy Agency, two scenarios from the Global Wind Energy Council (GWEC), and

two scenarios from China Wind Energy Development Roadmap 2050 released by the China National Renewable Energy Centre (CNREC) (Supplementary Figure S2 and Supplementary Table S2). The average predicted capacities is used as the base case in the current analysis, achieving a total wind power capacity of approximately 1000 GW by 2050, in line with the CNREC Base Scenario and the GWEC Moderate Scenario. To understand how uncertainty in future wind power deployment will influence future waste generation, the minimum and maximum future capacities are also considered from the previous predictions. The minimum capacity prediction, 635 GW capacity in 2050 is taken from the IEA-New Policies Scenario, wherein annual capacity increase returns to 2010 levels and only gradually increases after 2030. The maximum capacity prediction, 1600 GW by 2050, is taken from the China Wind Energy Development Roadmap Active 2050 Advanced scenario, where wind power provides more than 30% of China's electricity supply towards the carbon neutrality target by 2060. Wind turbine capacity which is retired in the future is assumed to be replaced by new turbines, to keep the total installed capacity at a steady state. Offshore wind power is not included in the research scope, due to the small market share (2.1%), incomplete database, and uncertainty around its future development path in China.

Wind turbine size evolution (step 2). Technical improvements have led to the development of larger wind turbines and longer turbine blades. An analysis of the market share of installed capacity in the Chinese wind power market from 2005 to 2018 reveals that the average power for individual wind turbines has increased from 1.5 MW to 2.0 MW. Normal probability distribution functions are used to predict the future lifetimes and evolution of blade size. This distribution is often used in dynamic material flow analysis[48,49] and is found to be well suited to model wind turbine lifetimes[50]. The market share of turbine blades has transitioned from nearly 80% of 1.5 MW to 50% of 2.0 MW between 2010 and 2018. Following the observed historical trends, we assume that the average wind turbine size in operation increases by 0.5 MW every 6–8 years following the growth pattern of the market share of 2.0 MW, with the dominant wind turbine size evolving from 2 MW today to 5.5 MW in 2050 (see Supplementary Fig. S3). The market share of the dominant wind turbine size never exceeds 50%. Wind turbines are assumed to have a typical lifetime of 20 years[22,50,51]. Lifetime extensions are possible if wind turbines and their rotor blades can be proven to be safe and not harmful to the environment via analytic methods and monitoring/inspections. However, a detailed analysis and verification of continued operation after 20 years must be provided individually for each wind turbine. Many decommissioning contractors are currently stockpiling blades in the hope of future cost-effective recycling options, where landfilling is not an option[52,53] However, this is outside the scope of this paper, and consideration of the uncertain lifetime would overly complicate the analysis. Research into lifetime uncertainty can be a focus in future work.

Wind turbine blade inventory (step 3). Wind turbine blade weight is related to the wind turbine size and power. The detailed inventory data of each wind turbine blade model is shown in Supplementary Figure S4. Despite the availability of carbon fibre material, which could help reduce the weight of turbine blades, most wind turbine blades in China are still made using GFRP due to their lower cost, especially in the onshore market[54]. Therefore, we assume all onshore wind turbine blades are made from 100% GFRP.

MAN, O&M, and EOL wind turbine blade waste (step 4-5). The waste generation ratio in each of the three main stages of waste generation (MAN, O&M, and EOL) is shown in Supplementary Table S3. Manufacturing waste consists mainly of dry fibre offcuts, composite offcuts, resin residue, and vacuum consumables; O&M waste is generated during routine maintenance, repair of accidental damage, and blade upgrading; EOL waste is the retired blades. The percentages represent the relative fractions of finished blade product mass. The number of wind turbine blade manufacturing factories (existing and in planning to be built) in each province used for MAN waste prediction can be found in Supplementary Data 1 (SS4).

Life cycle assessment of wind turbine blade waste treatment (step 6 and 10). The goal of the LCA is to compare the environmental impacts of different waste treatment options for wind turbine blades in China. The functional unit chosen for this study is one kilogram of wind turbine blade waste. Two environmental metrics are considered: primary energy demand (PED) and greenhouse gas (GHG) emissions, based on the most recent IPCC 100-year global warming potential factors in terms of CO_2 equivalents (CO_2eq)[55]. For all waste management options, an equivalent set of activities are considered in process models: waste handling; transport; waste treatment processes; and the recovery of waste outputs (energy and recyclates). The life cycle inventory data input to the LCA process model is based on experimental data, literature, life cycle databases (e.g., Ecoinvent 3.7), process models and onsite plant operation. Shredding of blade waste is included for EOL waste but excluded for manufacturing blade waste. Recycled GF is allowed to replace virgin GF based on the retained strength property. The impact of the replacement ratio is discussed in Section 2.6. We consider seven approaches to handling the wind turbine blade waste: waste handling processes (landfill; municipal incineration; cement kiln co-processing); waste recycling processes (mechanical recycling with landfilling of residual materials or incineration of residual materials); pyrolysis recycling; fluidised bed recycling; chemical recycling) (see Section 1.5 in SI, Figures S5-19).

Environmental impact intensity of wind turbine blade waste (step7, 8 and 9). The environmental impacts of treating wind turbine blade waste vary substantially between the options and can contribute to changes in overall PED and GHG emissions. The environmental credit generally comes from three aspects: the credits generated from incineration (i.e., electricity and heat); the replacement of virgin GF production by recovered fibre; the avoidance of virgin resin production using recovered resin products.

The PED used to treat the wind turbine blade waste is shown in Supplementary Fig. S20a. Excluding the benefits of energy recovery or the use of recycled glass fibre materials, advanced recycling processes (i.e., pyrolysis, fluidised bed and chemical recycling) require additional energy inputs to treat the wastes and have larger PED than conventional landfill, incineration, and mechanical recycling methods. For the pyrolysis method, the recycled GF and waste heat do not offset the energy demand of the processing energy input, which results in a positive net PED. For fluidised bed methods, the PED credits exceed the energy consumption, which results in negative net PED.

The GHG emission of these treatment methods is shown in Supplementary Fig. S20b. The incineration and mechanical + incineration options both produce a large amount of GHG emissions from the combustion process, as the carbon content of GFRP is released to the environment as CO_2. Emissions from pyrolysis, fluidised bed and chemical methods are mainly related

to energy consumption in the recycling process. Overall, the GHG emissions exceed the credits obtained from energy recovery and material recovery (i.e., resin and fibre), giving a positive net GHG emission, except for mechanical recycling and fluidised bed methods.

Cost analysis (step 10). The total cost of the complete wind turbine blade recycling process consists of six steps: dismantling, handling, and shredding, transportation, recycling, transporting the residues to final disposal (landfill/incineration) and credits (i.e., recyclates/energy). Therefore, the WT blade net EOL cost consists of EOL process cost and recyclate value:

$$C_{net} = \sum_{Process}\left(C_{dism} + C_{hS} + C_{trans} + C_{recyc}\right) - \sum_{Recyclates}\left(C_{fib} + C_{res} + C_{fil} + C_{ener}\right) \quad (1)$$

where C_{dism} is the dismantling cost, $C_{h\&s}$ is the handling and shredding cost, C_{trans} is the transportation cost, C_{recyc} is the recycling/disposal cost, C_{fib} is the recovered fibre value, C_{res} is the recovered resin value, C_{fil} is the recovered filler value, C_{ener} is the recovered energy value.

For each EOL option, the recycling process is briefly described and then the recycling cost and recyclate value are discussed considering an annual inflation rate of 2%. The cost data of landfill and incineration are obtained from industrial partners and literature review. For other EOL options, where there is no publicly available cost data, we solve the cost models using the best available data from literature, experiments, process models and industrial partners. For simplicity, the impact of location factors is excluded in Supplementary Table S5-6 and Table S8-10. Details of the model and estimation can be found in Section 1.7 in Supplementary Information (Figure S22-24) and Supplementary Data 1.

Data availability

- We use the ecoinvent database, onsite collected data, and process models to compile a high-resolution wind turbine blade database and generate a blade waste database and environmental and cost datasets.
- All data presented in this paper is available via the following link: https://doi.org/10.6084/m9.figshare.22960802.

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Author contributions

Conceptualisation: F.M., J.Y.; Methodology: F.M., J.Y., L.Z., J.M.; Software: F.M., J.Y., B.M., X.L.; Formal Analysis: F.M., J.Y., L.Z., J.M., B.M., X.L., K.P., L.Y., G.L., J.C.; Investigation: F.M., J.Y., L.Z., J.M., B.M., X.L., J.C.; Writing—Original Draft: F.M., J.Y.; Writing—Review & Editing: F.M., J.Y., L.Z., J.M., Y.C., B.M., Y.H., X.L., K.P., L.Y., S.P., G.L., J.C.; Visualisation: F.M., J.Y., B.M., X.L.; Supervision: F.M., L.Z., J.M., J.C.; Funding Acquisition: F.M., L.Z., J.M., J.C.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Fanran Meng, Lixiao Zhang or Jonathan M. Cullen.

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