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Wind Turbine Blade Wastes and the Environmental Impacts in India

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Abstract:
Electricity production by wind turbines is considered a clean energy technology, but the life cycle of wind turbines could introduce environmental risks due to waste generation, especially at the decommissioning process. This study predicts the future wind turbine blade waste arising in India, throughout all life cycle stages, from manufacturing until end of life, based on the installed capacities of existing Indian wind farms and projected future installations. Five alternative strategies for managing this waste stream are assessed in terms of life cycle greenhouse gas emissions and primary energy demand, including land filling, incineration, and mechanical recycling. For the base case scenario, it is observed that the total cumulative waste until 2050 is 2,75,299 tonnes, with on-site waste accounting for around 75% of this total. Waste generation is concentrated in regions with greater wind power deployment: Gujarat and Tamil Nadu alone account for 70% of total blade waste. Life cycle environmental impacts of waste management strategies are dependent on background energy systems, with incineration a significant source of greenhouse gas emissions, particularly when displacing glow-carbon grid mixes. Cement kiln co processing achieves net zero emission by converting waste into energy and raw materials for the cement. Mechanical recycling can achieve substantial reductions in primary energy demand and greenhouse gas emissions but achieving financial viability would likely require substantial regulatory support.

Keywords: Wind Power, Blade, Waste Prediction, Life Cycle Assessment, Recycling

List of Abbreviations:

CF :	Carbon fiber	EoL :	End of Life
GF :	Glass fiber	GFRP :	Glass fiber reinforced plastic
O&M :	Operation and maintenance	GHG :	Green house gas
PED :	Primary energy demand		

1. INTRODUCTION

Wind power is gaining more attraction in global energy market to combat climate changes due to both environmental and economic benefits. India is a world leader in wind energy, ranked third globally in onshore installed capacity as of 2019 (Global Wind Energy Council, 2024). Over the past decade, the wind energy installed capacity in India has grown by an average rate of 1,012 MW/year, leading to a total installed capacity of 47,363 MW in 2024, of which more than 85% is located in five states Gujarat (12,209 MW, 25.78 %), Tamil Nadu (11,042 MW, 23.31 %), Karnataka (6,564 MW, 13.86 %), Maharashtra (5,214 MW, 11 %) and Rajasthan (5,196 MW, 10.97 %). Wind power capacity is expected to continue to grow at an annual rate of 510 MW/year to 2040 (National Energy Board, 2016). Figure 1 shows intensity of wind power production in India.

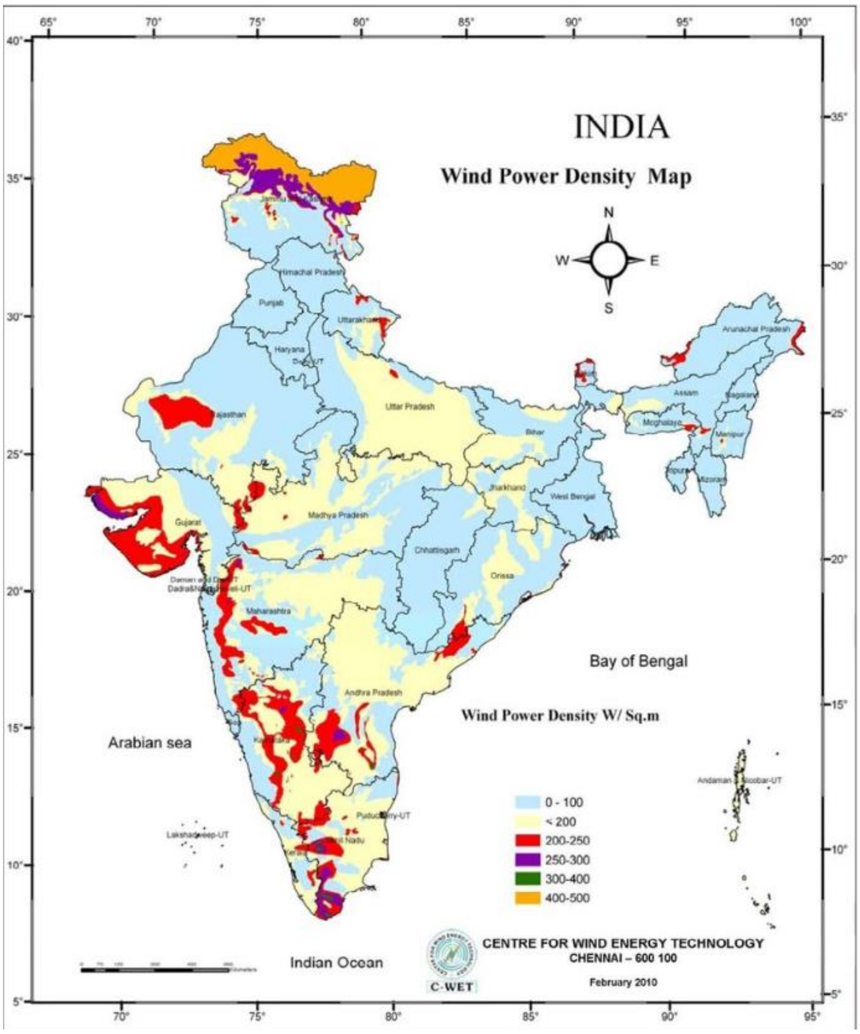


Figure 1: Wind Power Density Map (Courtasy: CWET, India)

While wind power serves as a clean energy solution that can help to reduce the carbon foot print of the electricity sector, the environmental impacts associated with waste generation from wind turbines are often neglected in many studies (Bonou et al., 2016; Savino et al., 2017). To ensure the sustainable deployment of wind power in India and globally, it is essential to better understand the potential life cycle environmental impacts of managing wastes arising during manufacturing, operation, and end-of-life (EoL) of wind turbines.

Improving the sustainability of waste management is a key policy priority in India, as evidenced by federal, provincial, and municipal regulations, for example those governing the recycling of ELVs and the handling of resulting waste streams. In contrast to such goals, however, the vast majority of composite waste at present is not recovered and instead land filled or incinerated (Marsh, 2003; Shuaib et al., 2015). Recycling has been recognized as a desirable waste management option to deal with composite wastes with the potential to recover value from the waste materials rather than being disposed in landfill or incineration, fulfilling legislative and sustainability targets.

Material flow analysis has been used to quantify flows and stocks of materials in wind energy system in the existing literature based on the historical and projected installed capacities. Kimetal. (2015) and Yanget al. (2020) evaluated the inflow materials requirement and the resource efficiency in Europe and China, respectively, due to wind energy development in the 2010s. Tazi et al. (2019), in particular, analyzed the material flow at the end-of-life stage of wind turbines in France until 2035. Using a more refined stock flow modeling framework, Fishman and Graedel (2019) and Cao et al. (2019) provided a more extensive material flow analysis until 2050 in the US and Denmark, respectively, considering the growth of offshore wind. These studies include both inflow and outflow of magnet materials required for wind energy development such as neodymium and dysprosium but have not considered blade waste.

Increasingly, several recent studies have specifically focused on addressing the concern related to the blade waste generation from the wind power sector in future decades. Liu and Barlow (2017) conducted a study to estimate the wind turbine blade waste until 2050, mainly for China, the United States, and Europe. The waste was carefully estimated throughout all the life cycle stages, from the manufacturing process to the EoL. Lefeuvre et al. (2019) performed a similar study to quantify the carbon fiber waste generated from the wind power sector until 2050. These global studies are by default broad, employing generalized assumptions, and so overlook important variations at the country level. Recently, Lichtenegger et al. (2020), Cooperman et al.(2021), and Chen et al. (2021) estimated the cumulative wind turbine blade waste generation until 2050 due to wind power development at a higher geographical level in Europe, the United States, and Guangdong, China, respectively. Lichtenegger et al. (2020) identified hotspots at a high level of geographical granularity in Europe with the expected waste in the future while Cooperman et al. (2021) compared the cumulative blade waste to the remaining landfill capacity in the United States. Chen et al. (2021) conducted studies based on three scenarios of the waste generation and their associated recycling potential. However, variations at the sub-country level are generally lacking in the literature, such as the projected future deployment of wind power, annual energy background systems, and the geographical concentration of wind farms within a country. To date, to the best of our knowledge, no similar studies have been performed in India, which is one of the top ten countries in global installed capacities and has a high potential for wind power development. In this study, we estimate the cumulative waste contributed by wind turbine blades until 2050 in India by considering a markedly higher geographical resolution at the national and provincial levels based on historic and projected wind power deployment.

The life cycle environmental impacts of managing composite wastes have been considered in previous studies. Liu et al.,(2019), and that of others, has considered a range of technologies for recycling carbon fiber based composites that would be similarly suited to recycling wind turbine blades comprised of glass fiber composites, including mechanical recycling (Li et al.,2016), pyrolysis (ELG Carbon Fiber Ltd, 2017; Naqvietal., 2018), fluidized bed (Mengetal., 2018b), and chemical recycling (Keith et al., 2018; Prinçaud et al., 2014). A very limited number of studies have considered the environmental impacts of managing wind turbine blade waste considering the future wind power installation. Liu et al. (2019) provided a life cycle assessment of EoL wind turbine blade waste treatment methods which evaluated the energy consumption without considering location-specific background energy systems (Liu et al., 2019). Lifecycle impacts of waste management, however, can be highly sensitive to the background energy systems. The greenhouse gas (GHG) intensity of electricity generation varies substantially between countries and regions, which will influence both the impact of waste treatment processes consuming electricity, as well as the benefits of processes that generate electricity as a product (eg., incineration). Consideration of national and regional variability in energy systems is essential to accurately estimate environmental impacts of wind turbine waste management. Figure 2 shows photographic view of failed composite wind turbine blade.

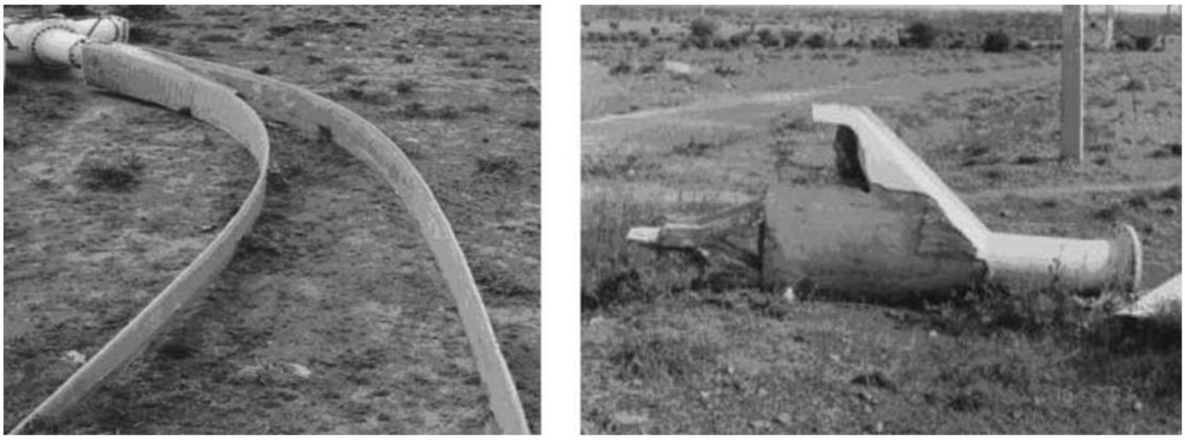


Figure 2: Failed Composite Wind Turbine Blades

Appropriate management of wind turbine blade waste is essential to ensure that ongoing deployment of wind power delivers a net environmental benefit. To the best of our knowledge, very little previous work has focused on the waste prediction and environmental impacts on a country with its own geographical location data. The present study builds on past work by considering a markedly higher geographical resolution (sub-national analysis), enabling a better understanding of how the concentration of wind power deployment within larger regions influences the life cycle environmental impacts of alternative waste treatment routes. We estimate the cumulative waste contributed by wind turbine blades until 2050 in India at the national and provincial levels based on historic and projected wind power deployment. Environmental impacts of alternative waste treatment routes are assessed and compared, considering the variation in annual background energy systems within India state level. It should be recognized that the wind power development in India is mostly regulated at the state level, which suggests the need for the results to be generated with higher resolution methods. Hence the dynamic electricity mix data from 2020 to 2040 is included in the present study. The location-specific estimate of waste generation will provide clarity on the estimated quantities of wind turbine blade waste in each Indian state, which will identify the hotspots of material availability and expected waste in the future. The environmental impacts of waste treatment quantified using high geographical level data and annual electricity mix data will provide a comparison of current waste management options with better accuracy than previous studies. These results will help to inform decision-makers in planning wind power development and waste management strategies to maximize the net benefit of exploiting this renewable resource.

2. Methods

The present study estimates the cumulative waste inventory in India at the national and state levels until 2050 and quantifies key life cycle environmental impacts: primary energy demand (PED) in terms of GJ and greenhouse gas (GHG) emissions in terms of tonnes carbon dioxide equivalent associated with alternative waste treatment options. The three main contributors that affect the total waste inventory are considered: the predicted growth rate of the installed capacity, the rate of waste generation during manufacture and useful life (routine servicing; unexpected incidents), and the life span of the blades, at the end of which all blade material enters the waste stream. Given uncertainty in predicting these factors, we consider high and low estimates of waste generation in addition to the base case scenario as shown in Table 1.

Table 1: Model assumption values for three scenarios

Scenarios	Growth Rate (Wind Energy Market Intelligence, 2019) MW/year	Affecting Factors		Lifespan (Wind Energy Market Intelligence, 2019) Years
		Manufacturing (Liu and Barlow, 2017) @ for first year in %	Annual O&M (Barlow, 2017) in %	
Low Estimate	353	12.1	0.02	20
Base Estimate	510	17.2	0.04	25
High Estimate	816	30.4	0.09	30

2.1 Wind turbine deployment in India:

Data related to wind energy development in India were gathered from Wind Power in India. For each existing wind farm in India, the information gathered includes the total installed capacity, year of commissioning, location (at state level), numbers of turbines, turbine manufacturer and model, and turbine diameter. Based on the database, most of the wind turbines in India till date were made by five manufacturers, which are M/s. GE Energy (25.5%), M/s. Vestas (27.2%), M/s. Siemens (18.5%), M/s. Enercon (14.0%), and M/s. Senvion (9.5%). Less than 1% of wind power capacity has been installed in Central and Northern states of India and therefore these states are excluded from the present study.

In the present study, the base case scenario assumes a growth rate of 510 MW/year based on a reference case's projection published by National Energy Board (2016) (Table 1). This annual growth rate would result in total installed capacities of 241,260 MW in 2040 and 292,267 MW in 2050. In 2040, the total installed capacity of wind power would provide approximately 13% of the total projected electric generating capacity. Centre for Wind Energy estimated the annual installed capacity could increase to 816 MW/year if 50% of the non- emitting energy is contributed by wind energy by 2040, and the present study adopts this annual growth rate in the high estimate scenario. The minimum wind power growth rate over the past 5 years is 353 MW/year and we set this as low estimate scenario.

2.1 Estimating wind turbine blade mass

The turbine blade material is assumed to be glass fiber reinforced plastic (GFRP) based on the available data provided in the manufacturers' website (Enercon, 2019; GE Renewable Energy, 2019; Senvion, 2019; Vestas, 2019; Wind-turbine models.com, 2019). Waste GFRP is assumed to have a representative GF content of 60 %wt and a polymer matrix (i.e., epoxy resin) content of 40 %wt (Wind Europe, 2020). The turbine blade mass data is not available for most wind turbine models installed in India till date; data from the above manufacturers are assumed to be representative of all producers. We estimate blade mass based on turbine blade diameter (Liu and Barlow, 2017), and calculate the weighted average blade weight per unit power based on current wind turbines installed in India. The weighted average for the modeled blade mass per unit rated power is estimated to be 12.35 tonnes/MW by considering 47 different turbine models.

2.2 Prediction of wind turbine blade waste

Wind turbine blade waste is estimated by considering waste generation at manufacturing, operational & maintenance (O&M), and EoL stages (Figure 3). Manufacturing and O&M wastes are estimated following a similar approach by (Liu and Barlow, 2017), and waste generation rates are shown in Table1. Manufacturing waste arises due to in-process wastes, blade testing process, and defective blades.

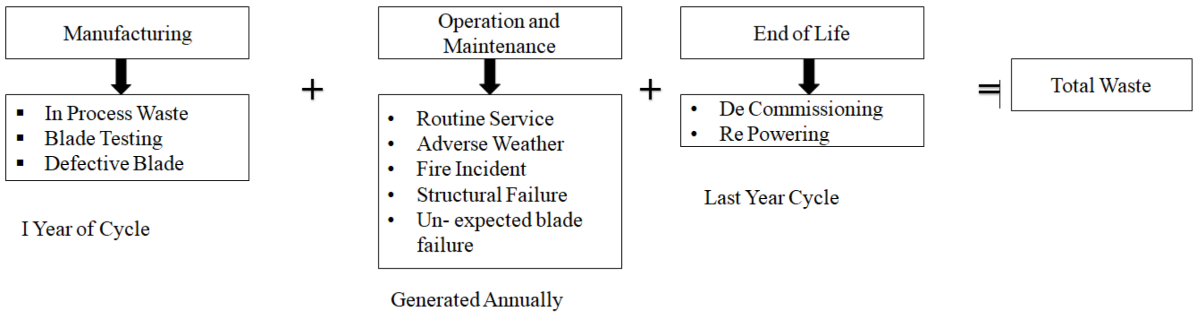


Figure 3: Total Waste generation prediction model

Although blade manufacturing occurs outside of India and, therefore, this waste arises outside of the country, we include this waste in the estimate as it is associated with wind turbine deployment in India. Blade testing and defective blades represent very small fractions of produced blade mass (≤0.2%).

The waste generated during the O&M process could be due to planned events such as routine maintenance and services or unplanned events such as adverse weather that damage the blade, unexpected failure of the blade, fire incident, and structural failure. We assume a small percentage of the waste generated during the O&M processes for every year (0.04% of the finished blade mass annually for the base case, see Table 1), as it is difficult to predict the exact years where a planned or unplanned event occurs. The generated wastes due to the unplanned event of O&M processes are estimated based on the incident statistics, in an online resource that documents the incidents related to the wind power sector internationally. From this resource, the present study compiled the incident records over the past 10 years in India related with all unplanned events. The fraction of turbines impacted by unplanned events is assumed to be representative of future incident rates (0.03 % of the finished blade mass per year). It is assumed that the fire and structural failure would require full replacement of all three blades, while the incidents due to adverse weather and unexpected failure would only require replacement of two out of three blades. Low and high estimates of waste generation from unplanned events are considered at half and double the historic incident rate, respectively. Combining the O&M wastes due to both planned and unplanned events, the annual percentage is estimated to be 0.02%, 0.04%, and 0.09% of the finished blade mass for the low, base case, and high estimate scenarios, respectively.

The EoL waste, comprising 100% of blade material, is generated once the wind turbine reaches its life time limit. Wind turbines could operate for a typical lifespan of between 20 and 30 years. The present study assumes 25 years for the base case, with 20 year and 30 year life spans considered for the low and high waste estimate scenarios, respectively.

2.3 Life cycle environmental impacts of blade waste management

Life cycle environmental impacts are assessed for different waste management options in terms of PED (GJ) and GHG emissions, reported as tonnes carbon-di-oxide equivalent (CO_2eq.) based on 100 year global warming potentials (Stocker et al., 2013). Five waste management options are analyzed in the present study: landfill, incineration with municipal waste, incineration in cement kilns, mechanical recycling with land filling of residual waste materials, and mechanical recycling with incineration of residual waste materials. For all waste management options, an equivalent set of activities are considered: waste preparation; transport; waste treatment processes; and use of product outputs of waste management (energy, recyclates). The functional unit is per ton of blade waste, and the inventory data were obtained from available literature and Eco invent database.

Based on the available data, out of the top five turbine manufactures in India mentioned in Section 2.1, only 25% of the plants are established inside India and the 25% of manufacturing waste is thus considered in quantifying the environmental impacts for all waste management options. The data of wind turbine blade manufacturer outside of India could change dynamically over time across different countries, and waste treatment techniques of manufacturing waste can vary significantly and be affected by the energy systems. Due to data unavailability, manufacturing waste generated outside of India is excluded in the environmental impact assessments in this study as the scope of the present study is on waste arising in India. The remaining smaller portion of manufacturing waste in India and onsite O&M waste are assumed to be significantly smaller in comparison to the EoL waste. By assuming that the material composition of each waste category is the same, the wastes generated during manufacturing, operation, and EoL processes are assumed to be treated in the same manner for each waste management option, as illustrated in Figure 5.

2.3.1 Waste preparation and transport:

For all the options, the waste needs to be first shredded into smaller sizes (~100mm) before being sent to the waste management plants. Let the transport distances of 200 km between each activity location (wind turbine installation to waste management facilities; between waste management facilities). This is based on that land filling, incineration and mechanical recycling plants would be constructed close to the wind farms. The uncertainty associated with transport distances due to hypothetical facilities will be discussed in Section 3. Materials are assumed to be transported by truck with 16 – 32 ton capacity.

2.3.2 Land filling

Wind turbine blade materials sent to landfill are assumed to be treated as plastic waste mixture in a sanitary land fill. Let there will no further GHGs (e.g., methane emissions associated with land fill gas) are emitted following the deposit of this material in land fill, due to its inert nature. Likewise, no energy recovery from landfill gas is associated with the disposal of this material by landfill.

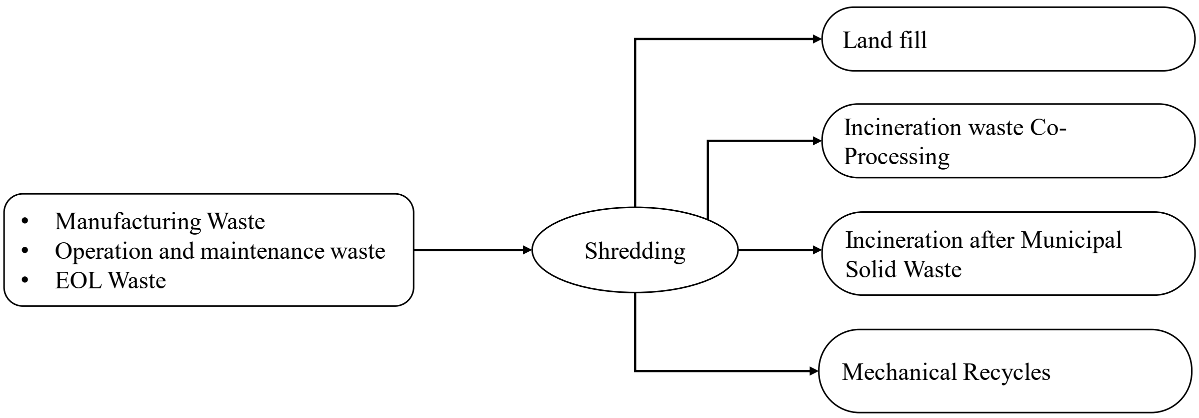


Figure 4: Various options of Waste management

2.3.3 Incineration

Thermosetting polymers have a calorific value and can be combusted as a source of energy. As glass fiber and the mineral fillers used in composites are incombustible, the calorific value of a composite depends principally on the proportion of polymer. Based on our assumed material of GFPR, we assume 60 % of incombustible material during the incineration process, giving a calorific value of 12.8 MJ/kg GFRP waste based on the calorific value of 32 MJ/kg resin (Pickering, 2012). We include two scenarios for incineration: waste is incinerated with municipal solid waste in a combined heat and power facility (Pickering,2012) and waste is incinerated in a cement kiln (EuCIA, 2013). Incineration in a cement kiln is assumed to produce heat that can replace petroleum coke (35. 8MJ/kg) (UK Department for Business Energy Industrial Strategy (BEIS), 2020) on an energy equivalent basis with an efficiency loss of 3% (Kara,2012) (i.e., 0.35 kg petroleum coke / kg GFRP). Incineration in a combined heat and power facility generate useful electricity and heat for subsequent use (Pickering,2012). We assume generation efficiencies of 13% and 25% for electricity and heat, respectively (Li et al., 2016). Generated heat and electricity are assumed to displace generation that would otherwise occur elsewhere. Therefore, we account for the state specific electricity grid mix to estimate the avoided energy demand and GHG emissions associated with the electricity output. For heat, we assume heat would otherwise be generated by combustion of natural gas in a boiler. Non-combusted materials (e.g., glass fiber, ash) are transported to landfill for disposal as inert materials.

2.3.4 Mechanical recycling

Mechanical recycling of the composite wind turbine blades enables recovery of glass fiber and fine material suitable as filler for composite polymer applications. Of the input waste material, 21% is recovered as glass fiber and 30% as polymer filler (Palmer et al., 2009). Waste is firstly cut into 50–100 mm size pieces by shredder and then further grinded by hammer mill for size reduction. Grading procedures using sieves and cyclones separate the recyclates into fiber- and powder-rich fractions (Yang et al., 2012; Zhang et al., 2020). Recovered glass fiber can be used to displace the manufacturing process of virgin glass fiber. However, the mechanical properties of the recycled glass fiber may be degraded, while in complete separation of glass fiber from polymer resin can further reduce quality. A material substitution ratio of 0.78, indicating that one ton of recovered glass fiber can avoid the production of 0.78 tonnes of virgin glass fiber, is based on relative retained tensile strength of recycled and virgin glass fiber (Liu et al., 2019; Palmer,2009). Recovered filler material can substitute calcium carbonate; however, as the energy inputs and GHG emissions associated with production of calcium carbonate are very low, this benefit of recycling is excluded from the current study. The remaining 49% coarse portion cannot be usefully reprocessed due to undesired bonding between coarse particles and composite materials (Li et al., 2016), and this portion is thus considered to be transported to either incineration and/or landfill for final waste treatment. Energy requirements for mechanical recycling process are estimated to be 0.27 MJ/kg GFRP as in (Howarth et al.,2014).

2.3.5 Electricity generation sources in each state

The life cycle environmental impacts of managing wind turbine blade waste are strongly dependent on background energy systems in place. Energy inputs to waste management processes contribute to a significant share of environmental impacts. Similarly, avoided impacts associated with the production of energy outputs (heat, electricity) depend on the source of generation they are displacing. In particular, each state in India regulates their own electricity grids and that there is little connection east to west to allow significant flow of electricity from one state to another. The present analysis accounts for this regional variation in electricity generation mix in assessing state specific impacts of the selected waste management routes. The electricity generation sources in India are projected until year 2040, and we assume the same energy background system from year 2040 until 2050. Based on this energy background system, the net annual PED and GHG emissions to produce 1 GJ of electricity in each state.

3 Results and discussion

3.1 Prediction of the total waste inventory

Cumulative wind turbine blade waste associated with India's wind power sector will total approximately 275,299 tonnes by 2050 (Figure 5).

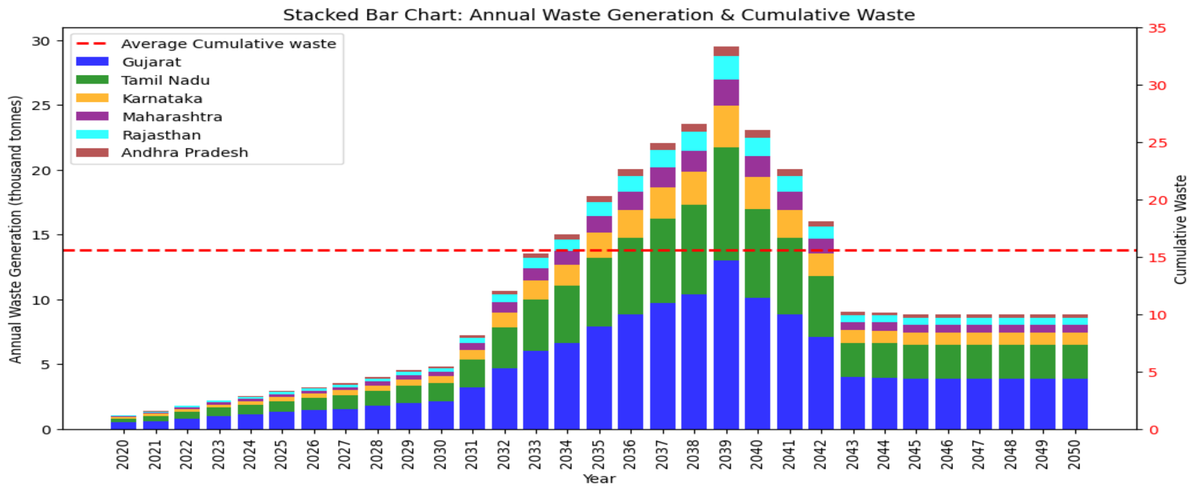


Figure 5: Annual and Cumulative waste generation predicted till 2050

Average annual waste generation is predicted at 8,881 t/yr, although this is expected to peak between 2036 and 2040 at nearly 29,000 t/yr. This peak reflects the rapid deployment of wind turbines 25 years prior (2011–2015) that reach their EoL during this period; at the same time, additional wind turbines are installed to replace this capacity and thus associated manufacturing process wastes arise.

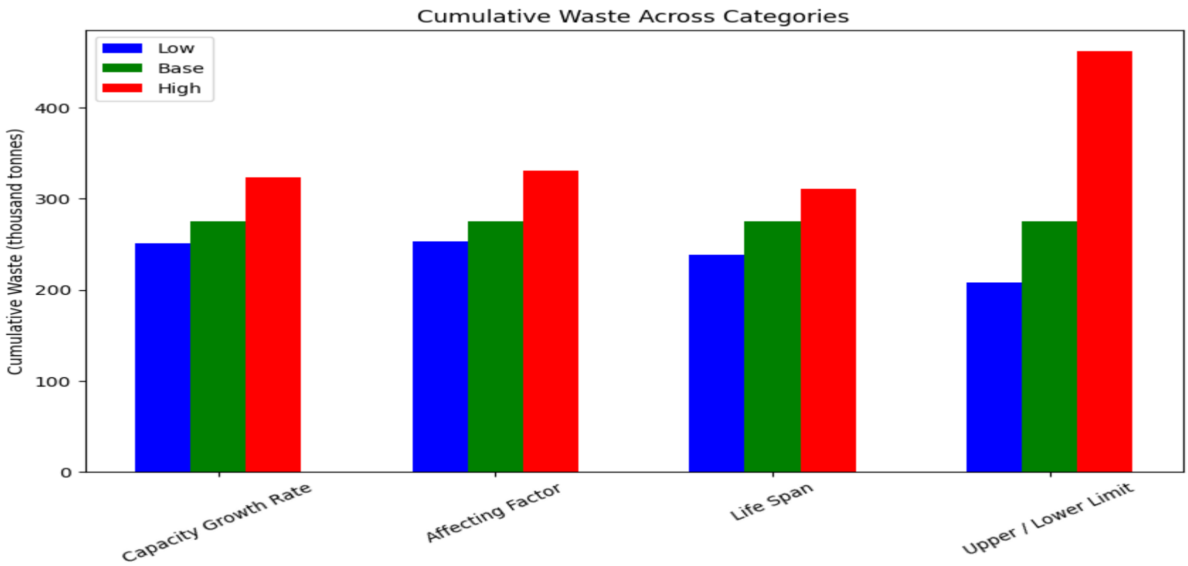


Figure 6: Sensitivity analysis for the total cumulative waste inventory in 2050: (a) the estimated value for the total waste for each individual contributor

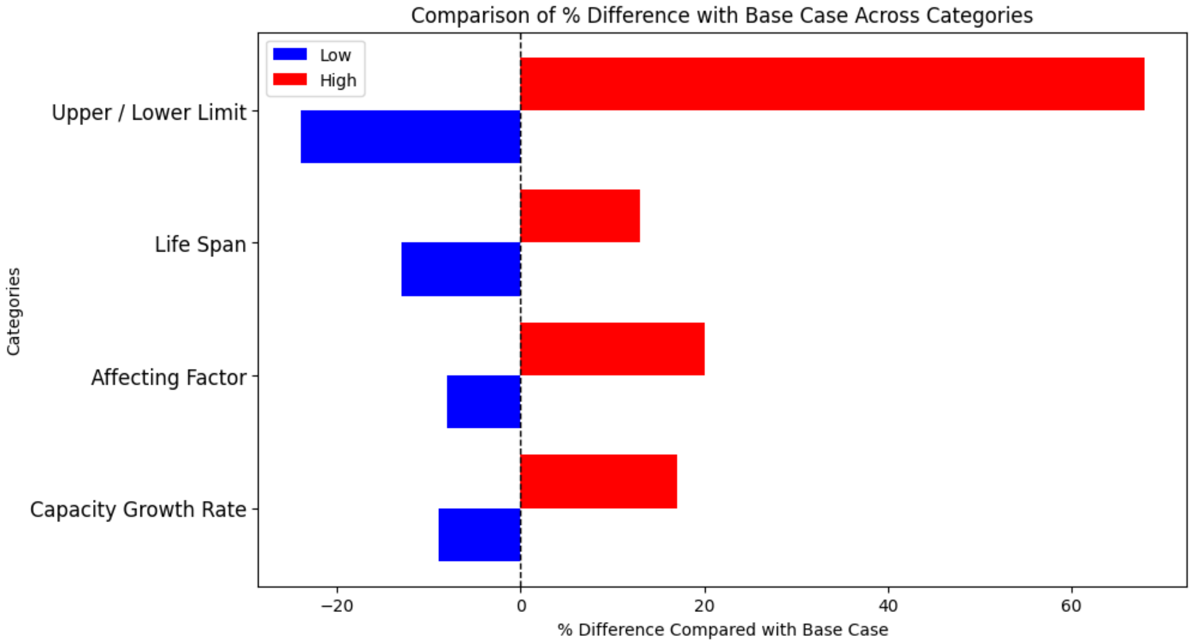


Figure 6: Sensitivity analysis for the total cumulative waste inventory in 2050: (b) the percentage difference (%) of the low and high scenarios when compared to the base case scenario.

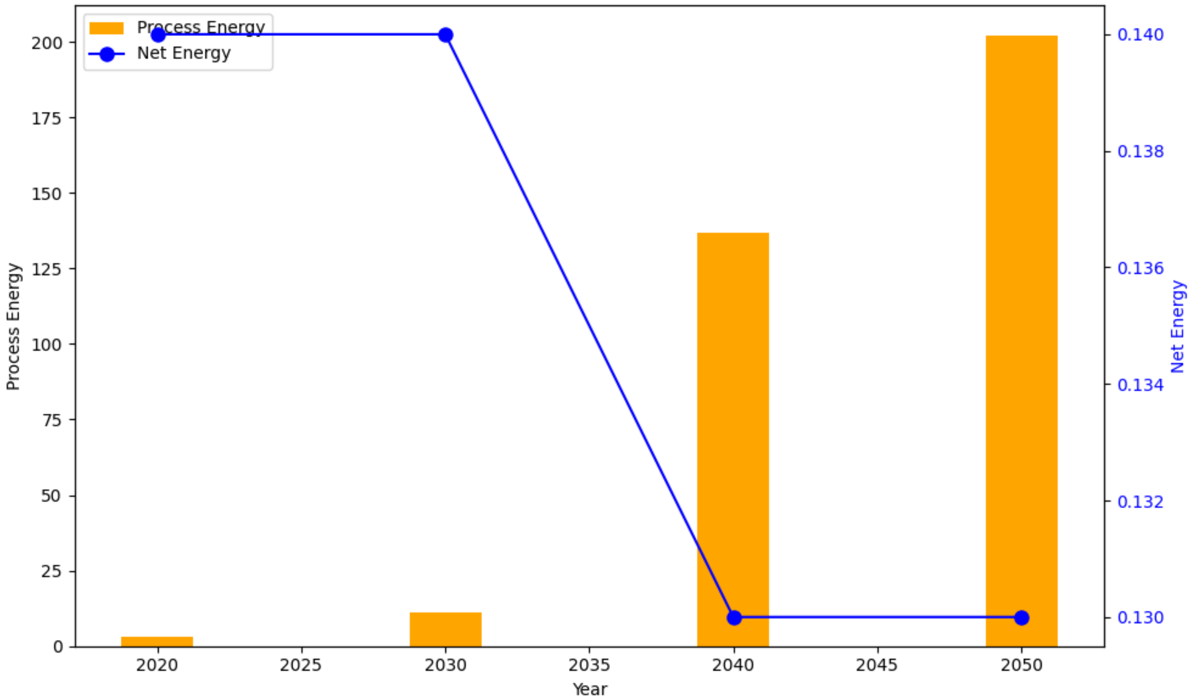
In contrast, upto 2030, blade waste generation will be minor (less than 3,000 t/yr), reflecting the small number of turbines reaching their EoL within this period. From mid 2040s, waste generation is driven primarily by assumed rates of wind power deployment after 2019, rather than historic data, and so approaches a linear trend. The dynamic pattern of the waste generation over years observed in Figure 6 is mainly due to the manufacturing waste and EoL waste.

Within India, the quantities of waste created are not evenly distributed, but follow location of historic and projected deployment of wind turbines. As a result, blade waste is concentrated in Gujarat and Tamil Nadu, which will see cumulative wastes of 111,573 tonnes and 79,657 tonnes, respectively. In contrast, blade waste in other jurisdictions will be significantly less: Karnataka, 34,562 tonnes; Maharashtra, 24,329 tonnes; Rajasthan 14,717 tonnes; and other states 10,256 tonnes. Of this total waste, approximately 25% is related to the manufacture of wind turbine blades. Manufacturing wastes associated with each Region's wind power sector are included in the above totals but may not be generated within the same area. Many wind turbine blade manufacturers are based outside of India is approximately 25% of the total. It is difficult to quantify the portion of the blades that will be manufactured inside and outside of India in the future, thus it is not clear where this portion of wastes will arise and thus be entered into waste management processes.

3.2 Sensitivity analysis of the total waste inventory

Waste quantity prediction is sensitive to assumptions about the growth rate of India's wind power sector, uncertainties in manufacturing and O&M waste generation, and the lifespan of installed wind turbines. Low and high estimates, 208,325 tonnes and 461,755 tonnes, respectively, bound the central base case estimate of 275,299 tonnes (Figure 7). Results are most sensitive to the projected growth of wind power within India by 2050, which directly influences wastes produced during manufacture, O&M, and at EoL. The lifetime of wind turbines is also an important factor, as shorter life spans result in more turbines reaching their EoL by 2050; additionally, manufacturing waste increases as new wind turbines must be commissioned to replace EoL turbines. The rate of manufacturing waste generation is also a significant factor, contributing approximately 7 % and 16 % variation from the base case for the low and high estimates, respectively. It is noted that failure rates may be reduced into future due to development of condition monitoring techniques that could reduce unplanned events. However, O&M wastes (grouped into affecting factor) are relatively small (0.7–1.7% of total cumulative waste until 2050) and so uncertainty in estimating these losses do not significantly impact results.

(a)



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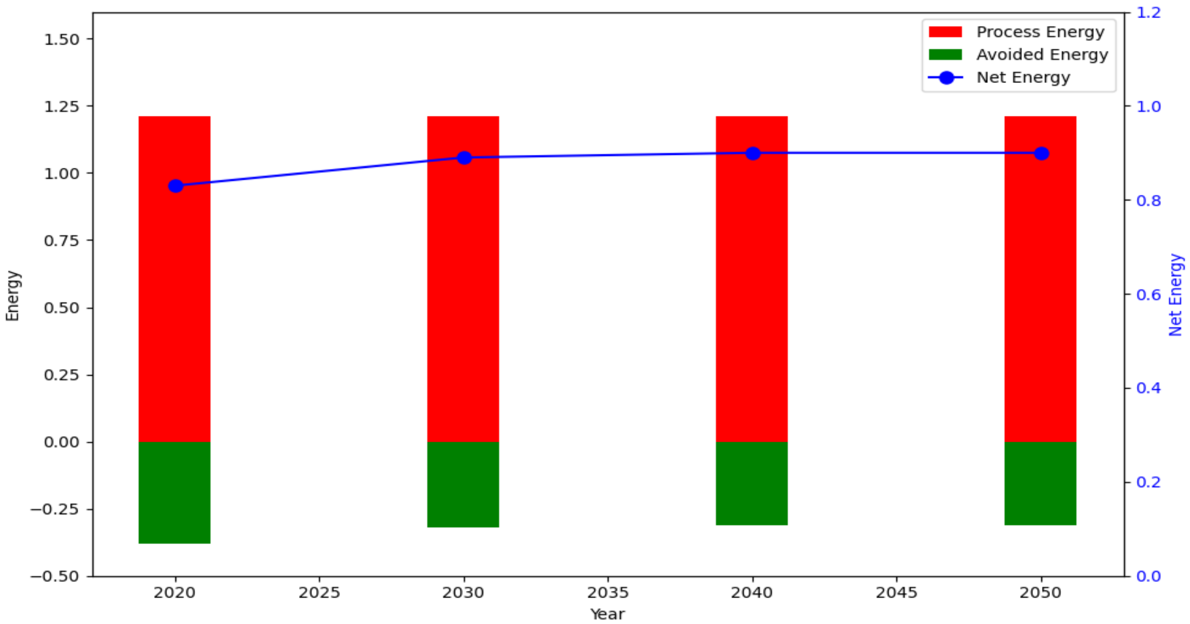

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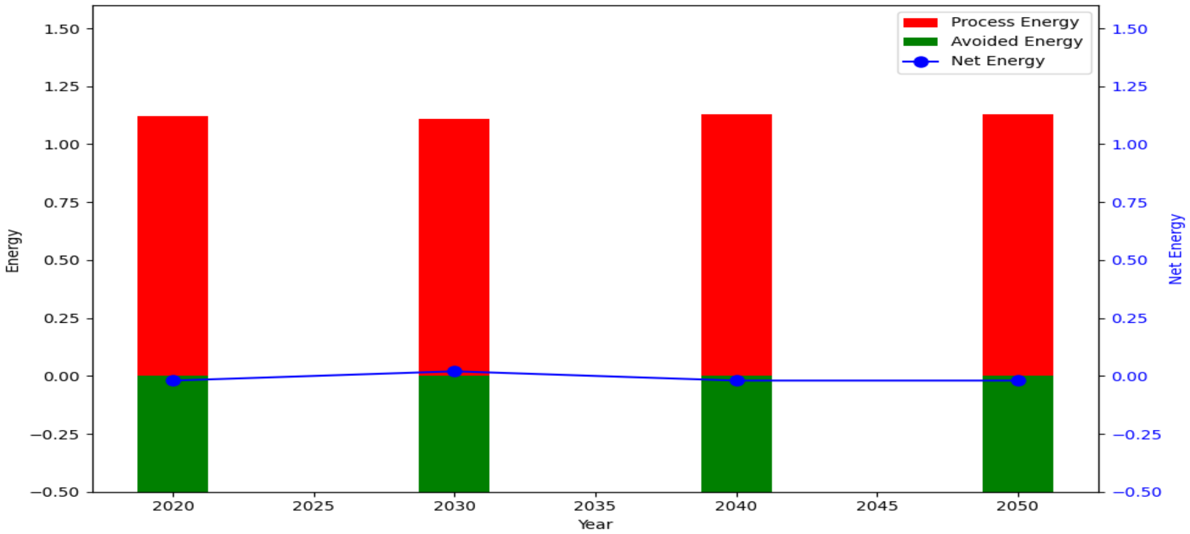

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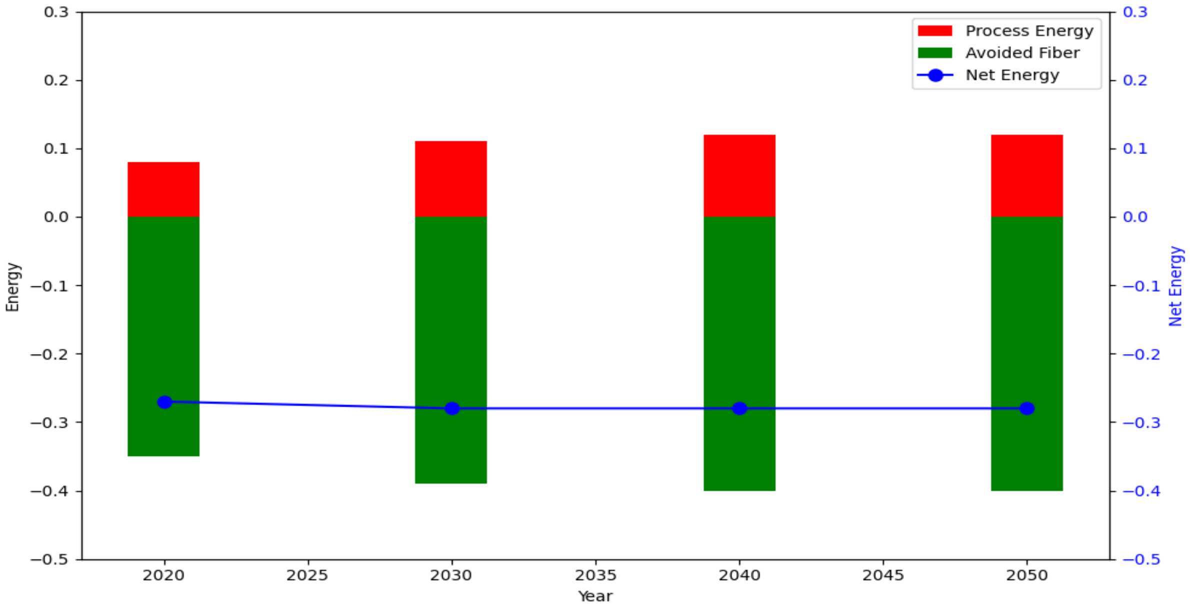

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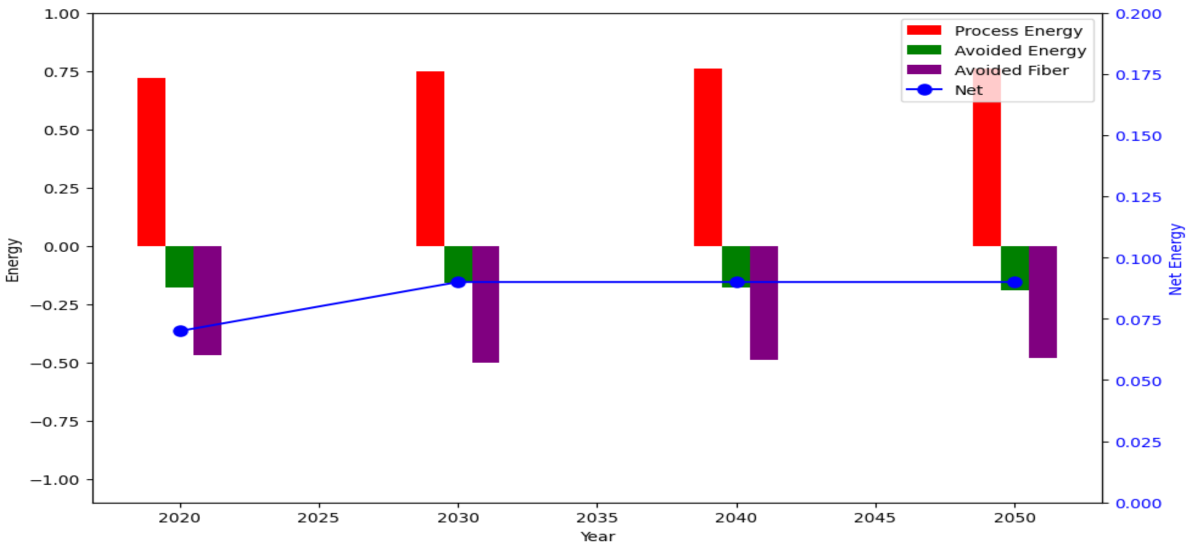


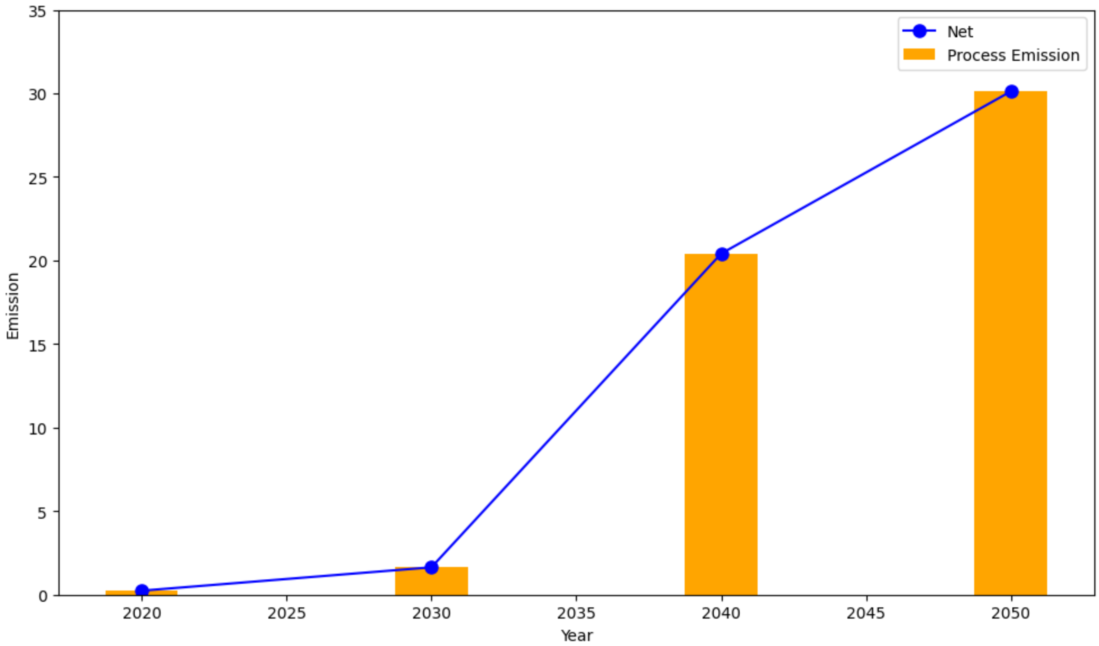
Figure 7: National average life cycle greenhouse gas emission for every decade with

treating one tonne wind turbine blade waste by a) land filling; b) incineration (with municipal solid waste); c) incineration (in cement kilns); d) mechanical recycling and land filling of residues; e) mechanical recycling and incineration of residues. The error bars indicate the maximum and minimum values of greenhouse gas emission across different states.

3.3 Life cycle environmental impacts of blade waste management

The environmental impacts of managing wind turbine blade waste are dependent on both the waste treatment route considered and the annual local energy sources that are consumed (or displaced). The national average primary energy demand (PED) and GHG emissions (Figure 8) per tonne waste are calculated based on their energy mix. The difference in transport distance has minor effects on overall results which has been merged into process related PED and GHG emissions. Therefore, uncertainty in transport is not significant for further sensitivity analysis.

(a)



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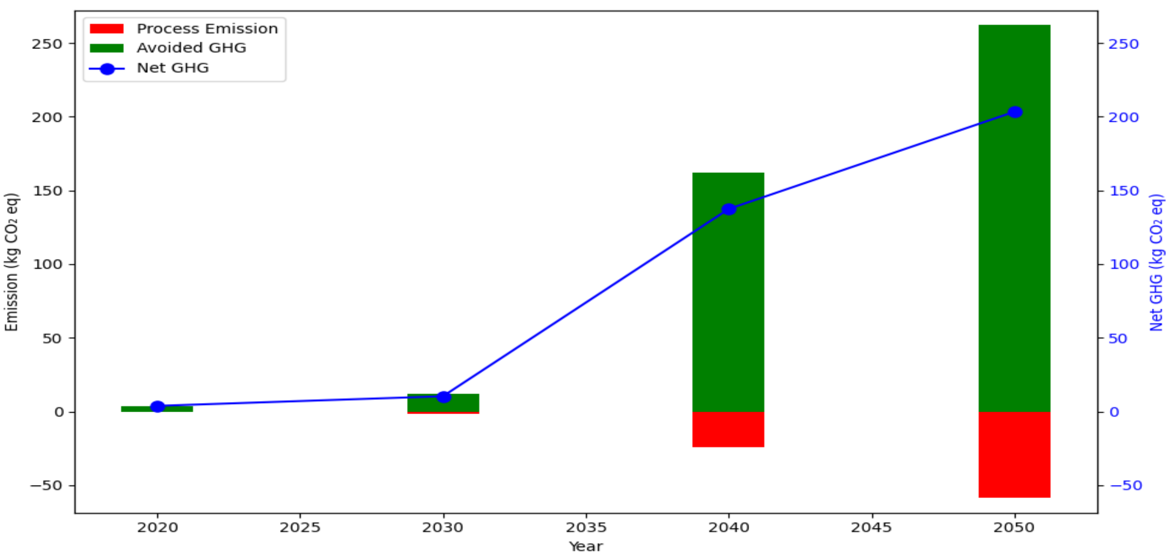

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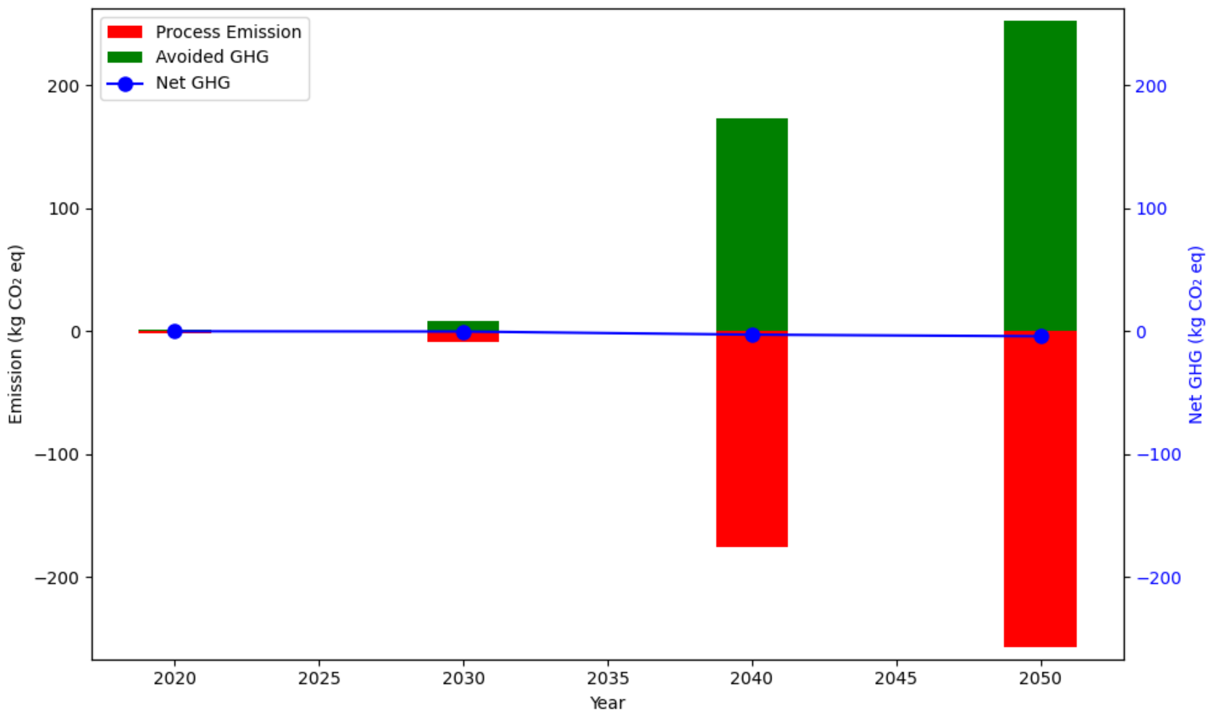

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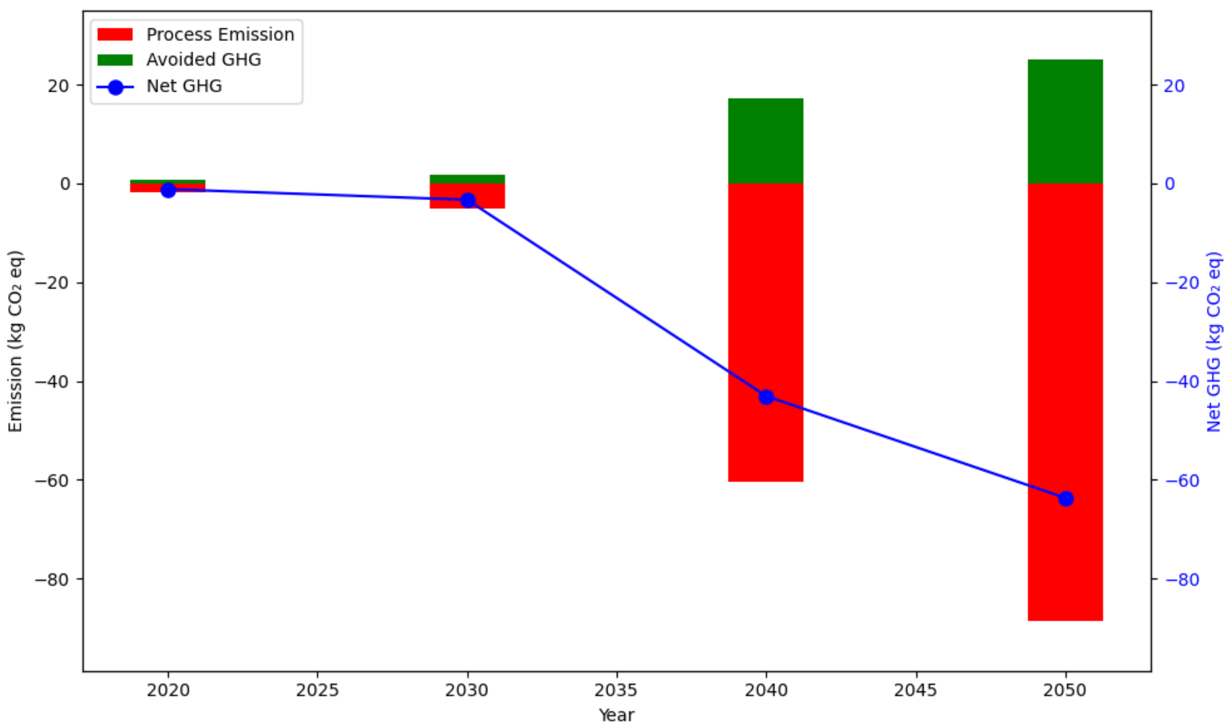

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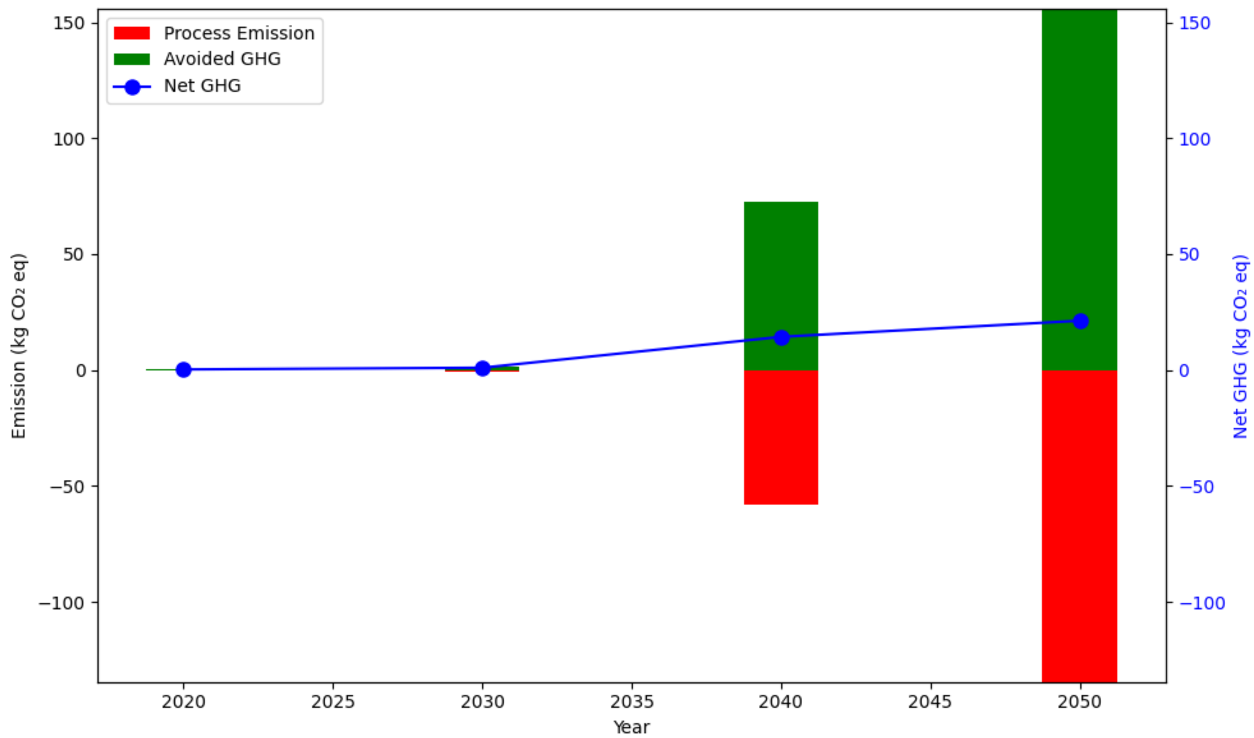


Figure 8: Spatial and temporal distribution of greenhouse gas emissions associated with wind turbine blade waste management: a) land filling; b) incineration (with municipal solid waste); c) incineration (in cement kilns co processing); d) recycling and land filling of residues; e) recycling and incineration of residues.

Land filling of blade waste exhibits a small energy requirement associated with waste transport and land filling operations. GHG emissions for land filling are also low, due to the inert nature of the blade material that avoids generation of methane-rich landfill gas.

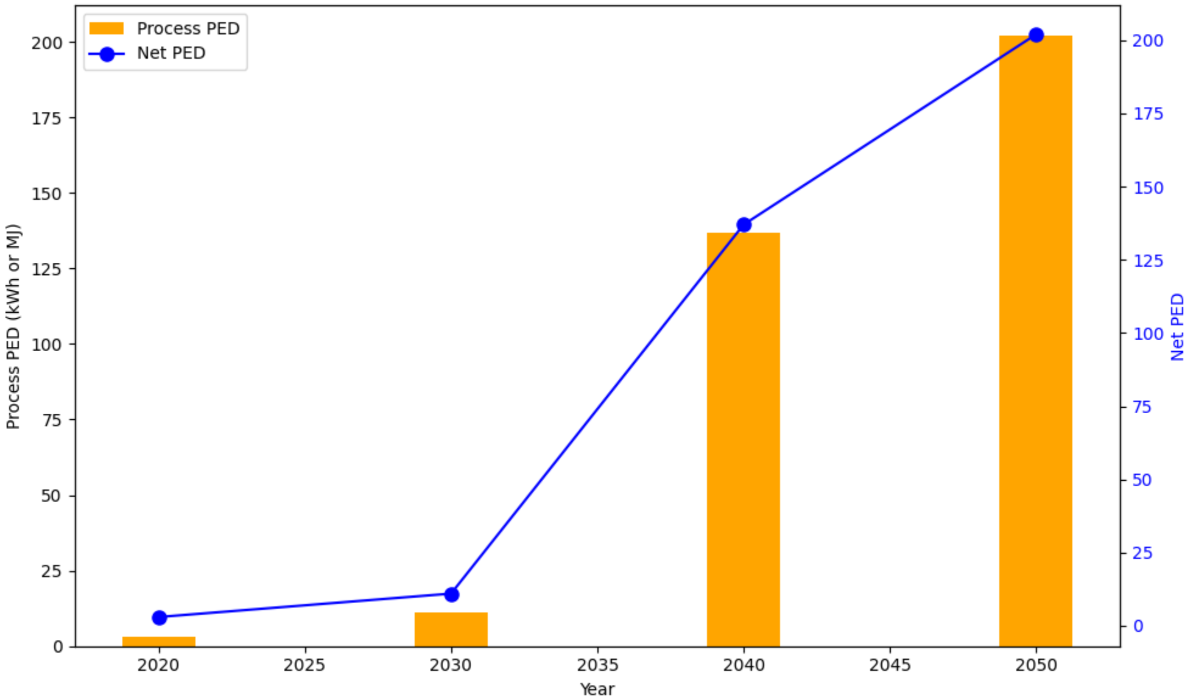
Incineration recovers the energy content of the combustible blade material and displaces energy use by other sources for heat and electricity in the incineration with municipal solid waste scenario or petroleum coke for heat in the incineration in cement kiln co-processing scenario, both resulting overall in a reduction in PED and GHG emissions (Figure 8). If the waste is incinerated with municipal solid waste, where provinces rely on fossil fuels for electricity generation, this net energy gain is relatively greater. For example, more than 80% of the electricity generating sources, displacing these energy intensive electricity generation routes results in a net PED of approximately 7 GJ/t blade waste in 2020 where the waste is incinerated with municipal solid waste. Similar results are found for other states that rely on non-renewable electricity sources. However, the net PED of these states increases to approximately 5 GJ/t in 2030 due to the reduction of avoided energy. In contrast, in states where electricity generation is dominated by renewable sources realize more modest reductions with a net PED of approximately 4 GJ/t blade waste. The net PED for these states is also consistent for every decade. Incineration of blade waste increases GHG emissions in all states, as the emissions related to the combustion of the polymer matrix material exceed the benefits of displacing other sources of heat and electricity production. States with greater reliance on fossil fuels for electricity generation have correspondingly greater emissions reductions from producing electricity from blade waste, and thereby realize lower GHG emissions (~0.6 CO_2eq./t blade waste) than provinces with less carbon-intensive electricity sectors (~0.9 CO_2eq./t blade waste) in 2020. However, the GHG emissions increased slightly towards 2030 as the coal slowly phases out. The reduction of coal consumption results in the increase of GHG emission to ~0.8 CO_2eq./t blade waste for year 2030. The rate of increase of GHG emission for becomes less rapid between 2030 and 2040 as the percentage of coal consumption for electricity generation becomes relatively low for these years.

If the waste is incinerated in a cement kiln, the PED and GHG emissions are insensitive to the energy background mix. For every decade, all states show consistent net reduction of 12.8 GJ/t in PED and net reduction of 0.02 CO_2eq./t for GHG emissions. It is noted the avoided fossil carbon emission of petroleum coke use is negated by the similar amount of fossil carbon emission from polymer combustion. This thus results in a near net zero emission.

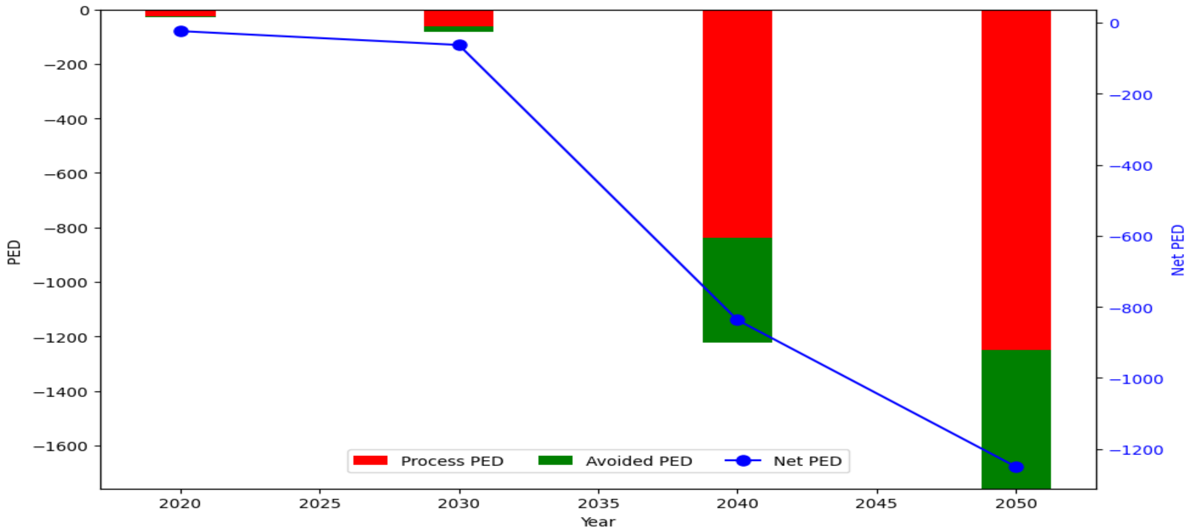
Recycling blade waste can reduce PED by displacing the manufacture of glass fiber with recovered fiber. The mechanical recycling process considered in the present study generates considerable quantities of residual materials: incineration of residues further reduces PED by displacing heat and power generation. As for the incineration route, the relative benefits of energy recovery from residues are dependent on the background electricity generation mix, with greater reductions achieved in provinces more reliant on non-renewable sources. Mechanical recycling with land filling of residual materials is the only waste treatment route considered that can achieve a net reduction in GHG emissions, as the benefits of recovering glass fibers outweigh emissions associated with the recycling and land filling processes. However, if residues are incinerated, emissions associated with polymer combustion negate the benefits achieved by glass fiber and energy recovery and result in a net increase in GHG emissions though it is noted that the net increase is not significant.

3.4 Spatial and temporal distribution of life cycle environmental impacts of blade waste management

(a)



(b)


PED
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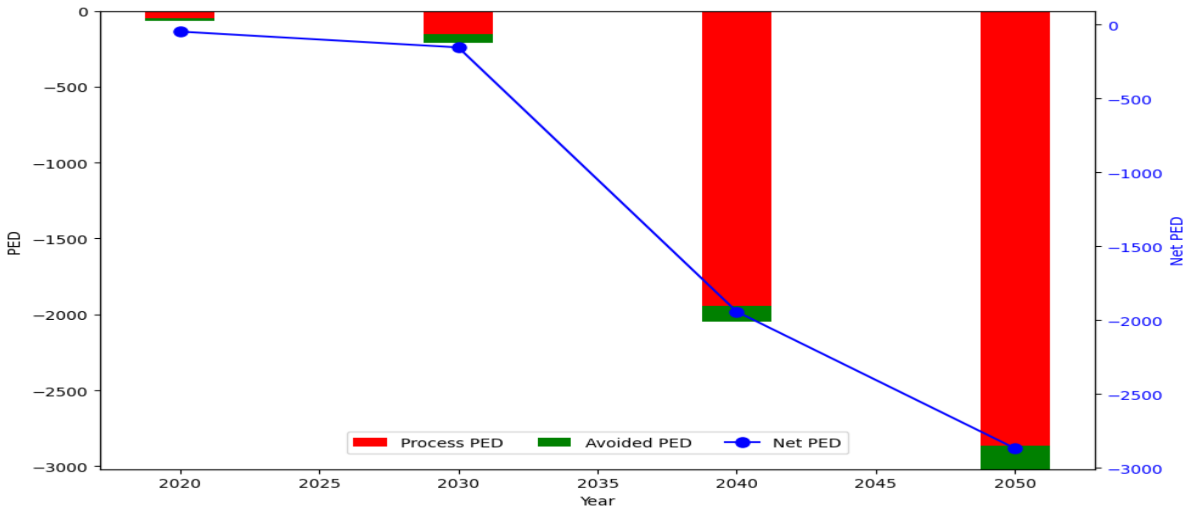
Year
Process PED
Avoided PED
Net PED
0
−200
−400
−600
−800
−1000
−1200
−1400
−1600
2020
2025
2030
2035
2040
2045
2050

(c)


PED
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Year
Process PED
Avoided PED
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−500
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−1500
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−2500
−3000
2020
2025
2030
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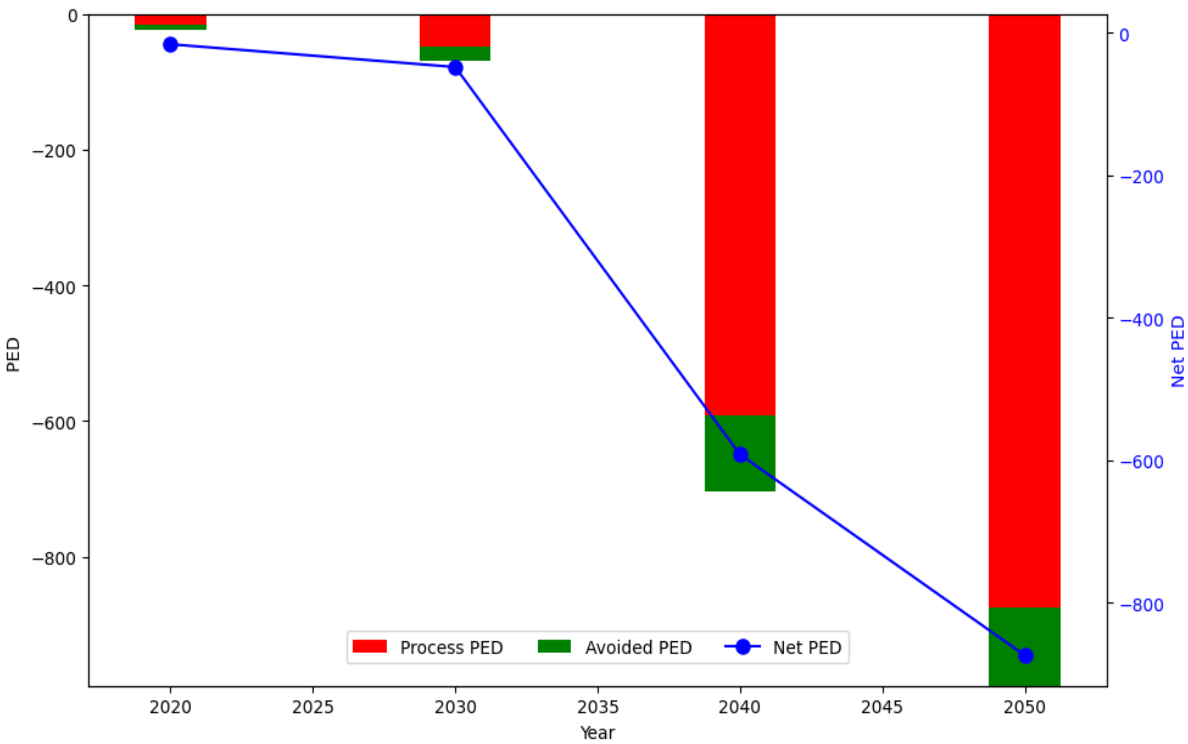
2045
2050

(d)


PED
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(e)

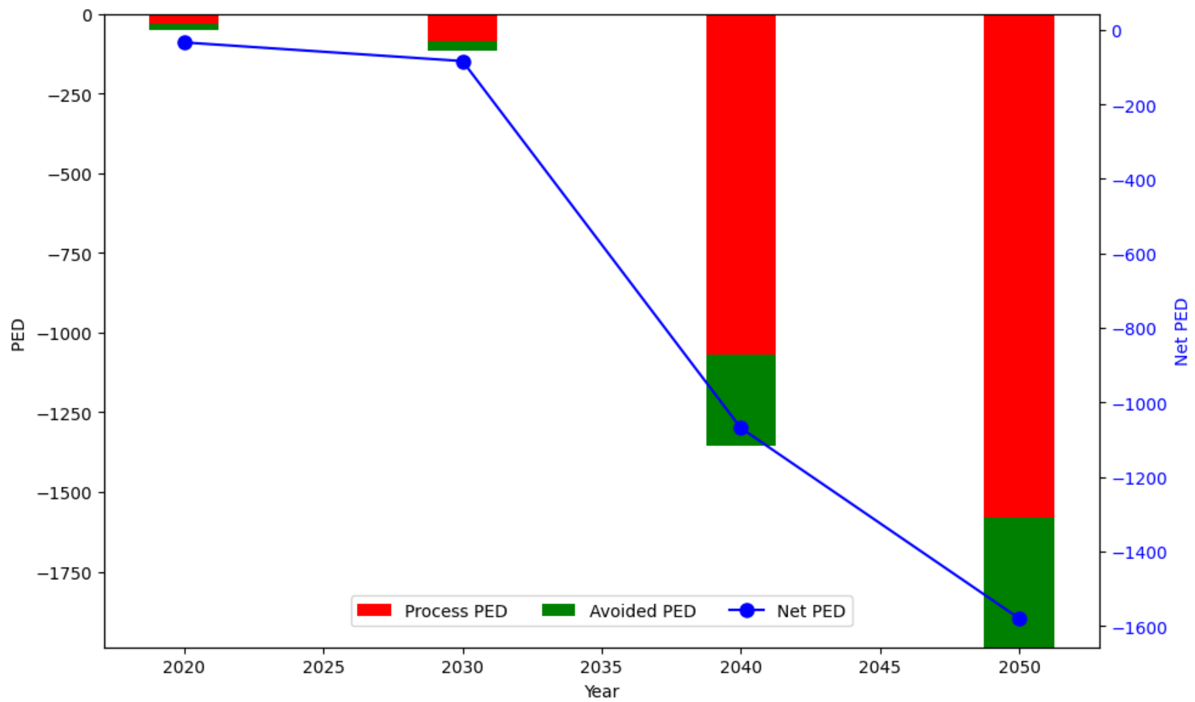

Figure 9: Spatial and temporal distribution of primary energy demand associated with wind turbine blade waste management: a) land filling; b) incineration (with municipal solid waste); c) incineration (in cement kilns co processing); d) recycling and land filling of residues; e) recycling and incineration of residues.

The generation of wind turbine blade waste, and therefore the resulting impacts of managing these wastes, is modest within the next 10 years, with GHG emissions for incineration with municipal solid waste estimated to reach only 10 k CO_2eq. by 2030 (Figure 9 (b). However, GHG emission for incineration in a cement kiln is estimated to result in almost net zero emission by 2030. Similarly, PED associated with wind turbine blade waste management is also expected to be modest over the next decade. However, the rapid growth in waste generation between 2030 and 2040, which reflects turbines installed between 2005 and 2015 reaching their end of life and being replaced, results in a corresponding order of magnitude increase in life cycle environmental impacts associated with waste management. By 2040, GHG emissions associated with incineration with municipal solid waste are predicted to reach 137 kt CO_2eq., whereas mechanical recycling with land filling of residuals could avoid 43 ktCO_2eq. by this time. Beyond 2040, impacts of wind turbine waste management continues to be generated, but growth is more subdued, reflecting more modest rate of installations from 2015 to present and projections to 2025.

Life cycle environmental impacts associated with managing wind turbine blade wastes varies significantly by province, due to spatial variations in the quantity of waste generated (discussed previously in Section 3.1) and the GHG-intensity of state electricity mix (discussed previously in Section3.3). Integrating these findings reveals that environmental impacts are concentrated in Gujarat and Tamil Nadu due to their large share of current and projected wind turbine installations. These two states represent approximately 72 % of total national emissions related to wind turbine blade waste management (Figure 9). The impacts of incineration are particularly pronounced in these two states, due to the large role of renewable and nuclear electricity generation routes. The different patterns observed in the predicted waste quantity and the net environmental impacts for different provinces indicate the importance of considering local energy systems to achieve a higher accuracy in estimating net impacts of waste management systems.

3.5 Wind turbine blade waste management and life cycle environmental impacts in context

To ensure the sustainability of wind power installations, it is necessary to plan for and regulate the management of inevitable wastes arising from manufacturing, O&M, and end of life. In a broader context, the overall impacts of wind turbine blade waste management appear small. Cumulative blade waste generation of 275kt by 2050, estimated in this study, is equivalent to only 1 % of waste disposed in India in a single year at present. The GHG emissions implications of blade waste management are also modest. Based on an average capacity factor for wind turbines in India of approximately 30%, even the highest GHG emissions case for blade waste management (incineration) would represent an emissions rate of 0.4 g CO_2eq./kWh produced, equivalent to 4% of life cycle emissions associated with wind power. In contrast, life cycle GHG emissions associated with natural gas combined cycle generation would be approximately 1000 times this estimated impact of blade waste management.

The present study demonstrates the potential GHG emissions advantage of developing and deploying viable recycling routes for wind turbine blade wastes. However, current wind turbine blades, primarily comprised of GFRP, are a challenging component to effectively recycle due to the nature of their constituent material. Globally, there are very few examples of composite recycling processes in operation, and these are based on recovering higher value carbon fibers (Meng et al.,2018b; ELG Carbon Fiber Ltd, 2020) rather than comparatively low value glass fibers. Through co-processing in the cement kiln the GFRP waste is converted into energy and into raw materials for the cement which is technically possible and cost effective (EuCIA, 2013). But it is achieved by replacing one form of fossil carbon from petroleum coke with another from polymer matrix and thus just achieves net zero GHG emissions (see Sections 3.3 and 3.4). Moreover, in co-processing the fiber shape of the glass disappears and therefore cannot be used in other composites applications which is not an efficient way in circular economy. Although mechanical recycling has demonstrated substantial reductions in PED and GHG emissions, achieving viable recycling systems in practice will be challenging. This is due to high costs associated with disassembly and recovery of glass fibers from wastes (Li et al., 2016), the reduction in their mechanical properties and size, and competition with low cost primary production of glass fibers. Policy support, in mandating or otherwise encouraging more circular management of wind turbine blade wastes, is likely to be required. In the absence of financially viable recycling routes, or where cost is not justified by achieved benefits (e.g., social cost of carbon), land filling represents a low-impact alternative that can achieve very low GHG emissions for waste management. The inert nature of the material ensures other environmental impacts associated with land filling will be minimal. While incineration offers the recovery of energy from blade waste, associated GHG emissions make this an unattractive option.

While the present study assumes GFRP to be the turbine blade material, it is recognized that new materials may be adopted over the next few decades, specifically when the offshore wind energy becomes more established. To accommodate larger power rates, the development of larger turbines is required, so carbon fiber could be more commonly used as the blade material owing to its high specific mechanical properties (Lefeuvre et al., 2019; Sommer et al., 2020). Offshore wind turbines in India could potentially utilize carbon fiber as the blade material to develop larger turbines with higher installed capacities. While India has a great potential for offshore wind power development, especially in the coastal regions of East and West side of India, offshore wind power in India is expected to be around 10 GW by 2030 (Global Wind Energy Council, 2020). By assuming a slow growth rate of the offshore wind development (as compared to the onshore wind development with existing technologies) and 25 years of wind turbine blade lifespan, the change of blade material due to offshore wind development has a minor impact on the waste generation and its associated environmental impacts until 2050. The possibility of using carbon fiber for wind turbine blades can be explored as well as its impacts on waste generation and management when offshore wind becomes more developed in India.

Uncertainty in how blade wastes will be managed in future does not bring into question the role of wind power in transitioning India towards low carbon energy systems. However, the timing of these impacts will coincide with the timeline for commitments net-zero carbon emissions by 2050. While the deployment of wind power to date has demonstrated the ease of achieving reductions in GHG emissions by displacing fossil fuel generation, management of associated wastes indicate some of the challenges in reaching net-zero emissions targets.

4 Conclusions

This study predicts the future wind turbine blade waste arising in India, throughout all lifecycle stages, from manufacturing until end of life, based on the installed capacities of existing Indian wind farms and projected future installations. Five alternative strategies for managing this waste stream are assessed in terms of life cycle GHG emissions and PED, including land filling, incineration, and mechanical recycling. For the base case scenario, it is observed that the total cumulative waste until 2050 is 275,299 tonnes, with onsite waste accounting for around 75% of this total. Waste generation is concentrated in provinces with greater wind power deployment: Gujarat and Tamil Nadu states account for 70% of total blade waste. Life cycle environmental impacts of waste management strategies are dependent on background energy systems, with incineration a significant source of GHG emissions, particularly when displacing low carbon grid mixes. Mechanical recycling can achieve substantial reductions in PED and GHG emissions but achieving financial viability would likely require substantial regulatory support and thus can be the focus of future work.

Increasingly, offshore wind turbines are using carbon fiber reinforced plastics as blade material rather than glass fiber. The higher financial value of carbon fiber may help to justify recycling as a waste management route, and we have previously demonstrated the technical, financial, and environmental viability of carbon fiber recycling with reuse in the automotive sector (Meng et al., 2018a, 2017). While offshore wind has yet to be deployed in India (as of 2019), there is a future opportunity with substantial wind resource in the Eastern and Western coastal regions of India. As carbon fiber is a high value product, high cost associated with recycling / dismantling / transportation can be justified by potential environmental benefits and thus can be the focus of future work looking at advanced technologies recovering high values while avoiding conventional landfill and incineration.

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