Destructive Restoration Part 4 - Renewables

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1. Introduction

We imagine a world with renewable energy, electric vehicles and sustainable materials that power the future.

Climate change is a global problem that demands innovative solutions now.

Our industrial revolution led to pollution. And mountains of waste.

We believe that the future can be bright.

And we know that inventing circular supply chains, turning waste into profit and solving the environmental impacts of new products before they happen … will save our planet.

– Redwood Materials Home Page
  https://www.redwoodmaterials.com

In case you don't know what Redwood Materials is, it is a company founded by JB Straubel. In case you don't know who JB Straubel is:

Jeffrey Brian ("J. B.") Straubel… J.B. spent 15 years at Tesla, as Co-Founder and Chief Technical Officer until moving to an advisory role in July 2019.[1]

He was also a lecturer at Stanford University, where he taught the energy storage integration class (CEE 176C & CEE 276C) in the Atmosphere and Energy Program for the 2015-2016 academic year.

In 2017, Straubel established Redwood Materials, working on the recycling of lithium-ion batteries and other e-waste.

Prior to Tesla, Straubel was the CTO and co-founder of Volacom along with Harold Rosen. Volacom worked closely with Burt Rutan at Scaled Composites to design a specialized high-altitude aircraft platform using a novel hydrogen-fueled electric power plant. At Volacom, Straubel co-invented and patented the new long-endurance hybrid propulsion concept that was later licensed to Boeing.

In the area of technical expertise, Straubel has consulted with VC firms Taproot Ventures and Kleiner Perkins, in addition to several other private equity investors, to conduct technical diligence reviews for many start-ups in the energy and clean energy technologies category. Straubel is on the board of QuantumScape and also consults with Amory Lovins at the Rocky Mountain Institute.

QuantumScape is a leading developer of solid-state lithium metal batteries.[2]

[1] Wikipedia Article on J. B. Straubel, https://en.wikipedia.org/wiki/J._B._Straubel
[2] New Battery Technology, March 2021, https://energycentral.com/c/ec/new-battery-technology

This paper is about the processes used to recycle the market-leading renewable energy products, including PV panels, wind turbines blades and batteries.

Parts 1-3 of this series are described and linked below;

Destructive Restoration – Part 1, The Klamath: Every machine made by humans reaches the end of its useful life. This will be the first post in a short series on what should happen to electric generation projects when it is no longer economical to restore, repurpose, nor continue to use them for their intended purpose.

However this first post is special. It is partially drawn from my deep past and partially an agreement to restore a natural resource and everything around it through the creative destruction of a series of old projects near the California-Oregon Border.

https://energycentral.com/c/ec/destructive-restoration-%E2%80%93-part-1-klamath

Destructive Restoration – Part 2, Nuclear: This is the second in a three-part series on the right way to decommission electric generation plants where it is no longer economical to restore, repurpose, nor continue to use them.

https://energycentral.com/c/gn/destructive-restoration-%E2%80%93-part-2-nuclear

Destructive Restoration – Part 3, Coal: Coal-burning power plants are worst offender when it comes to greenhouse gas (GHG) emissions. They also have other emissions that seriously worsen health effects (Sulphur Dioxide, Mercury, and other toxic metals). And then there is the coal ash, which contains contaminants like mercury, cadmium and arsenic. Coal ash is typically stored in ponds, which risk pollution of water tables and can destroy down-stream communities in the event of a dam-break.

Coal plants also are much less cost-effective than gas-fired plants (especially combined-cycle, which are also much cleaner), and many renewables. This is mainly due to the costs for coal-shipping, handling, and processing, and coal-ash storage.

Given the above, it is not surprising that many coal-fired plants are being decommissioned. This post is about the proper process for decommissioning these plants and related facilities.

https://energycentral.com/c/cp/destructive-restoration-%E2%80%93-part-3-coal

2. Why the Urgency

One of the main drivers of the rapid expansion of renewables is their rapid decrease in capital cost per unit power output, and recurring cost for energy storage capacity and power. Also these metrics are major drivers of repowering projects that are 15 to 25 years old. When a project is repowered, what does the developer do with the old components? In keeping with the renewable creed, there is really only one correct answer: recycle them.

The following are typical life-time and components in various renewables. Note that I'm treating battery energy storage systems (BESS) as renewables because they are frequently paired with utility-scale PV arrays to mitigate variability. Since BESS are also used for other functions, I will treat them separately below.

2.1. PV Arrays

Photovoltaic (PV) Arrays are very long-lived, and it not unusual for manufacturers to guarantee a 25-year lifetime for panels (warranty on maximum degradation of output) and inverters. Thus only the earliest large projects are half-way through their life.

The percentages below are of the total project cost. The major components in a large project include:

- PV Panels (35-40%)
- Mounting Structure (including trackers, if used, 10-15%)
- Inverters (4-6%)
- Transformers and other electric components (not incl. invertors 10-15%)

2.2. BESS

Battery energy storage systems (BESS) are long-lived, albeit currently not so much as PV Arrays. Batteries in current BESS are starting to use different chemistries than those used for battery electric vehicles (BEVs). Also, it is possible to control the duty-cycle better with BESS than with BEVs, resulting in potentially longer lifetimes. One other change for current BESS designs is that they are starting to use standard modular cabinet designs rather than custom configurations for each project.

BESS major components consist of batteries, inverters. chargers, enclosure hardware and controls. Given the above changes that are in progress, and the proprietary nature of these designs, I will not attempt to define percentages of each, although batteries probably dominate the costs.

2.3. Wind Turbines

There are basically two designs here, onshore and offshore, and they have different designs for a number of reasons:

- Onshore turbines are much smaller than offshore (the largest onshore turbines are typically 6 MW, and Offshore around 14 MW)
- Onshore turbines generally have gear-boxes, and offshore generally are direct drive. One of the reasons for this is the next bullet.
- Onshore turbines are much easier to access than offshore turbines and thus typically more frequent maintenance is justified for maximum lifetime. Typical major maintenance interval for onshore turbine gearboxes is 10 to 15 years.

In researching wind turbine lifetime, I found general agreement that they should last about 20 years, and there is operational experience to back this up. There were also indications that lifetimes could be extended to 25 years through aggressive maintenance.

The main components of wind turbines are the nacelle (generator, any gearing and various minor components), the blades, the mast (including the support structure) and the hub which will be more complex for (most modern) variable pitch designs.

3. Major Recycling Targets

The following components are targets for recycling:

Specialized:

- PV Panels
- Batteries
- Wind turbine blades

Standard Process:

- Electric components (transformers, wiring, etc.)
- Power Electronics (primarily inverters)
- Low power electronics
- Structural and enclosure components
- Generators (wind)
- Wind turbine hub (Metal mechanical assembly)

Windmill hubs are typically cast in steel, or alloys of steel and aluminum. Manufacturers from India and China are major manufacturers of windmill hubs.

Power electronics are heavily used in machine control, industrial automation and variable-speed motor drives, and thus there is already a strong demand for recycling.

Standard components have well-evolved processes for recycling, and also have valuable materials that make recycling viable.

Below we will cover the processes that are used for recycling specialized components.

3.1. PV Panels

Most PV cells are fabricated from silicon wafers. The cells are then mounted in a frame that ranges in length and width from roughly 65” x 39” to 78” x 39”. When a frame, cells and other components are assembled it is commonly called a photovoltaic (PV) panel (also a solar module).[3]

As current PV installations reach the final decommissioning stage, efficient recycling and material recovery are preferable to disposing of panels in landfills. Solar panels are mostly glass and metal, both of which are easily recyclable materials. For glass, however, the demand for recycled material has decreased significantly in the US in recent years. This low recycling rate is due to the single-stream recycling widely used in the US (for household items, for example), which leads to more contamination than the

[3] Photovoltaic Advancements, Nov 2020, https://energycentral.com/c/cp/photovoltaic-advancements

multi-stream approach used elsewhere. The result is a greater processing need that produces less usable "cullet" (recycled glass for glassmaking).[4]

PV glass has additional challenges due to the presence of other materials embedded within the PV glass. On the other hand, assuming materials such as copper, silver, and silicon can be recovered efficiently, recycling these PV panel components could offer some cost savings in a PV circular economy model.

Recycling Panels based on silicon involves separating and recovering glass, the PV cells, and metallic components. The glass, PV Cells and metallic components then each go through a separate sub-process. Glass and metallic components use standard recycling processes for those materials.

Eliminating the PV cell encapsulation from the laminated structure uses approaches such as thermal, mechanical, and chemical depending on the design. Recovering metals from silicon cells use chemical methods such as etching; or other processes used in the metal refinery industry.[5]

The silicon PV cells can also be recycled in standard electronic waste facilities.

3.2. Batteries

The first challenge in recycling or disposing of Li-ion batteries is that they are classified as hazardous waste, due to their chemistries and combustibility. As a result, many regulatory guidelines must be followed at the batteries' end-of-use. Having different chemistries, including lithium manganese oxide and lithium nickel cobalt aluminum oxide, complicates the logistics of recycling due to the possibility of mixing different chemicals in unfortunate ways. [4]

From a market perspective, one of the largest challenges is the lack of resale value for the Li-ion battery components. As mentioned, the costs of these batteries have declined significantly in recent years. Today, lithium is relatively inexpensive to mine, especially compared to the cost to recover and recycle lithium, given the limited infrastructure and demand. However, cobalt, nickel, and manganese components can still drive value streams in recycling, as they are more expensive.

Apart from environmental and social responsibility for clean energy technology advancement, energy security can be an additional factor behind the support for a robust market of repurposing and recycling Li-ion batteries. If the US wants to decrease its dependence on overseas mining and investment, then pursuing a domestic recycling sector is a wise course. While the Coronavirus pandemic has led to a temporary drop in demand for lithium, electric vehicle sales are still predicted to rise over the next few decades, as is utility-scale battery storage power capacity in the next few years.

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[4] James Gignac and Jessica Garcia, Union of Concerned Scientists, "Solar Panel Recycling: Let's Make It Happen", October, 2020, https://blog.ucsusa.org/james-gignac/solar-panel-recycling

[5] Keiichi Komoto, Jin-Seok Lee, "International Energy Agency Photovoltaic Power Systems Program, " End-of-Life Management of Photovoltaic Panels: Trends in PV Module Recycling Technologies, Jan 2019, https://iea-pvps.org/wp-content/uploads/2020/01/End_of_Life_Management_of_Photovoltaic_Panels_Trends_in_PV_Module_Recycling_Technologies_by_task_12.pdf

Government can play a role in increasing the circularity of Li-ion batteries. Indeed, in 2019, the US Department of Energy (DOE) launched the ReCell Center[6], a Li-ion battery research and development recycling center led largely by the Argonne National Laboratory in partnership with advisors from the National Renewable Energy Laboratory (NREL), Oak Ridge National Laboratory, and several universities. The ReCell Center has an environmental and economic directive with a goal to foster a battery recycling industry in the US.

Additionally, the DOE is looking beyond its research partnerships for innovative ideas to help support an increase in Li-ion battery recycling, including through the Battery Recycling Prize [7] competition. Finalists from the three-phase competition will pilot business models and technology solutions for commercial-level recycling. This effort seeks to ensure that the life cycle of Li-ion batteries can be harnessed for its full market potential here in the US as demand continues to increase through EVs and energy storage applications.

3.3. Wind Turbine Blades

Wind turbine blades require disposal or recycling when the turbines are decommissioned at the end-of-use stage, or when wind farms are being upgraded in a process known as repowering. Repowering involves keeping the same site and often maintaining or reusing the primary infrastructure for wind turbines but upgrading with larger capacity turbines. The blades might be replaced with more modern and typically larger blades. Either way, the fiberglass blades, once they're no longer needed, pose the greatest challenge to end-of-use considerations for wind energy.[8]

While it's possible to cut the blades into a few pieces onsite during a decommissioning or repowering process, the pieces are still difficult and costly to transport for recycling or disposal. And the process of cutting the extremely strong blades requires enormous equipment such as vehicle mounted wire saws or diamond-wire saws similar to what is used in quarries. Because there are so few options for recycling the blades currently, the vast majority of those that reach end-of-use are either being stored in various places or taken to landfills.

Indeed, Bloomberg Green reported earlier this year on wind turbine blades being disposed of in landfills. Even though the waste stream represents only a tiny fraction of US municipal solid waste, it's clearly not an ideal situation. As wind turbines are being decommissioned or replaced, the necessity arises for more creative recycling solutions for used blades.

The good news is that some efforts at developing alternatives are underway. Two large utilities in the US, PacificCorp and MidAmerican Energy, for example, have recently announced plans to partner with the Tennessee company Carbon Rivers to recycle some of the utilities spent turbine blades instead of landfilling them. The technology used by Carbon Rivers is being supported through grant funding by the US Department of Energy and will be used to break down and reuse fiberglass from used turbine blades.

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6 ReCell Center, https://recellcenter.org/

7 U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, "Lithium-Ion Battery Recycling Prize", Dec 17, 2020, https://www.americanmadechallenges.org/batteryrecycling/

8 James Gignac and Jessica Garcia, Union of Concerned Scientists, "Wind Turbine Blades Don't Have To End Up In Landfills", Oct 2020, https://blog.ucsusa.org/james-gignac/wind-turbine-blades-recycling

Since Europe is ahead of the U.S. in deploying utility-scale wind turbines (>1MW), they are also ahead of the U.S. in recycling them.

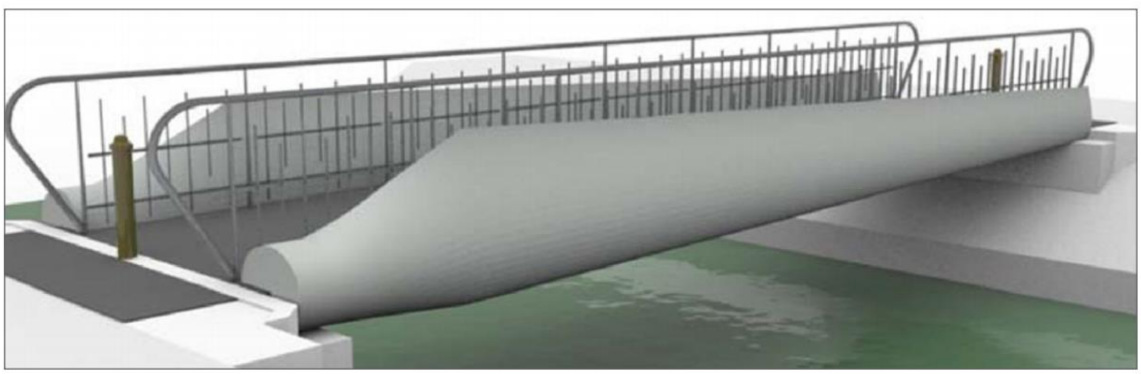
… WindEurope (representing the wind energy industry), Cefic (representing the European Chemical Industry) and EuCIA (representing the European Composites Industry) have created a cross-sector platform to advance approaches for the recycling of wind turbine blades, including technologies, processes, waste flow management, reintegration in the value chain and logistics.[9]

Today around 85 to 90% of wind turbines' total mass can be recycled… However, wind turbine blades are more challenging to recycle due to the composite materials used in their production. While various technologies exist to recycle blades, and an increasing number of companies offer composite recycling services, these solutions are not yet widely available and cost-competitive…

Today, the main technology for recycling composite waste is through cement co-processing. Cement co-processing is commercially available for processing large volumes of waste (albeit not in all geographies yet). In this process the mineral components are reused in the cement. However, the glass fiber shape is not maintained during the process, which from a waste hierarchy perspective may be less preferred. WindEurope, Cefic and EuCIA strongly support increasing and improving composite waste recycling through the development of alternative recycling technologies which produce higher value recycled materials and enable production of new composites. Further development and industrialization of alternative thermal or chemical recycling technologies may provide composite-using sectors, such as building & construction, transportation, marine and the wind industry, with additional solutions for end-of-life…

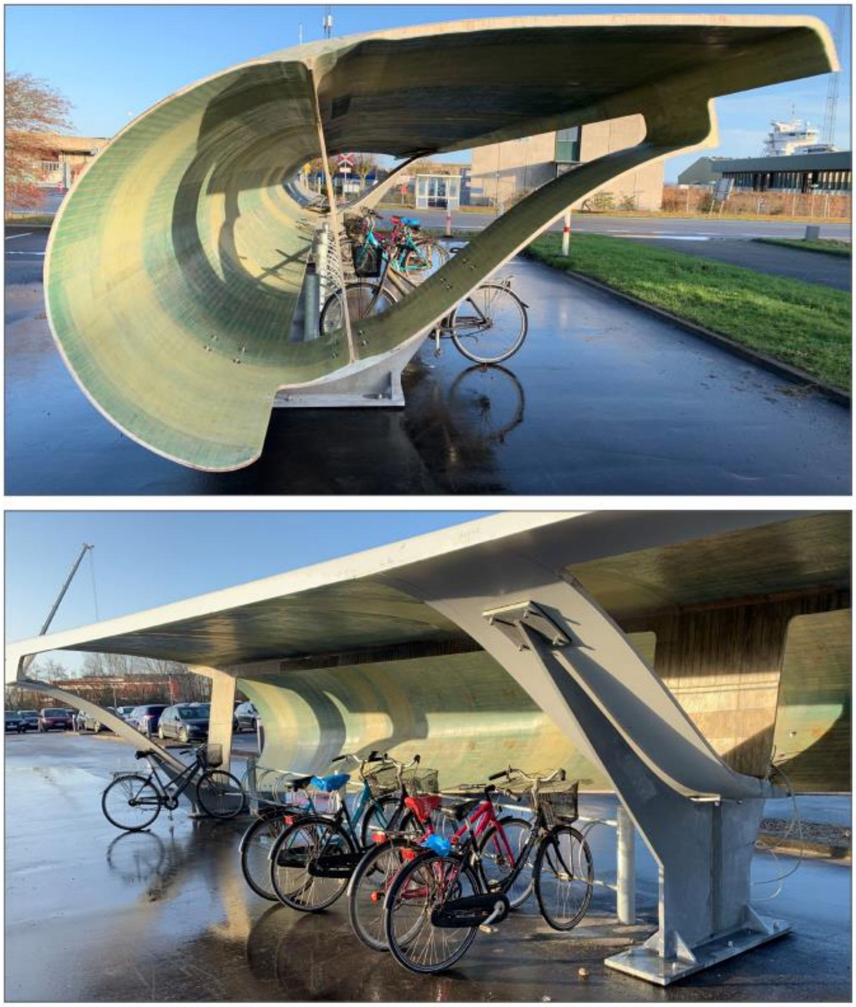
3.3.1. Repurposing

There are many projects in Europe that repurpose turbine blades. The pictures below illustrate some of these.



A conceptual design of pedestrian bridge using A29 wind blades as main girders, Re-Wind research project [24]

[9] Marylise Schmid, WindEurope; Nieves Gonzalez Ramon, Cefic; Ann Dierckx, Cefic; Thomas Wegman, EuCIA; "Accelerating Wind Turbine Blade Circularity", May 2020, https://windeurope.org/wp-content/uploads/files/about-wind/reports/WindEurope-Accelerating-wind-turbine-blade-circularity.pdf



Bike shed in Aalborg, Denmark

3.3.2. Recycling via Mechanical Grinding

Mechanical grinding is a commonly used technology due to its effectiveness, low cost and low energy requirement. It does however drastically decrease the value of the recycled materials. The recycled products, short fibers and ground matrix (powder), can be used respectively as reinforcement or fillers. Because of the deterioration of the mechanical properties, the incorporation level of filler material is extremely limited in thermoset composite applications (less than 10%). For re-use of the fibers as reinforcement in thermoplastic applications, the variation in composition and potential contamination with resin particulates has a negative impact on reinforced thermoplastic resin manufacturing speed and thermoplastic resin quality. This could be minimized if the separating and dismantling processes were upgraded and could be suitable in cases where no more value retention is possible.

3.3.3. Recycling via Pyrolysis

Pyrolysis is a thermal recycling process which allows the recovery of fiber in the form of ash and of polymer matrix in the form of hydrocarbon products. Although it allows for the lowest value loss from industrial-scale technologies, there is still a loss of value. Matrices are turned into powder or oil, potentially useable as additives and fillers. The fiber *surface is often damaged due to the high temperatures, resulting in a decrease in mechanical properties. Pyrolysis requires high investment and operating costs.*

Economic viability depends on the scale and re-use that the matrix-obtained chemicals can have. To date, this recycling technology is only economically viable for carbon fibers. It is, however, not currently implemented at large scale since the volumes of carbon fiber reinforced composites are low. With the next generation of mega-turbines, the required weight reduction and mechanical properties will enhance the preferred use of carbon fiber composites and the market volume might grow accordingly.

3.3.4. Recycling via Solvents

This is a chemical treatment where solvents (water, alcohol and/or acid) are used to break the matrix bonds at a specific temperature and pressure. It offers many possibilities due to a wide range of solvent, temperature and pressure options. Compared to thermal technologies, the use of solvents requires lower temperatures to degrade the resins, resulting in a lower degradation of fibers. Treatment with super-critical water seems to be the most promising technology since both fibers and resins can be retrieved without major impacts on their mechanical properties. This process is easily scalable but investment and running costs are high and it is still at a relatively low technological readiness level.

To date, only the carbon fibers are recycled through solvents. However, it is not currently implemented at large scale since the volumes of carbon fiber reinforced composites are low (see comments at the end of the prior subsection).

4. Recycling Output

The following elements, and compounds, alloys and structures using these elements result from recycling the above-specified renewable hardware. (in alphabetical order):

- Aluminum: structural and mechanical components
- Carbon: mostly carbon fiber
- Cobalt (elemental from batteries)
- Copper (electrical and electronic components reduced to elemental copper)
- Gold (elemental from electronics)
- Iron (alloys from structural components, gearing and enclosures)
- Lithium (elemental from batteries)
- Manganese (Batteries and a component in many metallic alloys)
- Neodymium (Magnets used in wind turbines)
- Nickel (mainly batteries)
- Palladium: (electronics)
- Silicon (glass, glass fiber, PV cells and electronics)
- Silver (electronics, including PV panels)
- Tantalum (electronics)
- Tin (electronics)