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Description:	By: Mo Li, Ph.D., UC Irvine
Filer:	Silvia Palma-Rojas
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Next-Generation Wind Energy Technologies and Their Environmental Implications

Mo Li, Ph.D.
Assistant Professor
Department of Civil and Environmental Engineering
Department of Chemical Engineering and Materials Science
University of California, Irvine

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Question 4

- Are the environmental life cycle aspects of the new composite materials and technology innovation being evaluated in the design and development of next-generation land-based and offshore wind technology?

Environmental Life Cycle Impacts of Wind Turbine Blades

- 1st generation of WT blades are reaching end of life. Most waste is sent to landfill.
- Macroscopic quantitative assessment of environmental life cycle impacts:
  1) Analyze global data to calculate the amount of WT blade materials consumed in the past;
  2) Consider eco data for raw materials, manufacturing, transportation, operations and maintenances.
- Main findings:
  1) A typical 45.2 meter 1.5 MW blade: 795 GJ (CO2 footprint 42.1 tonnes), dominated by raw materials and manufacturing processes (96% of the total).
  2) Based on the 2014 installed capacity, the total mass of WTB is 78 kt, their energy consumption is 82 TJ and the carbon dioxide footprint is 4.35 Mt.

Table 1. Materials listed in the bill of materials.

Major	Supporting	Consumable	
Carbon fibre UD	Steel accessories	Continuous filament mat	Resin flow pipes
Glass fibre UD	Copper accessories	Peel-ply/release film	T-fitting and infusion valve
Glass fibre multi-axial fabric	Aluminium accessories	Vacuum bag film	Mould cleaner and releasing agent
Resin	Balsa	Porous membrane	Hand Spray adhesives
Resin Curing agent	PVC	Flow mesh layer	Gel coat
Structural adhesives	Paint	Breather bleeder	
Structural adhesive curing agent	Putty	Vacuum bagging sealant tape	

Liu & Barlow, *Mater. Sci. Eng.* 2016

Environmental Life Cycle Impacts of wind turbine blades

Table 6. Material usage and energy consumption ratio of a 1.5 MW blade.

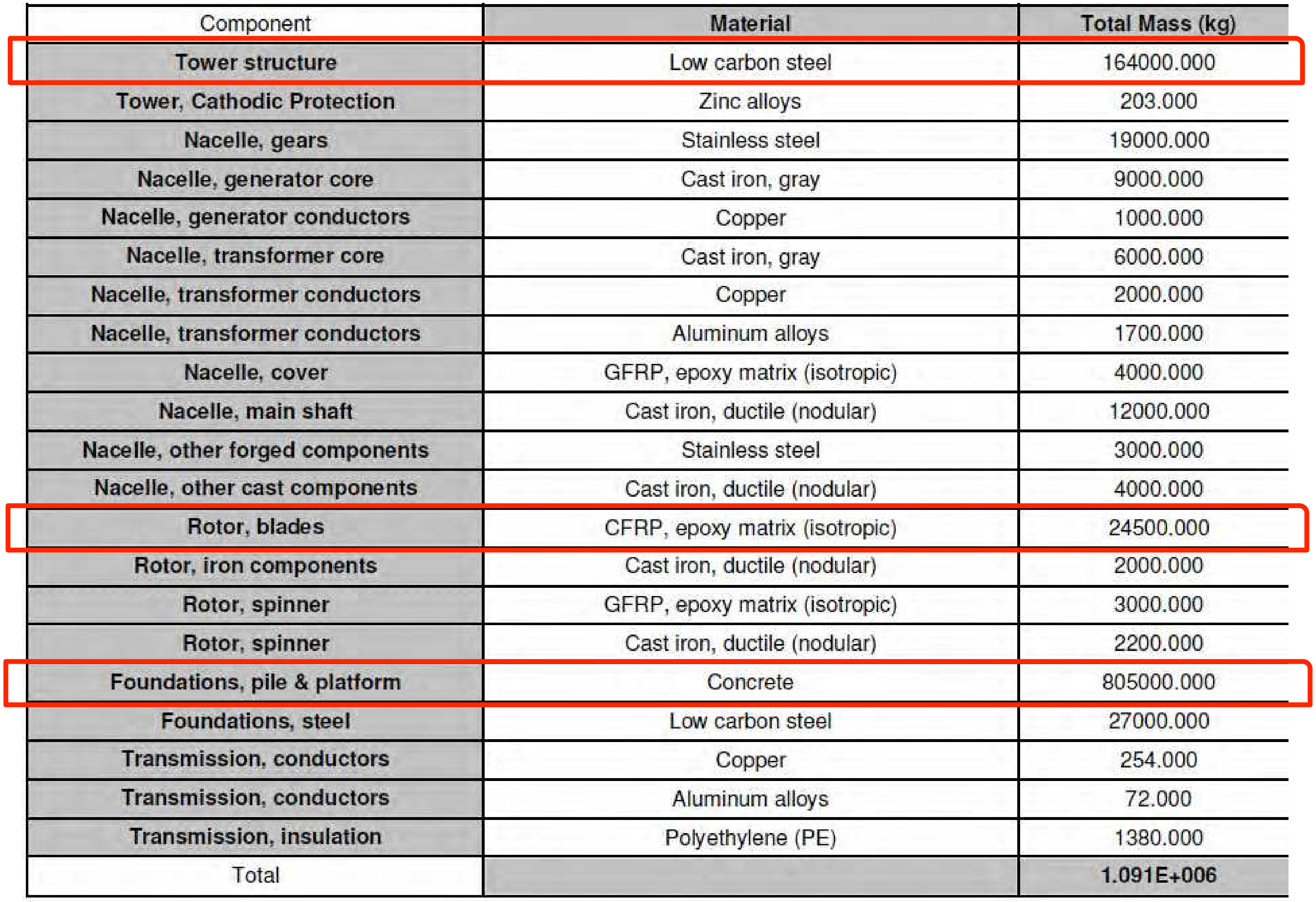
	Material by weight	Energy consumption
CF/GF fabric	60.4%	38.6%
Resin and adhesives	32.3%	56.7%
Steel	1.1%	6.0%
Copper	0.3%	2.5%
Aluminium	0.0%	0.6%
Balsa	2.3%	0.3%
PVC	1.7%	0.1%
Paint	0.9%	0.3%
Putty	0.7%	1.3%
Spray Adhesives	0.0%	1.3%

Table 8. GFRP and CFRP blade comparison.

Model	45.2A-1.5-IVB (full glass fibre, GFRP)	45.3-DW93 (carbon fibre spar, GFRP+CFRP)	% increase of CFRP over GFRP
Total energy consumption (GJ)	795	1194	+50.3%
Total CO_2 footprint (tonnes)	42.1	67.7	+60.9%
Total water consumption (tonnes)	989	1,079	+9.1%
Energy payback time (months)	2.02	2.27	+12.7%

Liu & Barlow, *Mater. Sci. Eng.* 2016

Life Cycle Analysis of Wind Turbine

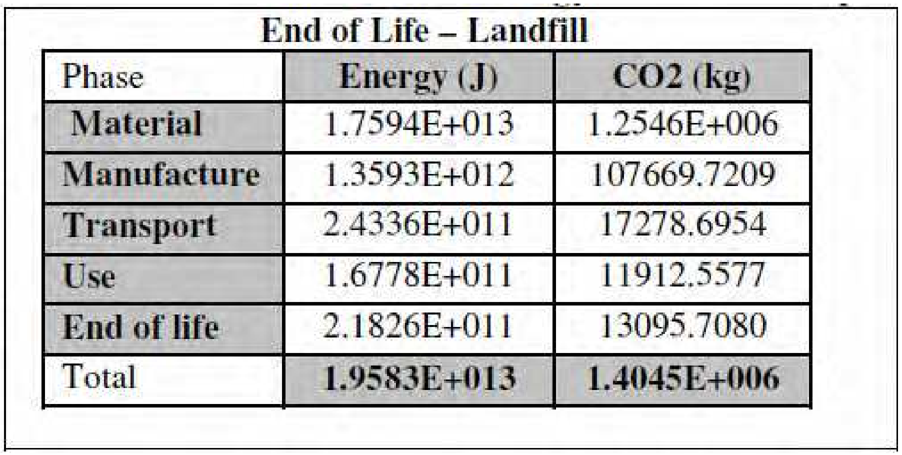


Component	Material	Total Mass (kg)
Tower structure	Low carbon steel	164000.000
Tower, Cathodic Protection	Zinc alloys	203.000
Nacelle, gears	Stainless steel	19000.000
Nacelle, generator core	Cast iron, gray	9000.000
Nacelle, generator conductors	Copper	1000.000
Nacelle, transformer core	Cast iron, gray	6000.000
Nacelle, transformer conductors	Copper	2000.000
Nacelle, transformer conductors	Aluminum alloys	1700.000
Nacelle, cover	GFRP, epoxy matrix (isotropic)	4000.000
Nacelle, main shaft	Cast iron, ductile (nodular)	12000.000
Nacelle, other forged components	Stainless steel	3000.000
Nacelle, other cast components	Cast iron, ductile (nodular)	4000.000
Rotor, blades	CFRP, epoxy matrix (isotropic)	24500.000
Rotor, iron components	Cast iron, ductile (nodular)	2000.000
Rotor, spinner	GFRP, epoxy matrix (isotropic)	3000.000
Rotor, spinner	Cast iron, ductile (nodular)	2200.000
Foundations, pile & platform	Concrete	805000.000
Foundations, steel	Low carbon steel	27000.000
Transmission, conductors	Copper	254.000
Transmission, conductors	Aluminum alloys	72.000
Transmission, insulation	Polyethylene (PE)	1380.000
Total		**1.091E+006**

Ghenai, *Sustainable Development*, 2012
Haapala & Prempreeda, *Int. J. Sustainable Manufacturing*, 2014

Life Cycle Analysis of Wind Turbine

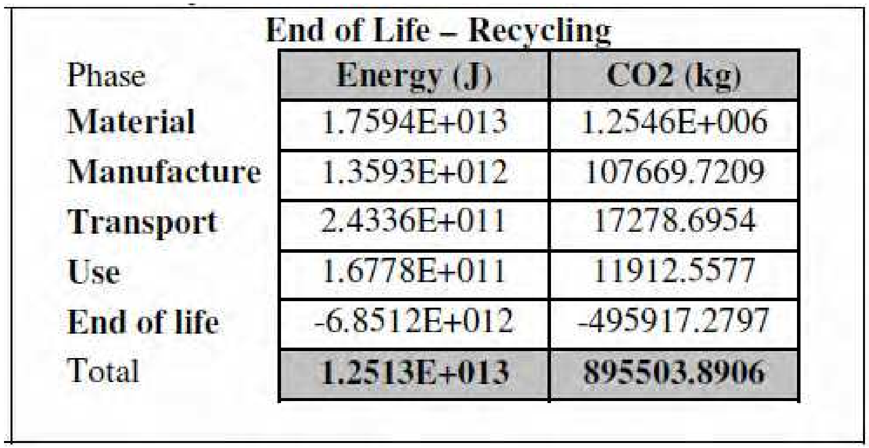
Landfill



End of Life – Landfill

Phase	Energy (J)	CO2 (kg)
Material	1.7594E+013	1.2546E+006
Manufacture	1.3593E+012	107669.7209
Transport	2.4336E+011	17278.6954
Use	1.6778E+011	11912.5577
End of life	2.1826E+011	13095.7080
Total	**1.9583E+013**	**1.4045E+006**

Recycling



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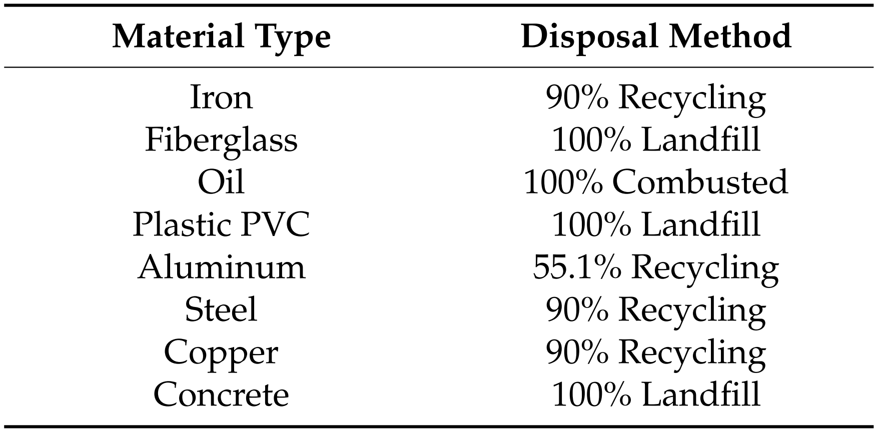
Manufacture	1.3593E+012	107669.7209
Transport	2.4336E+011	17278.6954
Use	1.6778E+011	11912.5577
End of life	-6.8512E+012	-495917.2797
Total	**1.2513E+013**	**895503.8906**

Table 4. Disposal and recycling strategy * [48].



Material Type	Disposal Method
Iron	90% Recycling
Fiberglass	100% Landfill
Oil	100% Combusted
Plastic PVC	100% Landfill
Aluminum	55.1% Recycling
Steel	90% Recycling
Copper	90% Recycling
Concrete	100% Landfill

Ghenai, *Sustainable Development*, 2012
Chipindula et al., *Sustainability*, 2018

Question 4

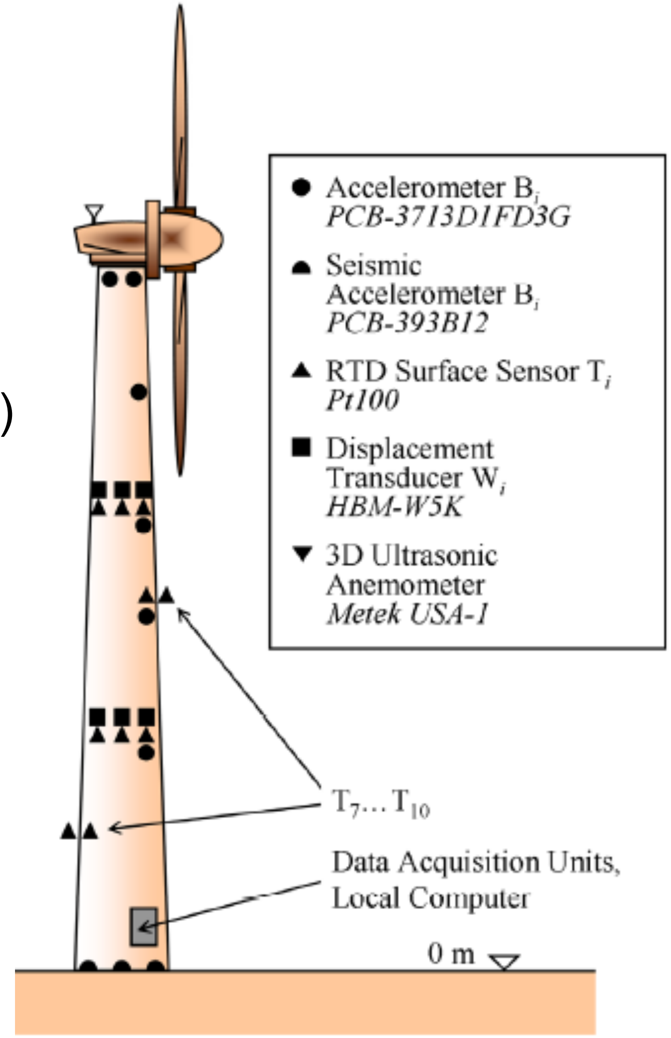
- Are the environmental life cycle aspects of the new composite materials and technology innovation being evaluated in the design and development of next-generation land-based and offshore wind technology?
  - It is important to evaluate how new materials, bigger blades, taller towers and foundation designs, and advanced manufacturing processes affect life cycle environmental impacts of wind turbine structures.
  - Consider impacts on birds, bats and ecosystem.
  - Explore new strategies to reduce life cycle environmental impacts, especially during raw materials and manufacturing processes.

Question 5

- There is a growing need for monitoring techniques and systems, which can provide information about structural defects and potential damage in next-generation and offshore wind turbines, such as instances of fatigue cracking or higher than expected levels of vibration.
- What type of monitoring technology is currently used in the field? Is there any need to develop or improve technologies that provide accurate and real-time data for proactive maintenance in larger land-based and offshore technologies?

Structural Health Monitoring and Damage Detection Methods for Wind Turbines

- Visual inspection (new developments include videoscope, flying remote visual inspection device, etc.)
- Vibration analysis (e.g., compare mode shapes between the reference and an inspection stage.)
- Point-based strain measurements (conventional strain gauges or optical fiber sensors)
- Acoustic emission method
- Ultrasonic testing techniques
- Radiographic inspection
- Thermal imaging method



Ciang et al., *Meas. Sci. Technol.*, 2008
Schubel et al., *Renew. Energ.*, 2013
Tchakoua et al., *Energies*, 2014
Li et al., *Smart Mater. Struct.*, 2015

Smarsly et al. *First International Conference on Performance-Based Lif-Cycle Structural Engineering*, 2012

Current SHM Methods

<table>
<tr><th>Current methods</th><th>Blade monitoring</th><th>Steel tower monitoring</th><th>Concrete tower monitoring</th></tr>
<tr><td>Visual inspection</td><td colspan="3">• Limited to surface visible damage
An autonomous drone locates the wind turbine, automatically comes up the most efficient inspection path, and collects images for inspectors to make decisions.


Skyspecs, https://skyspecs.com/skyspecs-solution/autonomous-inspection/</td></tr>
<tr><td>Vibration analysis</td><td colspan="3">• Requires the deployment of a variety of sensors and computationally intensive analysis techniques;
• Focuses on global behavior rather than local damage;
• Affected by environmental change, e.g., weather change affects the modal behavior.</td></tr>
<tr><td>Point-based strain measurements</td><td colspan="3">• Not sensitive to damage away from the sensor locations;
• Only measures surface strain change at sensor locations;
• Difficult to detect concrete cracking, damage or degradation.</td></tr>
</table>

Current SHM Methods

Current methods	**Blade monitoring**	**Steel tower monitoring**	**Concrete tower monitoring**
Acoustic emission method	• Must be near damage source for accurate measurement; • High cost; • Data contamination due to noise and secondary source.		• High signal attenuation in concrete; • Data contamination due to noise and secondary source.
Ultrasonic techniques	• Power hungry instrumentation; • Environmental condition significantly influences test quality.		
Radiographic inspection	• Sensitive to cracks and voids; • Does not evaluate global structural performance; • Expensive instruments, and labor intensive.		
Thermal imaging	• Lower resolution; • Labor intensive; • Unsuitable for early fault detection because T develops slowly.		

Ciang et al., *Meas. Sci. Technol.*, 2008
Rumsey & Paquette., *Proc. of SPIE,* 2008
Liu et al., *Renew. Energ.*, 2010
Márquez et al., *Renew. Energ.*, 2010
Schubel et al., *Renew. Energ.*, 2013
Tchakoua et al., *Energies*, 2014
Ruan et al., *Smart Mater. Struct.*, 2014
Li et al., *Smart Mater. Struct.*, 2015

Question 5

- What type of monitoring technology is currently used in the field? Is there any need to develop or improve technologies that provide accurate and real-time data for proactive maintenance in larger land-based and offshore technologies?
    - The size of wind turbines has increased over the years. It is difficult to perform inspection and maintenance (height, remote and offshore location)
    - Continuous monitoring is extremely important to improve safety, minimize down time, provide reliable power generation, and lower costs related to maintenance and logistics (especially that the turbine price increases with larger capacity).
    - Research on reliable, low cost, continuous and ***spatial*** damage sensing that can be integrated into a wind turbine system would be beneficial to reduce life-cycle costs and to make wind energy more affordable.