Development of a Comprehensive Circular Economy Model for utility-scale wind and solar power: A Case study of DTE Electric and Gas

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Abstract

Within the next two decades, the first generations of utility-scale wind and solar technologies will enter their end-of-life (EoL). To achieve a pollution-free energy goal, power utilities are exploring the implementation of circular economy (CE) principles with quantitative tools. CE is a pathway to managing the substantial material waste generated when the current generation of infrastructure expires. A major barrier to implementing CE in today's energy market is the lack of understanding of the economic and environmental impacts of nonlinear waste pathways. To address this gap in understanding, the project developed an LCA-based model to evaluate the costs and benefits of implementing CE strategies across economic and environmental impact categories. A literature review was conducted to identify prevalent CE strategies, followed by a dynamic material flow analysis (MFA). The results were integrated into a user-friendly tool, bridging the EoL knowledge gap for renewable technologies in the power sector context. Using the tool we identified circular-economy strategies that offer clear potential for GHG benefits by displacing virgin production of materials, but at higher cost. The tool was used in a case study to evaluate GHG and cost performance for a 4MW wind and solar system, and for the wind and solar systems installed by DTE Energy between 2008 and 2020.

1. Introduction

1.1 Background

A new systematic approach is needed to transform the current linear economic system to one that reduces consumption and develops new capabilities. Confronting global challenges such as climate change, pollution, and diminishing natural resources with business-as-usual development alone is insufficient. A circular economy (CE) is a solution that reduces material use, and employs "waste" as a resource to produce new products and potentially cut greenhouse gas emissions, supported by the transition to renewable energy[11]. While a circular economy creates considerable opportunities, challenges and limitations exist within this framework.

The lack of a consensus on a circular economy definition or what it means for a given product, process, or infrastructure system poses an issue[6,44]. Literature on circular economy frameworks primarily focuses on product-based systems such as electronics, clothing, and household items. Emphasis is placed on recycling, reusing, or reducing consumer products. However, process or infrastructure-based systems often generate non-traditional wastes that are difficult to fit into existing circular economy schemes. Consequently, a knowledge gap in framework application exists for certain process-based or infrastructure-based systems[43]. For example, the glass fiber composites of Wind Turbines are difficult to recycle and lose much of their value at end-of-life (EoL), which makes applying a circular economy framework to Wind Turbine systems challenging. The knowledge gap in applying CE frameworks, and heterogeneity in definitions, is an enduring hurdle for the realization of CE in infrastructure and process-based systems.

Ambiguity exists regarding how CE is guided by policy regulations. For example, CE requires reverse-logistics to collect material waste from users, and some of these materials are hazardous or cumbersome to transport. From a regulatory standpoint, who should be responsible for these materials? While there have been attempts made to provide guidance in the area of policy implementation, these efforts have not proven to be fully effective. Furthermore, these policies require time and resources that many regions simply lack, resulting in stagnation[21].

The circular economy concept is rooted in life cycle systems thinking to minimize material waste by creating a “closed-loop” in a product system. We can quantify the impacts of a product or system using life cycle assessment (LCA). LCA is an analytical method to evaluate environmental impacts of products or services throughout their entire life cycle[31]. The results of LCA provide decision-makers with the means to choose alternative energy solutions that reduce environmental impacts[38]. However, different assessment goals and scopes, even for similar products or processes, can generate a variety of results. For example, scopes can be limited to specific phases of a product life cycle (e.g. cradle-to-gate, gate-to-gate), but can also be more holistic (e.g. cradle-to-grave or cradle-to-cradle). Diverse LCA objectives and scopes drive variation in LCAs, but variation is also driven by the availability and quality of primary data.

With considerable variation in definition, system scope, data availability, and accessibility, the applicability of an LCA study can come into question. One way to enhance the validity of an LCA study's goal and scope is by adhering to the LCA standards established by the International Organization for Standardization, specifically, the ISO 14040, 2006 standard[24]. Compliance to these international standards fosters transparency, which is crucial for interpreting or comparing analyses with heterogeneous data and objectives[20]. Recognizing the potential shortcomings and ongoing development of international standards is key in assessing the potential of a circular economy with LCA.

Currently, the materials used in power systems do not operate along circular economy pathways. The majority of materials follow a linear one-dimensional manner: raw fuel is extracted, transported, converted into electricity, and then consumed. Circular economy principles are best applied only to the portion of the system that is not consumed to make power, specifically the materials used for equipment and physical assets. However, there are no real-world examples of utility-scale CE implementation for renewables, or knowledge of trade-offs. Studies on the environmental impacts of renewable technologies are biased towards manufacturing and upstream impacts, with high uncertainty surrounding the decommissioning process for these technologies[15,29]. Consequently, there is a knowledge gap regarding the EoL impacts of utility-scale renewable energy operations. However, the growth of renewable energy is a significant trend. In 2021, renewable energy accounted for 81% of capacity expansion globally. Wind and solar technologies constituted 88% of these additions[19].

1.2 Utility Scale Circular Economy in Michigan

In April 2021, the United States government set a target goal of a “carbon pollution-free power sector by 2035”[41]. Prior to the federal target, the state of Michigan mandated utilities to generate 15% of their electricity from renewables by 2021. Solar photovoltaics (PV) and Wind Turbines have been identified as central levers to achieve both long- and short-term carbon emissions reductions in power utilities[10]. The project client, DTE Energy(NYSE: DTE), is a publicly traded utility that serves 2.1 million electric customers in southeast Michigan. DTE plans to add 5,400MW of solar and wind generation capacity to the grid by 2032 and nearly double that between 2033 and 2042 for a total of 15,400MW of additional renewable capacity by 2050. Simultaneously, DTE is accelerating its timeline to decommission its coal-fired generation assets. Based on its most recent integrated resource plan, DTE is placing confidence in renewables to provide over 60% of its electricity within 20 years[10].

In Michigan, coal remains the dominant electricity fuel source. Coal-fired power plants typically follow a linear, one-dimensional model where raw fuel is extracted, transported, converted into electricity, and then consumed. The byproducts of coal-fired generation, namely fly ash, are often funneled into cement production. Society’s desire to fully capture the value of a resource is demonstrated in the handling of fly ash. From a circular economy standpoint, this recycling system is considered an “open loop” because the waste is recycled into a new product. A closed-loop system funnels waste back into its original product.

The majority of solar PV modules and the composite materials found in Wind Turbine blades are disposed of in landfills, presenting environmental risks and a loss of valuable materials[15,16]. As the commitment to reduce carbon emissions through solar PV and wind technologies grows, so does the projected volume of waste at their end-of-life (EoL). Renewables on Michigan’s grid today constitute a major future waste stream with the potential to cause significant environmental burdens and lose immeasurable value in raw materials if landfilled. With the circular economy gaining salience as a concept, DTE has recognized the need to explore alternatives to landfilling solar PV and Wind Turbines. Applying circular economy principles to EoL planning could potentially mitigate environmental impacts and retain the economic value embodied in PV modules and turbine blades.

1.3 Research Objectives

Project Significance and Objectives

The circular economy in energy utilities faces challenges unique to the industry. The electric and gas utility industry is highly capital-intensive. Most commercial contracts are signed for extended periods (roughly 10-25 years), and the state of Michigan regulates utilities and mandates long-term resource planning. Therefore, projecting changes in fuel supply, blackout/brownout risks, and maintenance schedules is crucial to safeguarding the interests of both the company and customers. In short, utility-planners must consider time scales spanning decades and require analytical tools capable of performing at the appropriate scope. As the goal of “net-zero” – achieving zero carbon emissions while maintaining power supply and reliability - becomes a shared objective among the industry, cradle-to-grave LCA should be applied to the planning process.

Our team developed an LCA-based circular economy model to provide a clearer picture of the emissions associated with various CE practices at EoL for wind and solar technologies. The model provides the costs and GHG performance of these strategies. Our model serves as an analytical tool that can identify the most effective CE strategies when Michigan’s wind and solar assets reach their EoL. With renewable generation expected to significantly increase in deployment by 2050[10], concerns are arising around waste management for wind turbines and solar panels. It is currently estimated that by 2050 there will be 43.4 million metric tons of waste from Wind Turbine blades in Europe alone[27]. By providing estimated levels of waste generation for renewable systems, we provide the means to understand the potential environmental impacts of Wind Turbine and solar PV waste, and the economic value that would be discarded if business-as-usual, landfilling, is pursued.

This project aimed to develop a circular economy utility model and use it to make recommendations for value-driven action steps that will position DTE as a leader in the clean energy transition within the United States.

Specifically, the project aimed to:

1. Conduct a literature review to identify prevalent CE strategies, metrics for measuring circularity, benchmarks for comparison, and policy frameworks
2. Build a tool that will evaluate the costs and benefits of implementing circularity strategies, including literature-informed benchmarks and appropriate metrics to measure progress quantitatively
3. Provide recommendations for DTE’s implementation of circularity in its services, aligning with its company values and “net-zero carbon emissions by 2050” commitment

The principles of circular economy have yet to be realized fully in the power sector at the scale of our investigation. In the current environment, any strategy will need constant reconsideration and iteration. Therefore, we built a model that serves as a starting point for future modeling and innovation by DTE. Similarly, our recommendations will prompt initiatives that will evolve with time.

2. Methodology

2.1 Methods & Approach

Research methods included literature review, dynamic material flow analysis (MFA) using database (ecoinvent) and client primary data, and EoL emissions calculations based on LCA literature and database entries (see Table 1 for emissions, cost, and energy data sources).

Our group identified CE strategies based on these criteria:

1. Availability of environmental impact data
2. Technological maturity (e.g. is the technology able to be applied at-scale and do commercial operations already exist?)
3. An established use/ market for the recycling products (e.g. can we reasonably expect the recyclate to be utilized?)

Based on our client’s primary data, Wind Turbines and solar panels are expected to enter the waste stream in 2038, with the rate of decommissioning increasing steeply over five years. Therefore, recycling methods must be capable of handling high material throughput, and the resulting recyclate must also have somewhere to go (e.g. a market or sector where it’s utilized). These factors led us to prioritize CE strategies where the recyclate could be utilized at scale, and disqualified strategies that were not proven at commercial scale or part of an existing, mature industrial process[13].

Mechanical crushing yields products with use-cases in insulation and construction materials[13], and was prioritized due to data availability. Co-Processing and incineration likewise turns turbine blade waste into binder for cement, a product with proven value and existing data. Co-Processing and incineration involve burning GFRP in a cement kiln and mixing the resulting ash/residual fiber into clinker for portland cement. These two methods met our criterion and became the primary focus of our Wind Turbine CE research.

Other recycling methods showed promise but lacked data or didn't meet our qualitative threshold of scale/maturity. Wind Turbine blade pyrolysis meets the conditions of technological maturity and reported recyclate (clean fuel gas, recovered fibers) value[41], but clear examples of how this recyclate could replace existing goods was a barrier to modeling the strategy (e.g. data availability). Recently developed methods such as chemical solvolysis, fluidized bed pyrolysis, and high-voltage fragmentation exist only at pilot and research stage, and currently lack the scale that would be appropriate for utility waste flows. While solar photovoltaics and Wind Turbines are a mature technology, the existing body of research focuses heavily on production-phase environmental impacts and costs[21]. Thus, a key limitation of this study became data availability for recycling and combustion emissions, with data for some technologies dating as far back as 2011. This runs the risk of ignoring improvements to energy or process efficiency for a given recycling process and is a point of inquiry for future studies.

Under our qualitative criteria we relied heavily on the assessment put forth by EPRI for wind-technology recycling, and the work of Latunussa, Ardente, Blengini and Mancini for solar panel recycling[22] in choosing strategies to model. Emissions estimates were made based on the reported energy intensity of each strategy in the literature (see Table 1), and the emissions factor for the identified fuel (Natural Gas or electricity) in ecoinvent. The one exception to this approach is Wind Turbine incineration and Co-Processing, where the incineration emissions of carbon fiber reinforced polymer were used as a proxy for incinerated glass fiber reinforced polymer (GFRP) due to unavailable emissions data on GFRP[5].

The CE strategies that we identified as market-ready and feasible were:

- Wind Turbines
    - Incineration and cement Co-Processing: wind blades are combusted for heat energy and the resulting residue is incorporated into cement clinker
    - Mechanical recycling: wind blades are crushed and used for insulation or cement binder
    - Business-as-usual (BAU): landfilling Wind Turbine blades
- Solar PV modules
    - Full Recovery End-of-Life Photovoltaic (FRELP) recycling: combined mechanical and thermal methods wherein modules are deconstructed and Ag, Al, Si, Cu, and glass are recovered
    - Business-as-usual (BAU): landfilling

2.2 Material Flow Analysis

A Material Flow Analysis examines the material flows entering and exiting a system during a specified period of time and can be used to calculate the total waste generated by a system, as well as the volume of waste generated at each time increment. For each time increment (in this case each year) the total mass in kilograms entering and exiting the system was calculated. The system in this analysis was defined as the total wind and solar generation assets operated by DTE between 2008 and 2050, excluding projected capacity additions beyond 2020. This analysis provides insight into the approximate years when the client will need to manage high volumes of material waste based on decommissioning their current renewable portfolio.

The client primary data consisted of the total number of solar and wind asset installations from 2008 to 2020. The MFA study period spans from 2008-2050, by which time all renewable assets at DTE circa 2020 will have been decommissioned barring lifetime-extension. Renewable capacity additions beyond 2020 were not included in the MFA or model calculations. The analysis was conducted by tallying the total number of solar and wind units in the system on a yearly basis.

Combining knowledge of unit totals in the system and turbine/panel net weights with ecoinvent-derived material compositions for Wind Turbines and solar modules allowed us to estimate total raw waste flows of the components in the system (e.g., glass fiber composite, silicon, copper wire, aluminum). This allowed us to identify the components that are commonly recycled and exclude those materials from CE calculations. This is in line with the common LCA practice of finding parts of processes that are highly similar and excluding them from calculation. For example, if you want to make a relative comparison of product A and product B in terms of environmental impact, you may omit certain life cycle steps that are identical. If product A and B both undergo the same amount of transportation, this portion of the product life cycle can be disregarded for the sake of comparing the two products. It does not contribute to a difference between product A and B’s environmental profile. If the interest is in the total impact of either product A *or* B, this step would be accounted for. In our study, Wind Turbine recycling strategies only differ substantially in how glass fiber reinforced polymer (GFRP) is handled, therefore the recycling pathway for the other materials are assumed identical and ignored in the calculations. This simplifies the calculation for the modeling team without losing track of the main comparison being made between each CE strategy.

Model building: We determined the weight of waste per-unit in kilograms using ecoinvent database entries (e.g. kilograms GFRP waste per turbine). Pairing this with primary data indicating the installation dates of their wind and solar assets, we can estimate the waste stream for each year during the study period in kilograms (MFA). Our literature review allowed us to identify the fuel input energy intensity of each recycling strategy in Megajoules (MJ) per kilogram recycled[5,16,22,24,44]. The energy intensities were converted into emissions based on ecoinvent reporting of fuel supply and combustion emissions[39].

To calculate net emissions for each strategy we calculated the difference between emissions generated by recycling processes, and the emissions avoided by displacing virgin materials after recyclate enters its second life. The team decided to model a best-case scenario wherein all recyclates displace their virgin-sourced competition. For cost, we combined the potential revenue and costs of the recycling processes to estimate net costs associated with each CE strategy. These cost figures were also literature-derived[4,8,13,25]. The model calculation scheme is provided in Figure 1. The modeling process required a variety of assumptions based on data availability and literature sources.

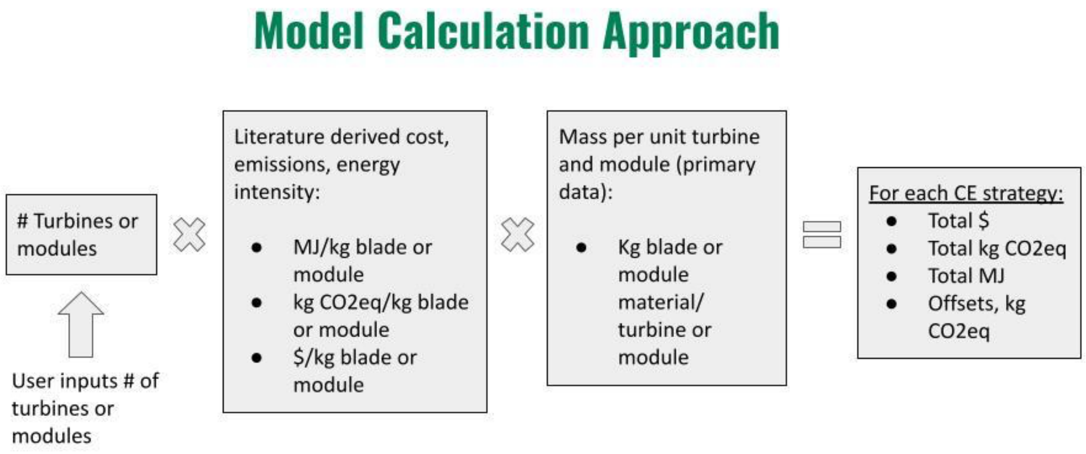

Figure 1: CE model calculation approach

PV System EoL Assumptions and Methods:

1. Photovoltaic (PV) module material is assumed to be silicon based.
2. Recycling cost figures are sourced from separate thermal and mechanical costing studies (e.g. the process is not carried out in one facility).
3. Emissions and energy figures are sourced from a pilot facility ("Full Recovery End of Life Photovoltaic project–FRELP) where thermal and mechanical recycling are centralized (e.g. the process is carried out in one facility).
4. Secondary market avoided emissions were calculated from embodied carbon of a panel with all virgin material.
5. Avoided emissions are calculated from embodied carbon of virgin materials equivalent to the amount of recyclate.
6. The service life of a PV module is 30 years.

<u>Wind Assumptions:</u>

1. Turbine tower, rotor, and nacelle are assumed to have equivalent EoL paths between CE strategies, thus these recycling impacts are not considered (e.g. focus on blades).
2. Landfilling and mechanical recycling emissions were calculated from the energy intensity of those operations[4], and the energy is provided by electricity from natural gas generators.
3. Incineration and cement kiln Co-Processing emissions were based on emissions for incinerating carbon fiber reinforced polymer (CFRP), which we deemed an acceptable proxy for GFRP incineration in cement kilns.
4. Cost estimation includes the teardown step for turbines, while carbon and energy accounting <u>ignore</u> the teardown step.
5. Avoided emissions are calculated from embodied carbon of virgin materials equivalent to the amount of recyclate. Recyclate glass fiber is less than virgin quality, but we assumed it is sufficient to replace virgin fibers in products where fiber length is not critical (e.g. insulation and simple construction materials).
6. Mechanical recycling energy intensity based on 150 kg/hr feed rate into the system.
7. The service life of a turbine is 30 years.

The system boundaries for each CE strategy are shown in the Figures 2-6. As previously noted, we assume that the teardown and transportation steps for each strategy are similar enough to ignore (in line with common LCA practice). Furthermore, making transportation estimates was not feasible given that we lacked data on site locations relative to existing recycling facilities. Therefore, the calculations for emissions and energy only concern <u>the events that take place within the respective recycling facilities</u> (represented by the red line in each process flow diagram). This boundary assumption highlights the main environmental trade-off between each strategy while avoiding the roadblock of limited data availability.

However, *costs* with respect to Wind Turbine recycling include the Wind Turbine teardown step. Despite the fact that the teardown step is a fixed cost[4] between CE strategies, therefore eligible for omission from the model, the team saw value in presenting the total costs because the teardown step is approximately 95% of total costs in every case. In other words, it illustrates that the cost difference between the CE strategies is marginal compared to the fixed teardown costs.

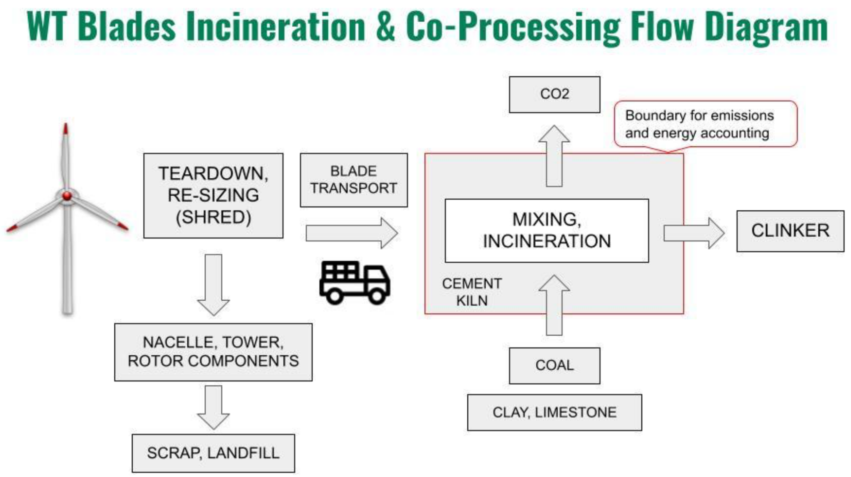

Figure 2: Wind Turbine blade incineration and Co-Processing flow

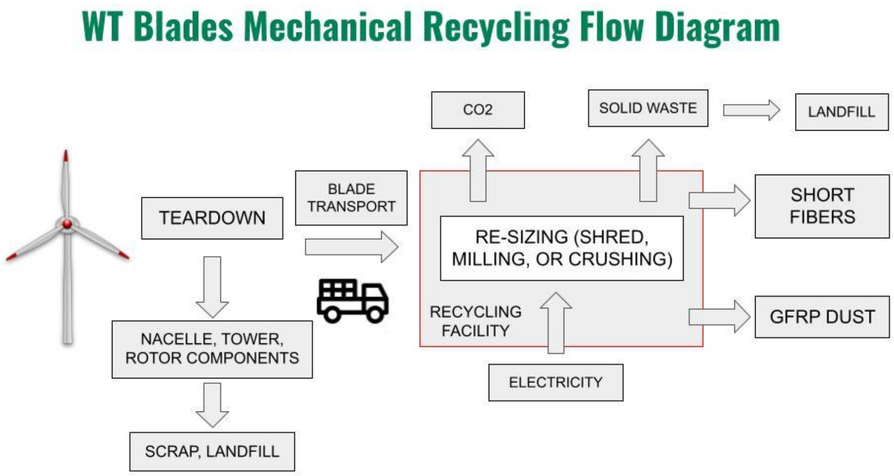

Figure 3: Wind Turbine blade mechanical recycling flow

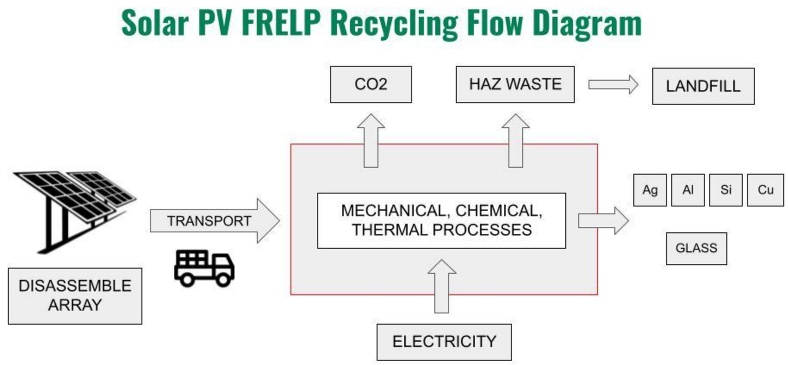

Figure 4: Solar panel FRELP recycling flow

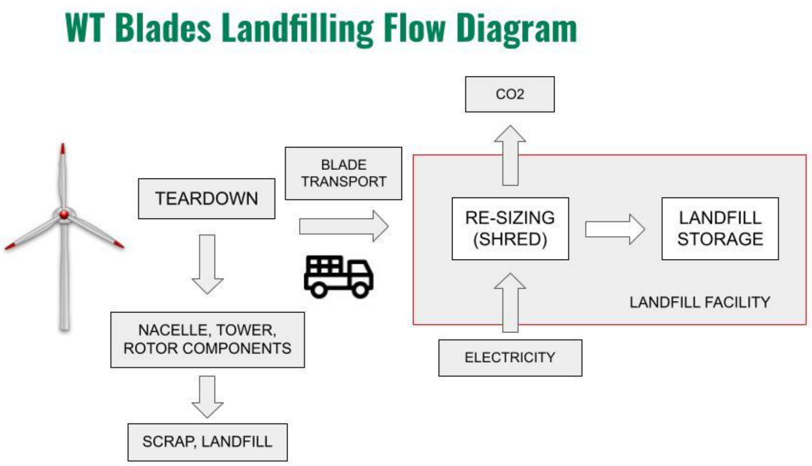

Figure 5: Wind Turbine landfilling flow

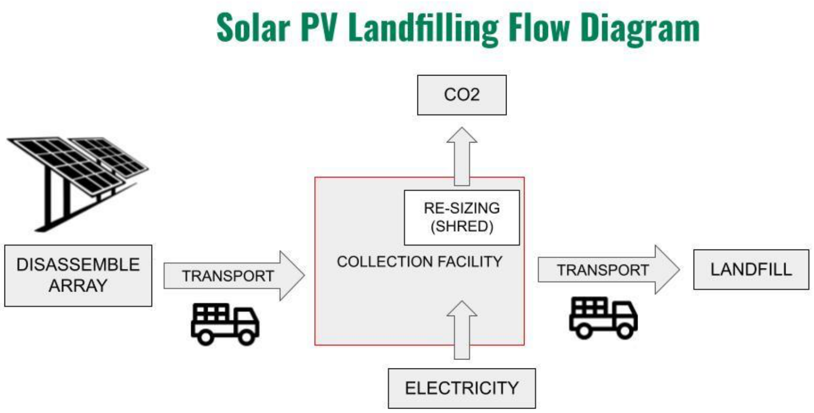

Figure 6: Solar PV landfilling flow

Author	**Data link**	**Where was it used**
Correia, Figuera	LINK[5]	GFRP calorific data; incineration process flow
EPRI	LINK[13]	Mechanical and co-process process flows; material recovery; % blade material recovery; cost estimates for each recycling method, and value of mechanical recyclate
Wei, Hadigegh	LINK[44]	Combustion emissions for CFRP resin (emissions for Co-Processing)
Pablo Tirado, natural gas,	LINK[39]	Energy intensity for landfill; mechanical processing emissions estimate

burned in gas turbine		
Lucia Valsasina, clinker production, GLO	LINK[42]	Virgin material emissions factor
glass fibre production, GLO	LINK[36]	Virgin material emissions factor
coal emissions factor	LINK[12]	Virgin material emissions factor
Liu, Meng	LINK[24]	Energy intensity data, Wind Turbine blades
Liu, Meng, Barlow	LINK[25]	Recyclate economic value
Cooperman	LINK[4]	Teardown cost and energy intensity data, Wind Turbine blades
Barcelo, Cline	LINK[1]	Portland cement emissions factor
Goe, Gaustad	LINK[16]	Energy intensity for landfilling and emissions, process flow, PV
Lunardi, Alvarez-Gaitan, Bilbao, and Corkish	LINK[26]	Overview of PV EoL management practices with mechanical and thermal recycling.
Latunussa, Ardente, Blengini, Mancini	LINK[22]	Energy intensity and carbon emission intensities. Also provides the process and boundary for the FRELP process, PV
Deng R	LINK[8]	Recycling Cost, PV
Copper Alliance	LINK[18]	Virgin material emissions factor

Pernelle Nunez	LINK[32]	Virgin aluminum material emissions factor
Silicon (Mg-Si Grade)	LINK[30]	Virgin material emissions factor
Material Composition	LINK[41]	Determining amount of material used in the offsetting values for copper, silver, aluminum, glass, and silicon
Embodied Carbon for PV	LINK[3]	Used for determining the secondary market emissions

Table 1: modeling data sources

Table 2 shows the carbon footprint of virgin material in kg CO_2eq/kg for the production of Wind Turbines and Solar PVs, followed by the Cumulative Energy Demand for the product in MJ/kg. Material data were used to calculate the potential energy savings and avoided emissions for different recycling strategies as well as the landfilling.

Recycling Product	**Emissions for virgin material production kgCO2eq/kg**	**Energy for virgin material production MJ/ kg**
Copper	3.80	51.30
Silver	66.00	21611.00
Aluminum	16.50	163.00
Glass	0.69	0.40
Silicon	5.19	39.60
Clinker	0.82	0.21
Portland Cement Binder	0.86	0.14
Fiberglass insulation	0.16	5.80
Displaced Coal	3.00	NA

Table 2: Emission factors and energy for virgin production

3. Results

3.1 Material Flow Analysis

The first part of the MFA determined the breakdown of materials for solar and wind power systems using ecoinvent data. As Figure 7.1 shows, when excluding the steel or concrete inputs into the technosphere, the majority of the remaining materials for Wind Turbines are cast iron, glasses and epoxy resin[40]. Steel and concrete in the form of reinforced concrete and low alloyed steel constitute such a large proportion of the total mass of wind turbines that they were excluded from Figure 7.1 for the sake of legibility. The makeup for Solar PV is shown in Figure 7.2. Major components are the tempering glass, solar glass, aluminum alloy and the ethylvinyacetate foil[41].

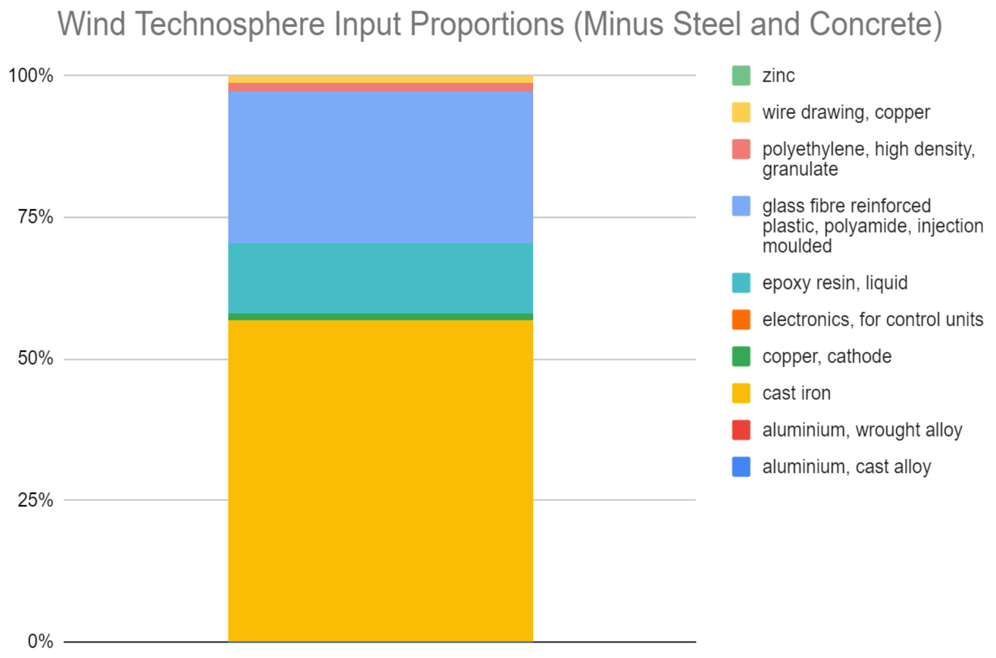

Figure 7.1 Material composition of Wind Turbine

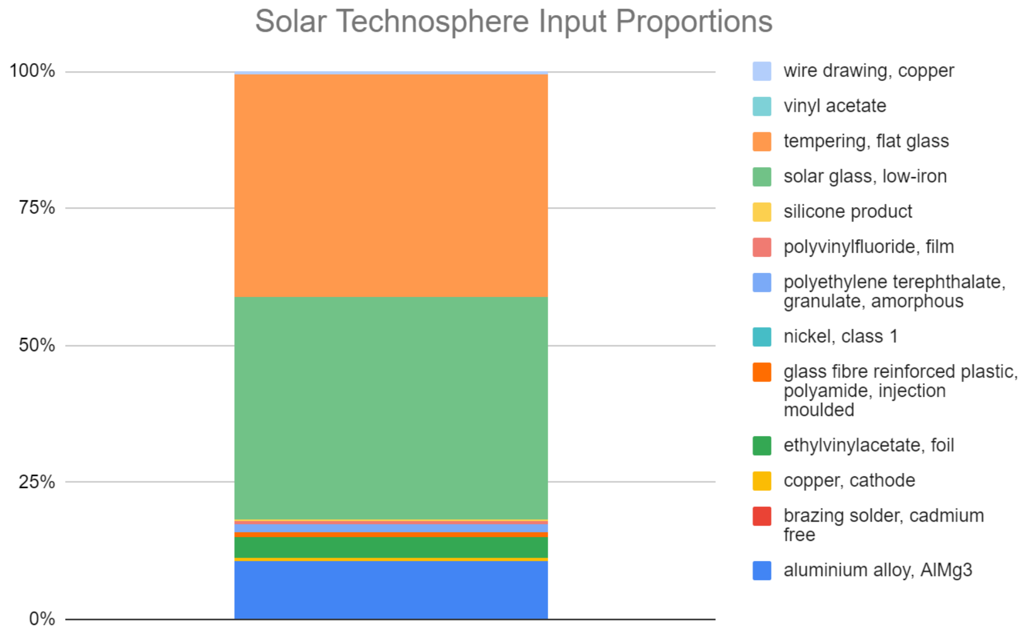

Figure 7.2 Material composition of Solar PV

A visualization of the stock flow for both wind and solar technologies is seen below in Figure 7.3. The stock flow utilized publicly accessible data from the Energy Information Administration. Figure 7.3 showcases our temporal scope, of 2008 - 2020, for the cumulative installations for wind and solar in the State of Michigan. The cumulative installations figures are able to provide a visualization as to when wind and solar systems are being decommissioned and entering the EoL process streams.

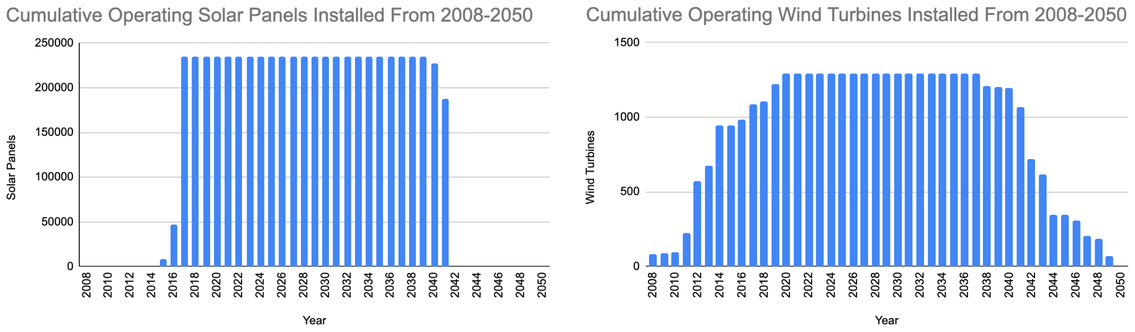

Figure 7.3 Cumulative installations of Wind Turbine/Solar PV installations from 2008 to 2050 in MI

When compared to solar, the rate of decommissioning is less abrupt in magnitude for wind. Solar experiences such large changes in the magnitude as a result of our MFA assuming that all panels from a given installation year are also all decommissioned once the system has exceeded its service life (25 years for solar, 30 for wind). The service lives were provided by our client based on their maintenance decisions. Wind and solar cumulative installations observe a period where there is no change in cumulative Wind Turbines and solar panels. This behavior is the result of our asset inventory cutting off in the year 2020. Therefore, there are no considerations of additional installations beyond 2020. The outputs of our MFA are only useful in providing context to the end-of-life waste streams magnitudes within our temporal scope of analysis.

3.2 State of Michigan Results

Figure 8.1 shows the net emissions of different circular economy strategies in kg CO_2 equivalent for a single 2MW Wind Turbine and an equivalent 2 MW of solar generating capacity which equals 6558 solar panels. Net emissions (negative = avoided emissions) refers to the CO_2 equivalents generated by a circular economy method subtracted by the potential savings of emissions achieved by replacing virgin goods with recycled goods. We refer to potential carbon savings as avoided emissions. Our method assumes that all of the recycled goods are able to replace their virgin equivalents. When net emissions become negative this does not indicate carbon sequestration, but indicates the potential carbon-based benefits of utilizing recycled materials from renewable assets to replace virgin-sourced goods in the economy. It should also be noted that the GHG benefit of power generation during the use-phase of the renewable assets is not included in this analysis. Wind Turbine Co-Processing is the most energy-intensive method with the highest CO_2 emissions. Co-Processing resulted in the highest emissions as this process includes combustion of waste material for heat which generates emissions. Mechanical shredding for Wind Turbines as a circular economy strategy resulted in negative net emissions. This implies that this particular end-of-life strategy produces a benefit (in the form of avoided emissions) for its secondary material use that outweighs the process emissions of recycling. In the case of Solar FRELP Recycling, we see a similar benefit for the end-of-life phase offsetting emissions from producing recovered and recycled products from virgin materials. An interesting point of analysis is with the strategy net emissions for the Solar Landfill and Wind Turbine Landfill. Figure 8.1 shows that the Solar Landfill net emissions are significantly higher than the Wind Turbine landfill strategy. This difference in magnitude can be attributed to the mass difference between the two technologies. The amount of energy and hence emissions generated through shredding a single wind turbine is less intensive than for an equivalent generation capacity for solar.

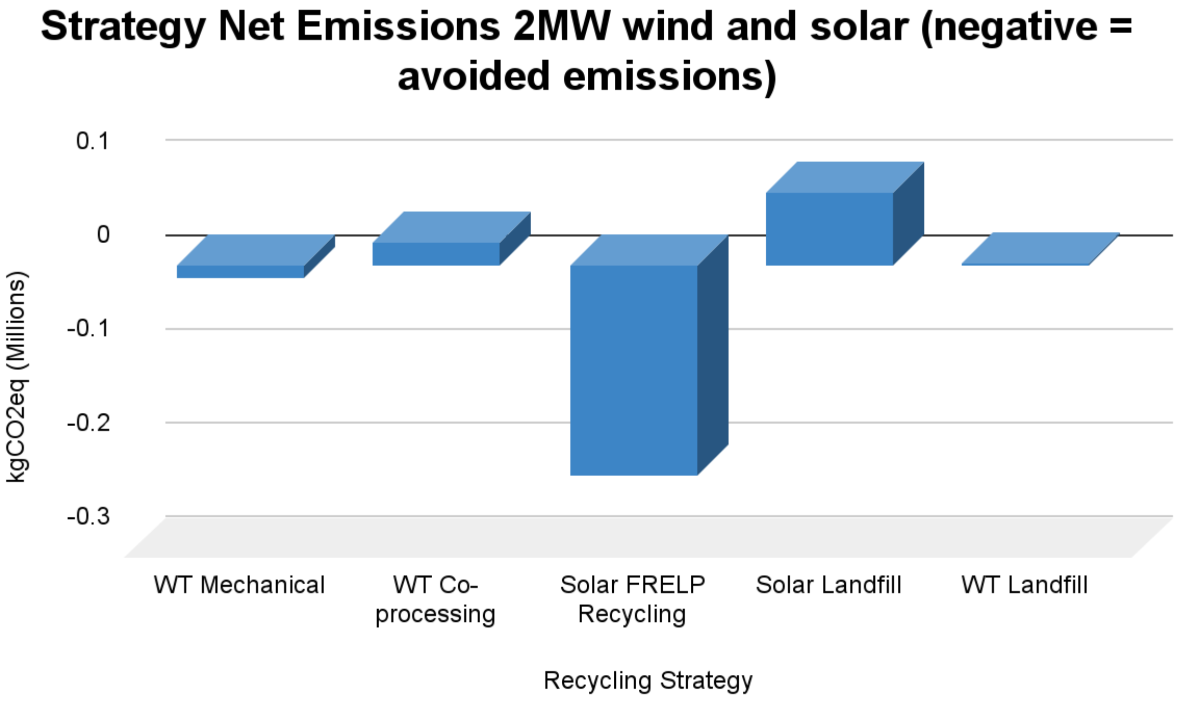

Figure 8.1 Net emissions in kg CO_2 equivalent in MI (2MW solar and wind) with avoided emissions

Figure 8.2 demonstrates the cost of different circular economy methods. The solar landfill had the lowest cost at $9,284 per 2MW, while Solar FRELP recycling had the highest cost at $73,111 per 2MW. Although the landfilling processes for wind and solar are established methods for the end-of-life phase, the large cost differences between the two are due to the additional processing costs associated with wind. The costs of wind turbine teardown (labor, transportation) are the major driver of cost difference between wind and solar landfilling. Ignoring the two landfilling strategies for each technology, Wind Turbine Co-Processing has the next lowest cost when compared to both wind circular economy strategies.

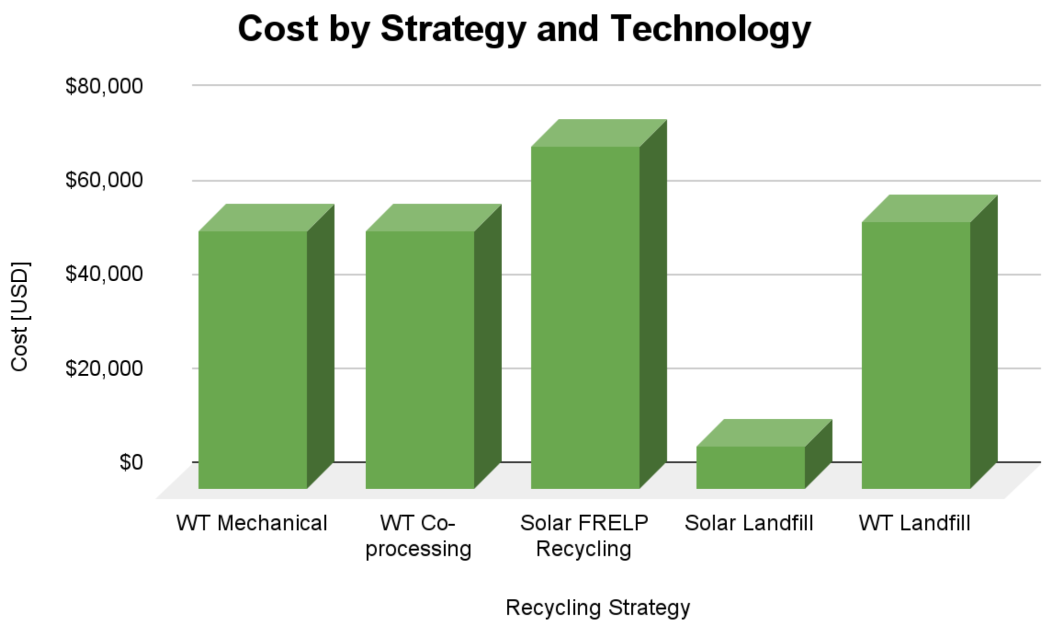

Figure 8.2 Cost in U.S. dollars of CE strategies in MI

Figure 9.1 indicates that the wind mechanical circular economy strategy has an overall negative net emissions, i.e, the emissions associated with implementing the process for this strategy is lower than the cradle-to-gate emissions associated with the process of producing recyclate material from virgin materials. It must be noted that the presence of an overall net negative is not indicative of any sequestering of carbon within a circular economy strategy. The reverse behavior is observed with the wind Co-Processing strategy which results in higher emissions output with utilizing this process than with producing output products with virgin materials. The timescale for Figure 9.1 has been condensed to only include the years 2035-2050. This choice of presenting the data was made as our analysis for determining the impact of the various circular economy strategies are valid for the end-of-life phase for wind systems installed between 2008-2020. The first wind systems to enter the decommissioning and tear down phase does not begin until 2038 which corresponds to the systems installed in 2008. Furthermore, the sharp peaks in the data (Figure 9.1 and 9.2) represents an assumption our analysis utilizes: systems all fully decommissioned and enter the end-of-life material stream in the same year of decommissioning; therefore, the net emissions associated with each circular economy strategy are concentrated in the respective years of decommissioning. The peaks in Figure 9.1 correspond to the high numbers of installations in 2012 and 2014.

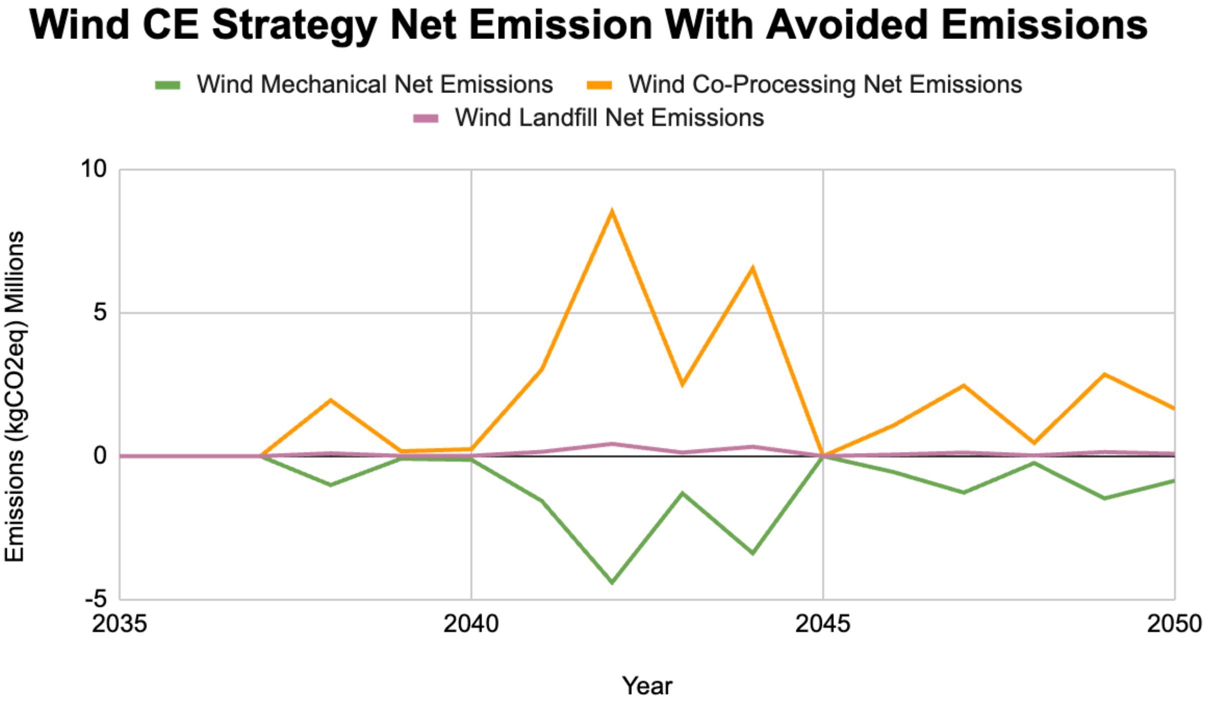

Figure 9.1 Net emission for Wind CE strategies from 2035 to 2050 in MI with avoided emissions

Similar to Figure 9.1, Figure 9.2 shows that the FRELP solar recycling method as a circular economy strategy has an overall negative net emissions impact, i.e. the emissions associated with the strategy are less than the avoided emissions of displacing virgin panel materials with recyclate. Figure 9.2 also has a similar condensing of the time period for net emissions. This choice is also driven by the fact that emissions from the circular economy strategies only occur at the end-of-life phase for solar panels. The peak of this Figure 9.1 corresponds to the peak installation year of 2017. Our model outputs utilize the assumption that the year in which a system is decommissioned is the same year it undergoes recycling and displaces virgin materials in its respective market. Furthermore, solar is a unique case for the State of Michigan where most of the current installed capacity at the State level comes from smaller distributed generation assets (i.e., rooftop solar) and not utility scale solar. Distributed solar power will be outpaced by the anticipated growth in utility-scaled systems that are outside the temporal scope of the analysis, and, hence, not included.

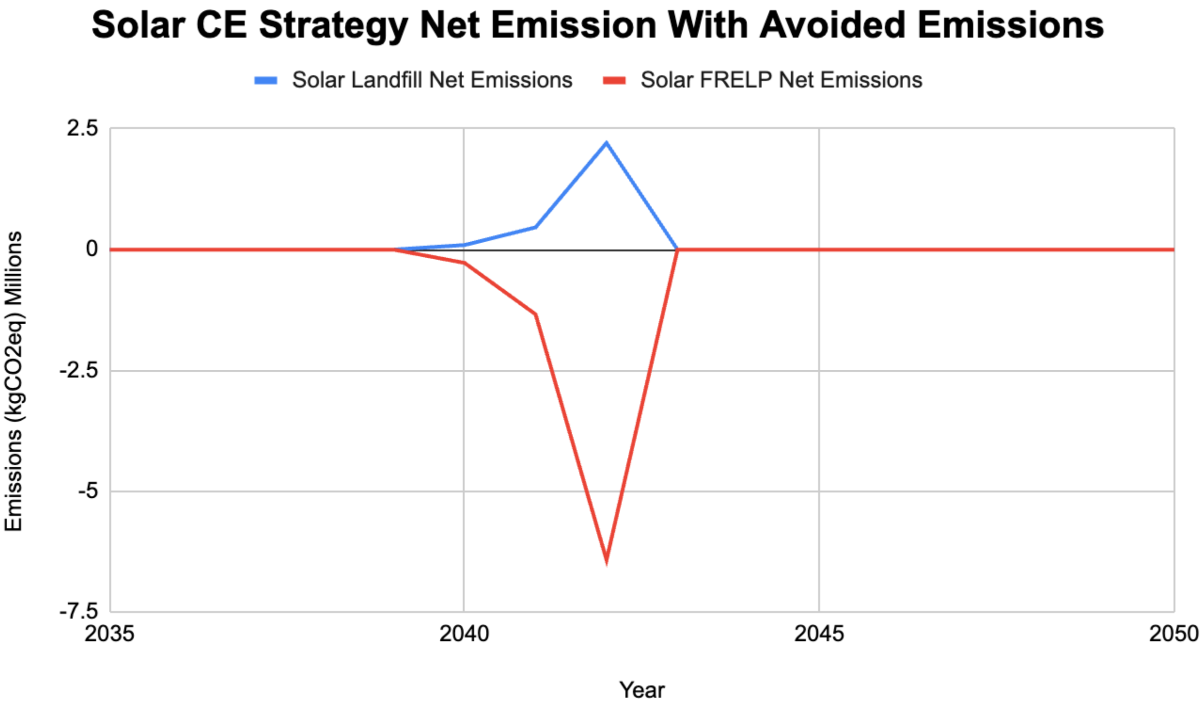

Figure 9.2 Net emission for Solar CE strategies from 2035 to 2050 in MI with avoided emissions

3.3 DTE Results

In this subsection, we analyzed the emissions and costs associated with circular economy strategies for DTE's current installations for wind and solar within the same time period our analysis considers. The emissions generated by the FRELP recycling for solar compared with the Landfill method shown below in Figure 10.1. These emissions presented in Figure 10.1 are representative of the end-of-life phase for the circular economy strategy. For DTE's current installations of solar, our model outputs showcase that the FRELP recycling produces 15% less emissions.

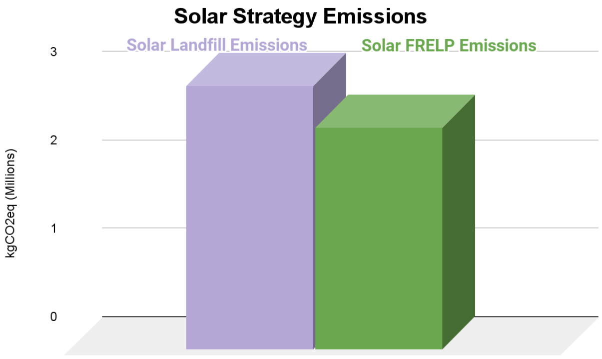

Figure 10.1 Total emissions of Solar CE strategies for DTE

Figure 10.2 incorporates the emissions associated with producing similar quantities of recyclate material from the solar panel with raw virgin materials. The difference between 10.1 and 10.2 shows the potential of displacing virgin materials in a circular economy, and how that can be attributed to EoL asset management decisions. FRELP Recycling appears comparable to landfilling in 10.1, yet generates benefits downstream as indicated by 10.2. Landfill emissions observe no change from their original values as shown in Figure 10.1 above.

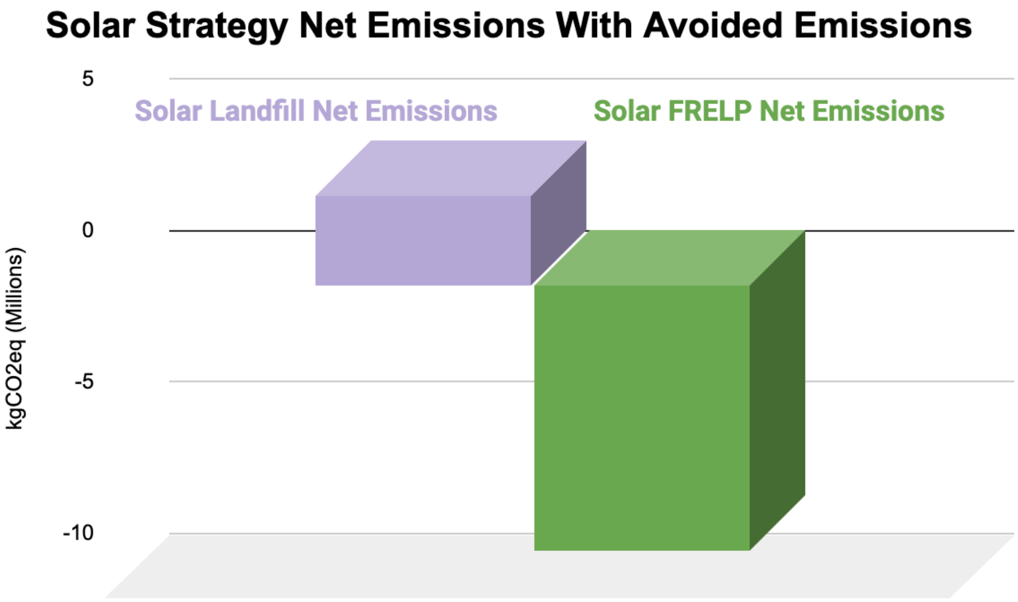

Figure 10.2 Solar CE strategy with avoided emissions

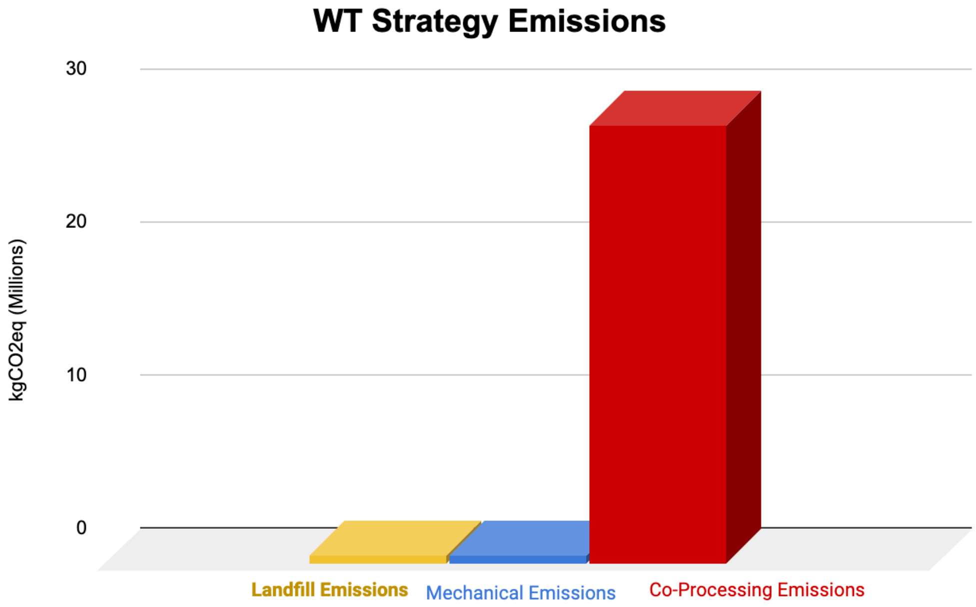

Figure 10.3 Total emissions of Wind CE strategies for DTE

Figure 10.3 shows the different circular economy strategies for wind-based power systems. It is shown that the landfill and mechanical circular economy strategies have very similar emissions at roughly 500,000 kgCO_2e. However, this is significantly different from what is seen with the Co-Processing strategy. Our model outputs indicate that the emissions associated with the Co-Processing strategy are roughly 28.59 million kgCO_2e, or 57 times greater than the prior two circular economy strategies for wind. This significant increase is associated with the combustion of the GFRP material and its additional CO_2 emissions streaming from it.

Figure 10.4 incorporates the emissions associated with producing similar quantities of recyclate material from the Wind Turbine blades with raw virgin materials. The difference between the two shows the avoided emissions when recyclate materials displace virgin materials. Our model indicates that the mechanical shredding method has net negative emissions when the recyclate material is used as insulation. Negative emissions indicate avoided emissions in the context of this study.

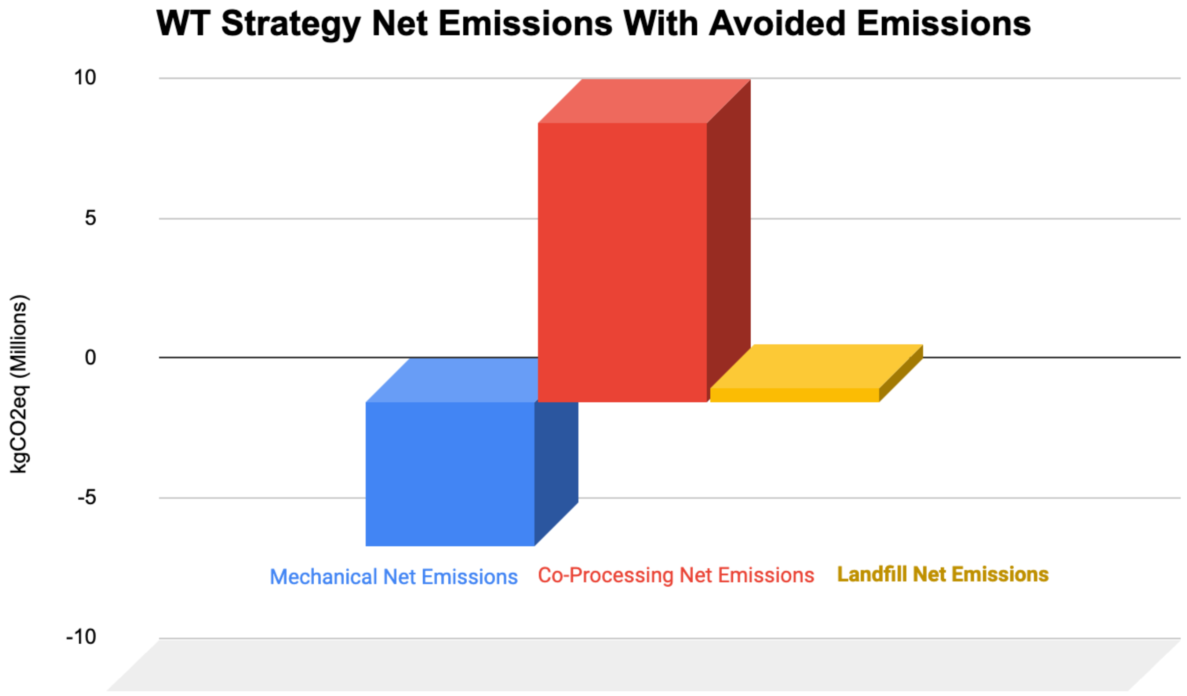

Figure 10.4 Wind CE strategy net emissions with avoided emissions

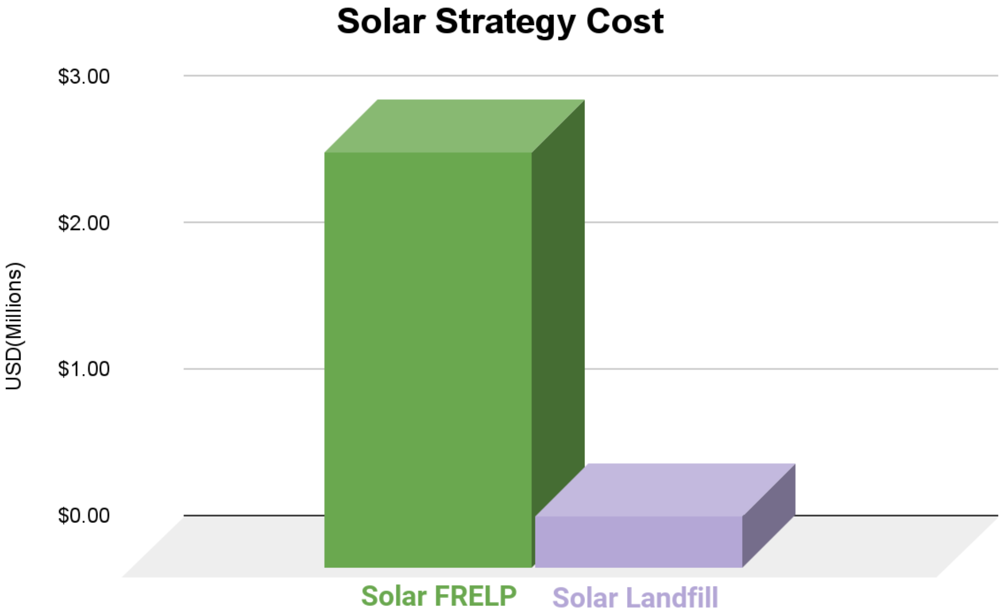

Figure 11.1 Total cost of CE strategy for Solar PVs

On the economic side, the costs of recycling strategies are calculated based on the costs of implementing each strategy, subtracting the value of virgin material recovered. Figure 11.1 shows the estimated cost for solar FRELP and landfill based on the DTE's installed solar PV until 2050. The landfill cost for solar is about $0.064/kg[8] including the decommission, dismantling the solar array, collecting panels prepared for transport to landfill, where the modules are shredded and separated for size reduction. Solar FRELP costs an average of $0.504/kg[8] for the extraction of valuable material such as copper, silver, aluminum, silicon and glass, and landfilling the ashes. The recovery of materials is not enough to offset the high cost of the operation based on the current material price.

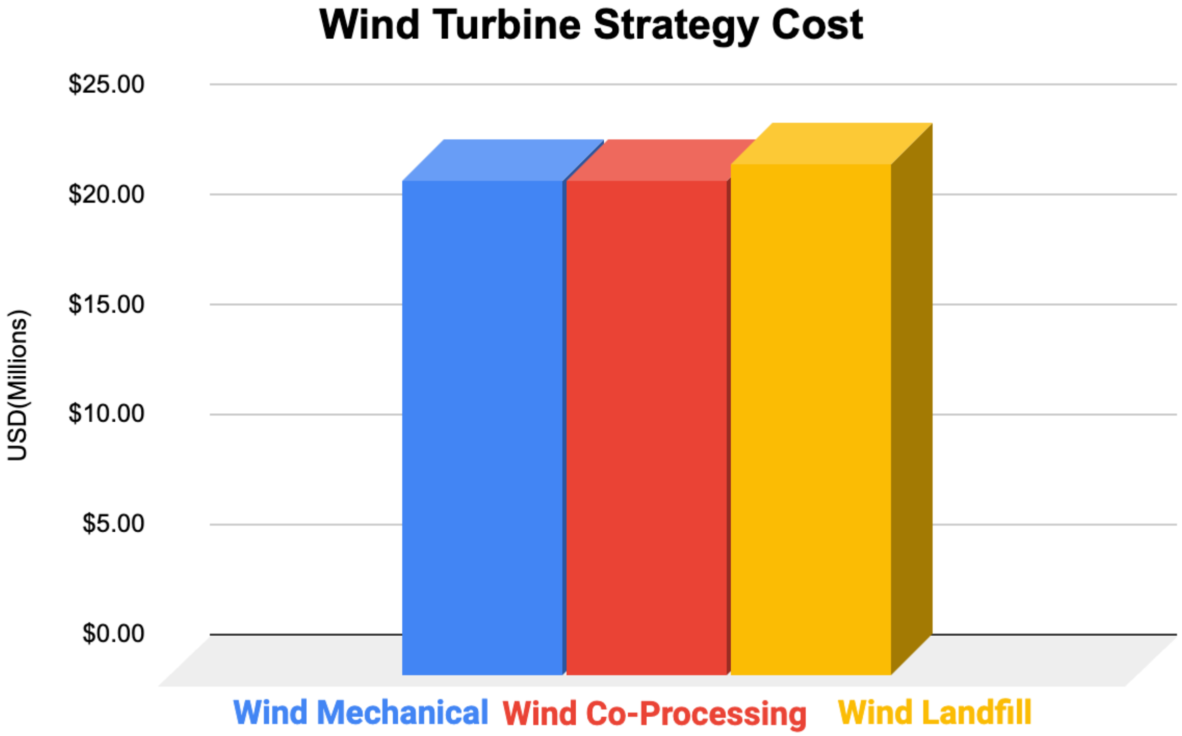

Figure 11.2 Total cost of CE strategy for Wind Turbines

Figure 11.2 shows that the Mechanical, Co-Processing, and Landfill strategies have roughly identical total costs for Wind Turbine recycling strategies, due to the large portion of the costs for all wind recycling methods sharing the teardown cost for the wind tower. The Wind Co-Processing method takes an average of $0.11/kg[4] to tear down and incinerate the Wind Turbines, however the recovered heat content and the incineration residual fibers as clinker components generate positive economic value on top of the cost. Wind Co-Processing is the cheapest method with a cost of $22.52 million total. The wind mechanical strategy has a higher cost of shredding blades or grinding to dust at $0.23/kg[44], with the recycled material being used as strong fibers and dust for flooring, walling, insulation, sound proofing, plastic lumber, cement binder. The cost is $22.554 million for DTE to use the mechanical recycling strategy. Meanwhile the Landfilling strategy has no recovery of any materials from the processes, thus having the highest cost of $23.3 million with an average cost of $0.177/kg[14].

4. Discussion

In order to evaluate the costs and benefits of implementing CE strategies and propose recommendations to DTE, CE models for Wind Turbine and solar panels were built at state and company levels. The CE strategies' performance was assessed using net emissions and costs as metrics. At the state level, modeling results suggest that a solar landfill strategy has the best cost performance and Wind Turbine Co-Processing strategy has the worst performance considering both net emissions and cost. Nevertheless, the solar FRELP recycling strategy and wind mechanical recycling strategy would each lead to less net CO_2 emissions in the long run but are not deemed the best due to higher cost. At the company level, recycling solar panels is a carbon negative EoL process when considering avoided emissions; and the efficiency of solar panels is an area of potential growth for PV recycling (drives down cost and impact). However, the cost of FRELP solar panel recycling is almost five times that of solar landfill. Therefore, solar traditional recycling strategy does not seem to be an economical option. For Wind Turbine blades, the mechanical recycling method is carbon negative if the market for recyclate is created. Given the cost of three wind CE strategies are almost the same, the mechanical recycling method could be the best option for DTE. The study also emphasizes that CE has potential to avoid short-term emissions through offsets, but only if the market for recyclate is ready to receive high material throughput within 15 years (for 2MW turbines and 270-335 Wp PV modules).

Economically, a solar secondary market strategy can be considered as a potential option for the solar industry, in which panels that are no longer suitable for utility power production are used in less demanding applications. In the rapidly growing solar industry, the solar panels that need to be decommissioned in the US are estimated to produce 1 million tons of waste by 2030, leading to considerable environmental and supply chain concerns and issues[35]. A Secondary market is able to deal with supply chain limits, decommissioned material, and diverting panels from landfills by maximizing asset and product life cycles as well as accelerating the adoption of solar energy worldwide to provide increasing business opportunities. Although many decommissioned panels are less efficient, they can still function at 80% of the original efficiency[27]. In this case, they can be refurbished and repurposed into the secondary market at a reduced price. While the secondary market is a promising approach to recycle PVs, it was not included in modeling as its cost is fairly uncertain and it has not received much attention in the US because the role it can play in substantially improving energy efficiency is largely untested.

In addition to CE strategies, policy intervention could drive market developments by stimulating more environmentally effective alternative solutions to the serious and imminent waste problem. Extended Producer Responsibility (EPR) refers to a policy approach that extends the responsibility of producers to the whole lifecycle of a product, including end-of-life management[33]. It requires producers to take responsibility for the full lifecycle of their products. Furthermore, EPR provides financial incentives or support systems to producers to ensure that they take environmental impacts into account with regard to raw materials, product design, and manufacturing processes[27]. The establishment of a monitoring framework is proposed in the future to guarantee transparency during the lifecycle of a product[27]. In essence, the purpose of EPR is to shift the recycling responsibility from local governments to private companies and finally to customers [33]. Presently, it has been applied in European countries, such as France and Germany, while Product Stewardship has been applied in the US without federal mandates. Therefore, EPR could be a potential policy mechanism to the US renewable energy industry in future.

Limitations and contingencies

In determining the environmental impacts and cost figures of the various CE strategies for Wind Turbine blades and solar panels several contingencies are acknowledged. First, are the chosen assumptions. For wind, limiting the scope of EoL analysis to only include the blades, can only provide a partial picture of the total environmental impacts of an entire Wind Turbine structure. The use of carbon fiber reinforced polymer (CFRP) as the material basis for incineration and cement Co-Processing introduces a layer of uncertainty with the true environmental impact of this process. This assumption was utilized primarily due to a lack of attainable primary data for glass fiber reinforced polymer (GFRP). Additionally, the feed rate is considered to be constant and set at 150 kg/hr which directly influences energy consumption requirements to drive the process. This feed rate also influences cost figures, but these sensitivities were not determined throughout this analysis. Additionally, various portions of emissions values were gathered from literature sources or industrial recorded data on databases. This inconsistency of data source also introduces variability to our modeled outputs for environmental impact. A clear need for industrial data to be recorded on these processes is known as a result of performing the analysis in this report.

Among wind recycling strategies, the cement Co-Processing strategy has been recently considered an emerging technology innovation to recycle Wind Turbine blades as a raw material for cement and has been developed only by few companies. As a result, there is not enough information about the strategy so far, particularly lacking cost data. In the absence of an exact price for this Co-Processing technology, we estimated the cost based on limited information when modeling, which makes modeling results less accurate. A follow-up research focus should be to track the progress of the technology and its market development. Beyond recycling strategies, it is also vital to involve end-of-life strategy into the earlier design stage of Wind Turbine blades in order to minimize waste production, which is not discussed in this study. Given the massive amount of Wind Turbine blades to be retired after 2025, future studies can focus on both recycling strategies and alternative design solutions including end-of-life consideration to improve the efficiency by involving more stakeholders in the full life cycle.

For solar, all of the analysis uses silicon-based panels. Because of this assumption on material type, and therefore, panel structure, our model is not reflective of the true composition of solar panels in Michigan statewide. While silicon panels dominate installed capacity, this reality of dominant panel technology may not continue to hold as solar development progresses. Future solar technologies will need to have their respective life cycle analyses conducted to understand how their EoL phase will influence the infrastructure required to properly reduce waste generation, which will in turn affect its overall environmental impacts. In addition, our secondary market research does not fully capture the nuances of the secondary life phase. For solar, the cost figures have more uncertainties in terms of implementation and operation, as the only figures our analysis were able to utilize were cost figures of prior literature analysis of solar panel recycling methods. These cost figures are not representative of the FRELP recycling and material recovery facility, as explained in our methods section (solar assumptions).

Another limitation is that our chosen system boundary does not capture all of the impacts of operations at the EoL, namely transportation. Transportation of materials from the generating facility site to the material recovery or reutilization facility and within these facilities are not considered within the scope of system boundaries. This omission cannot be assumed as an insignificant portion of environmental impact to an overall CE strategy; however, with no U.S based example of these facilities in place, the need to provide a realistic estimation on a particular CE strategy for a given technology was prioritized. There are optimistic outlooks on incorporating transportation figures in both cost and environmental aspects as EoL considerations continue to garner scrutiny.

We recommend future research to utilize or directly build additional data on the chosen processes utilized in this report to generate a more regional representative environmental impact. Additionally, we encourage further research on transportation impacts once suitable locations within the U.S. primarily focus on reutilization and recovery of materials for wind blades and solar panels. Lastly, additional research should be conducted with consistent system boundaries for both the energy inputs and emissions outputs and the cost attributions for a specific process. While the approach taken in this report provides a high level overview in the anticipated cost range of implementing a particular strategy, having consistent boundaries for cost and process would help provide more realistic cost figures for each given technology analyzed in this report. Furthermore, during the span of our study (2008-2050) the expected value of recyclate is highly uncertain. Therefore, the recovered material value from any of our modeled CE strategies is uncertain. Depending on advances in process efficiencies, for example FRELP-type facilities being improved and widely implemented, the cost of recycling itself could also change drastically by 2050. This is why we recommend regular iteration of cost and emissions modeling for long-term infrastructure planning by incorporating current literature, market data, and technology trends.

5. Conclusion

Our team has created a model which considers the end-of-life emissions of utilizing different circular economy strategies. The model output for both solar and wind technologies highlights the potential environmental benefits of adopting a circular strategy for the current generation of wind and solar assets. Using the tool we identified circular-economy strategies that offer clear potential for GHG benefits by displacing virgin production of materials, but at higher cost. FRELP recycling for solar and mechanical recycling for turbines achieved the lowest net emissions. The overall goal of this project was an LCA-based model that will evaluate the costs and benefits of implementing CE strategies across economic and environmental impact categories. Current literature has shown that there are barriers to implementing a circular economy strategy and retaining the value of waste materials. There are several challenges identified in understanding and highlighting the magnitude of environmental carbon emissions across different strategies. These challenges range from the assumptions regarding how the waste materials would be processed for material recovery, the purity and quality of the recovered materials, and the difficulties of estimating economic value in the material recovery and cost figures in implementing these solutions with current waste throughput.

There are clear benefits to adopting a more circular approach in material recovery for the end-of-life phase of these emerging, yet critical power infrastructure systems. With current trajectories of high renewable deployment by the mid century, additional research in the challenge areas we've identified can lay the groundwork for policy and market intervention. Furthermore, as the electrical grid begins to adopt more storage based technologies, the need for a similar yet thorough analysis for its end-of-life phase is required to identify the current limitations with this specific technology.

Future research should also consider the changing landscape for all technologies in the analysis and discussion. While most cost figures presented for solar and wind technologies are reflective of present-day costs, we anticipate that as waste streams increase and the infrastructure required becomes more refined and optimized for end-of-life material recovery, the implementation costs will decrease with the emergence of a new market. Identifying the policy and market conditions needed to capitalize on this recovery market will help provide incentives to the private sector, driving large-scale adoption of the circular economy strategies analyzed in this report.

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