Environmental Impacts of Decommissioned Solar, Wind, and Electricity Storage Systems
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Natural Resources Institute, Texas A&M University

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Shweta Singh, Ph.D.
Michael H. Young*, Ph.D.
Jani Das, Ph.D.

* - corresponding author

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Executive Summary

This report was produced through a subcontract between the Texas Commission on Environmental Quality (TCEQ) and the Bureau of Economic Geology (BEG) at The University of Texas at Austin (contract #582-24-50122 Work Order 4), with contributions from the Natural Resources Institute of Texas A&M University. The project stemmed from Senate Bill 1290 (SB 1290), which was passed in 2023 by the 88th Texas Legislature. SB 1290 requires a comprehensive assessment of the environmental impacts linked to the installation, operation, removal, and disposal of solar panels, wind turbines, and energy storage systems, specifically those focused on generation and end-of-life, also known as EoL. This study does not include impacts from sourcing or building these generation systems. The full text of SB 1290 is included in Appendix A of the main report.

Our report resulted from discussions with residents and members of citizen groups, representatives from power generation and recycling companies, trade associations, and research organizations. We read peer-reviewed literature and other technical reports, and we visited a solar panel recycling operation. We strived to understand the current state of knowledge about specific life cycle phases identified in SB 1290 and how they could impact the environment and watersheds. We identified locations of existing and planned facilities within groundwater conservation districts (GCDs) and river authorities (RAs) in Texas. Finally, the report includes a discussion on the current regulatory framework related to solar energy, wind energy, and battery storage in Texas, and areas where data on specific topics were limited.

Regulatory Framework and Environmental Protection

The State of Texas has an established regulatory framework to manage the environmental impacts of solar, wind, and energy storage systems on the environment. Key regulations include Senate Bill 760 (SB 760), passed in 2021, pertaining to solar energy, and House Bill 2845 (HB 2845), from 2019, relating to wind energy. These bills provide protection for landowners and ensure proper decommissioning of facilities, including restoration of land used for these facilities. Existing federal rules also play a major role in preventing pollution from leaching of metals or materials from relevant energy systems and through proper classification of waste material that leads to appropriate management.

Energy Storage Systems

SB 760 and HB 2845 specifically include energy storage systems in their definitions—when the battery systems are paired with generation—ensuring that they are regulated similarly to generation facilities with respect to landowner and financial assurances, restoration, and other criteria. Some counties or other jurisdictions may have their own guidelines that provide protection. However, uncertainties exist about regulatory enforcement of standalone energy storage facilities that are not paired with generation facilities, and about how design and installation guidelines could be implemented in unincorporated counties.

Life Cycle Assessment (LCA) and End-of-Life (EoL) Options

Our report presents the results from our study of solar, wind, and battery storage systems, focused on EoL options. Life Cycle Assessment (LCA) is an internationally standardized, comprehensive approach to determining the environmental impacts of processes and/or products. In this report, we compared EoL management options for disposal and recycling within solar and wind technologies. For batteries, however, we focused on recycling options, given the regulations regarding disposal in landfills.

Without accounting for the environmental benefits of using recycled material for new products (i.e., as a secondary market), our LCA results showed that mechanical recycling of solar panels is beneficial and can greatly reduce the waste volume that otherwise would be landfilled. Recycling of wind turbine blades, versus landfilling, was mixed; although wind turbine blades are not considered hazardous materials, their long-term durability means that they will not degrade through time, and their large size means that they will occupy a large amount of landfill space. For batteries, mechanical recycling was identified as beneficial in terms of environmental impacts, using NMC (Nickel Manganese Cobalt) and NCA (Nickel Cobalt Aluminum) batteries as surrogates for the LFP (lithium-iron-phosphate) batteries, which are typically used in electricity-grid applications.

Impacts on the Environment and Watersheds

SB 1290 specifically identified threats from installation, operation, and removal of solar, wind, and batteries on the environment and watersheds.

During construction and installation of solar and wind facilities, the potential negative environmental impacts include an increased risk of soil erosion (especially at large solar facilities) that often depends on pre-existing land conditions. For example, lands previously used for grazing could experience higher erosion and stormwater runoff after the solar or wind facility is installed, because the intact soil and vegetation are often ripped up during leveling and installation activities. This risk is addressed through the implementation of Best Management Practices (BMPs) and a Stormwater Pollution Protection Plan (SWP3) developed to address site-specific conditions and to guide industry when complying with the Texas Pollutant Discharge Elimination System Construction General Permit (TXR150000) for stormwater discharges from construction activities. If lands were used for production agriculture (where tilling is common) before installing solar or wind facilities, then future erosion could be reduced through the construction of berms, detention structures, and other features. Even with these measures in place, conversion of large land areas from natural conditions to industrial uses will fragment ecosystems; thus, avoiding sites near fragile landscapes and implementing stormwater BMPs can help reduce these impacts.

During operations, facilities can lead to both positive benefits and negative environmental impacts. Positive benefits, especially for solar facilities, can be realized through reduced erosion (with proper controls) and incorporation of agrivoltaics techniques where agricultural production is maintained (or even increased) in combination with electricity generation. This could also lead to enhanced biodiversity and soil health. Negative environmental impacts during normal operations can include increased soil erosion when mitigative measures are absent and the potential for birds to strike the turning blades of wind turbines. We considered different types of hazards, beyond routine operations, that could damage equipment and cause environmental impacts, such as hailstorms, tornados, and hurricanes. Although equipment and technologies are designed to be resilient from exposure to the natural environment for many years and have been shown not to leach significant quantities of metals, the results of only a few studies are available. Broadening studies to improve our understanding of how long-term exposure of damaged equipment could affect the environment would be beneficial.

We also considered the potential for battery fires, or thermal runaways, that could create hazardous conditions for first responders, fire fighters or neighbors and surrounding environment. Data from the Electric Power Research Institute (EPRI) listed 86 battery fires (four of which led to thermal runaways) globally since 2011, with the number decreasing to well below one incident per GW of storage. Innovations used in current designs are intended to prevent fires and to improve notifications and mitigative measures to quickly control these events, but they can still happen. As stated above, SB 760 and HB 2845 consider battery storage systems when they are components of solar and wind generation systems; however, some battery systems are standalone. It is unclear how these facilities can or should be regulated. Furthermore, although trade associations like UL and the National Fire Protection Association suggest design and mitigation practices, we are unaware of a Texas-wide training program for first responders who are on the front lines at fires, especially in rural areas. A consistent training program for first responders would benefit the public safety community and the residential community alike.

Solar Panel Disposal and Recycling

Utility-scale solar energy is relatively new in Texas, and EoL management decisions (disposal or recycling) of decommissioned panels by industry will become more common in the future when this infrastructure reaches EoL. We emphasize the importance of building a more robust recycling industry that can handle these future volumes and use secondary markets for recycled materials. Done successfully, this would greatly reduce the volume of waste that requires landfilling and the longer-term environmental impacts of acquiring new materials and equipment, regardless of whether they are solar or wind energy related. Recycling should be prioritized to recover valuable materials and reduce landfill volumes.

Wind Turbine Blade Disposal and Recycling

Landfilling is a common disposal method for wind turbine blades, but blades present challenges due to their size, material composition, and resiliency. For example, pre-processing activities, such as cutting and crushing, are energy- and labor-intensive. Long transportation distances for decommissioned blades are also an issue for large states, like Texas. We note that composite material recycling, whether glass fiber or carbon fiber, has already been done in the marine and vehicle transportation sectors; recycling these materials is not new. As with solar panels, recycling capacity currently is insufficient to handle future volumes. Building a more robust recycling industry in Texas would reduce pressure on local landfills.

Energy Storage System Disposal and Recycling

This study focused mainly on battery storage systems used in grid operations, on what are known as LFP batteries, not on batteries used in electric vehicles (EV's), which have different chemistries. Currently, LFP batteries are not widely recycled due to their low-value metal content, while batteries used in EV's are made with materials valuable enough to economically recover through recycling. Regardless of their chemistry, LFP batteries should not be disposed of in municipal landfills and need to be handled and managed as hazardous waste. Given the recent increase in battery deployments to support intermittent solar and wind generation, we can expect an increase in the need for EoL decisions on batteries in the next 10 to 20 years, giving industry an opportunity to innovate toward a solution for recycling LFP and other types of batteries.

Data Limitations and Future Research

In developing this report, we noted the scarcity of data, particularly regarding the recycling of LFP batteries and the long-term leachability of wind turbine blades that are either abandoned on ground surface or disposed of in landfill environments. We also noted lack of data in Texas on potential dual use of land for solar generation facilities and agricultural production, known as agrivoltaics. Maintaining agricultural production while generating electricity would allow landowners to continue, and possibly increase economic activity, while mitigating loss of productive lands. Although federal and Texas laws regulate specific pollutants in stormwater runoff or discharge (such as sediment) from migrating from the property during construction activities, a gap exists in the regulatory landscape during the industrial operation for solar, wind and energy systems, whereby stormwater runoff or flood waters without sediment or other pollutants can still flow to offsite locations and potentially erode another landowner's property. More comprehensive data in these areas are needed to fully assess these types of environmental impacts. Finally, a key gap in current research exists in the development of robust forecasting and predictive models for EoL volumes from solar, wind, and battery systems. Accurate volume predictions are critical for the effective planning and optimization of recycling infrastructure, enabling improved material management, and identifying new opportunities in the circular economy.

1. Introduction

1.1 Background

The Bureau of Economic Geology (BEG) at The University of Texas at Austin (UT Austin), and the Natural Resources Institute at Texas A&M University (TAMU) have focused on assessing the environmental impacts of operating and disposing of wind, solar, and energy storage systems in Texas. This project stemmed from Senate Bill No. 1290 (SB 1290), which passed in 2023 by the 88th Texas Legislature. SB 1290, under Section 2 (a) stated, “The commission shall conduct a study on the effects of the installation, operation, removal, and disposal of solar, wind turbine, and energy storage equipment.” SB 1290 requires a comprehensive assessment of the environmental impacts linked to a limited portion of the lifespan of renewable energy systems, those focused on generation and end-of-life, also known as EoL; SB 1290 does not include impacts from sourcing or building these generation systems. The full text of SB 1290 is included in Appendix A.

In response to SB 1290 and based on the approved contract between the Texas Commission on Environmental Quality (TCEQ or Commission) and UT Austin, the research team centered mostly on the environmental impacts of disposal and other EoL options for solar panels, wind turbines (mostly the blades), and battery energy storage systems (BESS) after decommissioning, and less on the installation and operations phases of these technologies. The EoL options include recycling, reusing, and landfilling.

We identify current regulations that are intended to reduce the risk of damage to the environment and watersheds at locations where technologies are deployed and installed, as well as where recycling or landfilling of these technologies takes place. The study considers opportunities for recovering recycled materials, and innovations in technology and recycling techniques that would reduce future waste volumes at landfill sites.

1.2 Statement of Problem and Environmental Issues

The growth of renewable energy capacity from solar, wind, and energy (battery) storage technologies is expected to continue in Texas; some of this growth is anticipated by the Electricity Reliability Council of Texas (ERCOT) in both their short- and long-term planning horizons (ERCOT, 2022a, and 2022b, respectively), though any number of conditions may alter the rate of change in capacity growth. This growth means that more land will be converted to energy generation. Given that most utility-scale generation from wind and solar occurs in rural areas, and that most rural lands in Texas are used for agricultural production (usually grazing, dryland cropping, or irrigated cropping), we can expect ongoing conversion of agricultural lands for energy development. Thus, ensuring compliance with State and Federal regulations with any siting questions (e.g., stormwater protection) during installation and operations is vital. Moreover, most solar, wind, and battery storage systems have anticipated lifespans in the range of 20 to 30 years. Given the ramp up in generation capacity growth over the last 10 years, and what is being anticipated over the coming decades, a substantial increase in the amount of equipment that no longer meets manufacturer specification is likely by 2035 or 2040. This means that decisions will be needed relatively soon on how best to manage this volume (or weight) of decommissioned material to avoid environmental impacts of disposing of and managing these technologies at the end of their lifespan.

This study aims to address the requirements of SB 1290 and conditions (e.g., hailstorms) that might lead to environmental impacts during operations. To better understand these impacts, we compiled existing information (mostly in peer-reviewed literature) and conducted targeted studies of available EoL options using life cycle assessment (LCA) to identify the options in terms of maximum resource recovery, minimum environmental impact, and other criteria.

1.3 Scope of the Report

This project was executed through a sequence of tasks and analyses that included questions of installation and operation, but that mostly focused on EoL options, which are probably less well known. We organize this report using the general study framework that follows the legislative mandate for understanding environmental impacts of these facilities, and the Scope of Work that was approved by TCEQ (on January 19, 2024). See Figure 1.1 for the general approach and steps.

1.3.1 Baseline Data Collection – Stakeholder Outreach, Literature Review, Site Visits

Analyses like these require a substantial amount of data, which often are disparate and difficult to assemble for an integrated review. We first arranged meetings with stakeholders and industry representatives to discuss the project approach and the need for information to improve our study. We generated questionnaires for use by industry experts to help focus on specific information needed. We identified literature from peer-reviewed journals, symposia, trade publications, and other sources, looking for fundamental data on environmental impacts from facility operations and existing methods of disposal, such as recycling, reuse, and landfilling within the state of Texas. Our focus was on waste handling and management methods. Subsequently, we developed a questionnaire on the EoL of solar, wind, and battery technologies for installers and recyclers. We also arranged meetings with industry officials, trade groups, and other stakeholders to address EoL barriers and collect valuable perspectives.

1.3.2 Life Cycle Assessment Modeling to Understand Environmental Impacts for Each Technology

Using the data collected from discussions and survey results, the literature search, and data from other international sources, we conducted an LCA for each method of disposal (recycling, reuse, and landfill) for solar panels, wind turbines, and batteries. This study was designed to analyze the environmental effects associated with each route. The LCA considers 16 different environmental impact pathways, including land use, particulate matter emissions, potential contamination from toxic compounds, and others. The objective was to evaluate and contrast the environmental impact of various "disposal" options occurring in the state of Texas. We attempted to understand the extent to which environmental outcomes can differ based on several aspects such as the combination of energy sources, efficiency, and geographical location.

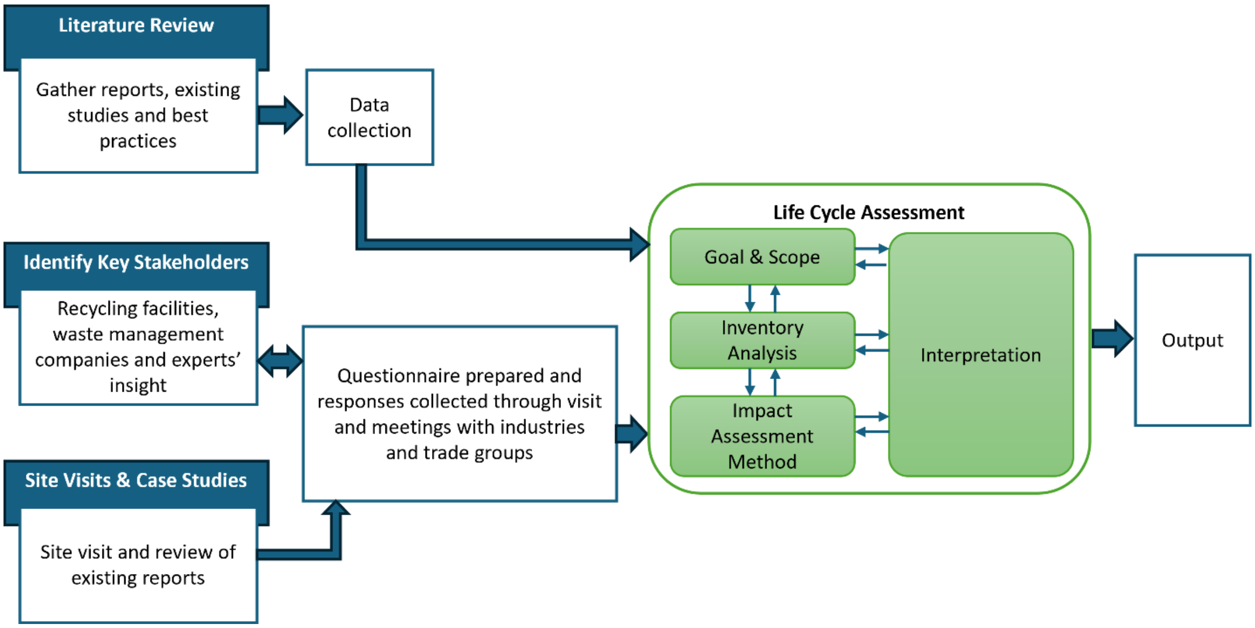


Figure 1.1 Framework of the study

1.4 Location of Existing Facilities

SB 1290 specifically noted the need to consult with Groundwater Conservation Districts (GCDs) and River Authorities (RAs). In cooperation with the Texas A&M University Natural Resources Institute, we assess the current and anticipated future generation capacity of wind, solar, and battery facilities within the jurisdictional boundaries of GCDs and RAs in Texas. The analysis compiled information from different datasets and evaluated the current state of energy generation and the anticipated future capacity of projects that are currently in the planning or approval stages. The geographic distribution of wind, solar, and battery facilities across GCDs and RAs was then determined. The goal of this analysis is to better understand whether and where facilities are clustered within specific districts, so that district leadership can become better informed on activities in their jurisdictions.

Two primary data sources were used for this assessment. For existing facilities, data were sourced from the U.S. Energy Information Administration Energy Atlas – Power Plants dataset. This geospatial dataset includes detailed information about the location, capacity, and fuel type for every power plant across Texas (Appendix Table B.1 and Table B.2). For projected generation capacity, data were obtained from the ERCOT Interconnection Queue (as of July 2024), which provides a list of projects in the planning or approval stages, along with their interconnection agreement statuses. A key attribute of this dataset is the financing status of each project, which we used as a proxy to gauge the likelihood of the project proceeding to actual interconnection and construction (i.e., facilities in the queue with financing in place are more likely to be constructed). The interconnection dataset only provides county-level information (Appendix Table B.1 and Table B.2) rather than precise geographic locations, so we proportioned facilities across jurisdictional boundaries when necessary (this occurred in only a few cases). In addition, future projects listed in the ERCOT queue are of widely varying capacities (and in some cases, the capacities are not available). When totaling the number of facilities in a particular jurisdiction, the capacities should be considered, because these affect the area needed to host the facility.

The analysis, despite the challenges of addressing the jurisdictional boundaries issue, shows the breadth of the distribution of existing and potential future wind, solar, and battery systems within specific GCD and RA areas (Figure 1.2 a-d). Tables of data are found in Appendix B. The figures are organized by GCDs (Figure 1.2 a, b) and RAs (Figure 1.2 c, d). The results show more than 60 GCDs without any wind, solar, or battery facilities with their boundaries, around 20 GCDs with two wind and solar facilities and then a diminishing number of GCDs where facilities are more prevalent. Considering locations of potential new facilities (Figure 1.2 b), the breadth of facility placement within GCDs increases, especially for battery facilities. The data indicate that 35 existing facilities are within GCD boundaries, potentially increasing by an additional 611 new facilities within the next several years. The trends for facility placement within river authorities are similar. Results show several RAs without any facilities within their borders, and a few RAs that host larger numbers of facilities, especially wind facilities (e.g., Brazos River Authority and Red River Authority host 56 and 57 facilities each, respectively). Looking forward, most new facilities are dominated by solar and battery technologies.

We note that the total number of existing and potentially new facilities will not overlap completely, because GCDs are organized in some areas of Texas that are not within RA boundaries and vice versa. That said, the results do show a spreading out of new facilities across Texas, which will help in distributing the electricity generation, rather than concentrating the generation.

Figures 1.3 and 1.4 present existing and projected capacities for solar, wind, and battery systems within GCDs and RAs. Together, these figures offer an overview of the current operational capacities and projected future growth for each technology, providing insight into the present landscape and highlighting anticipated expansions in solar, wind, and battery installations for GCDs and RAs, underscoring regional strategies for energy development and resource management.

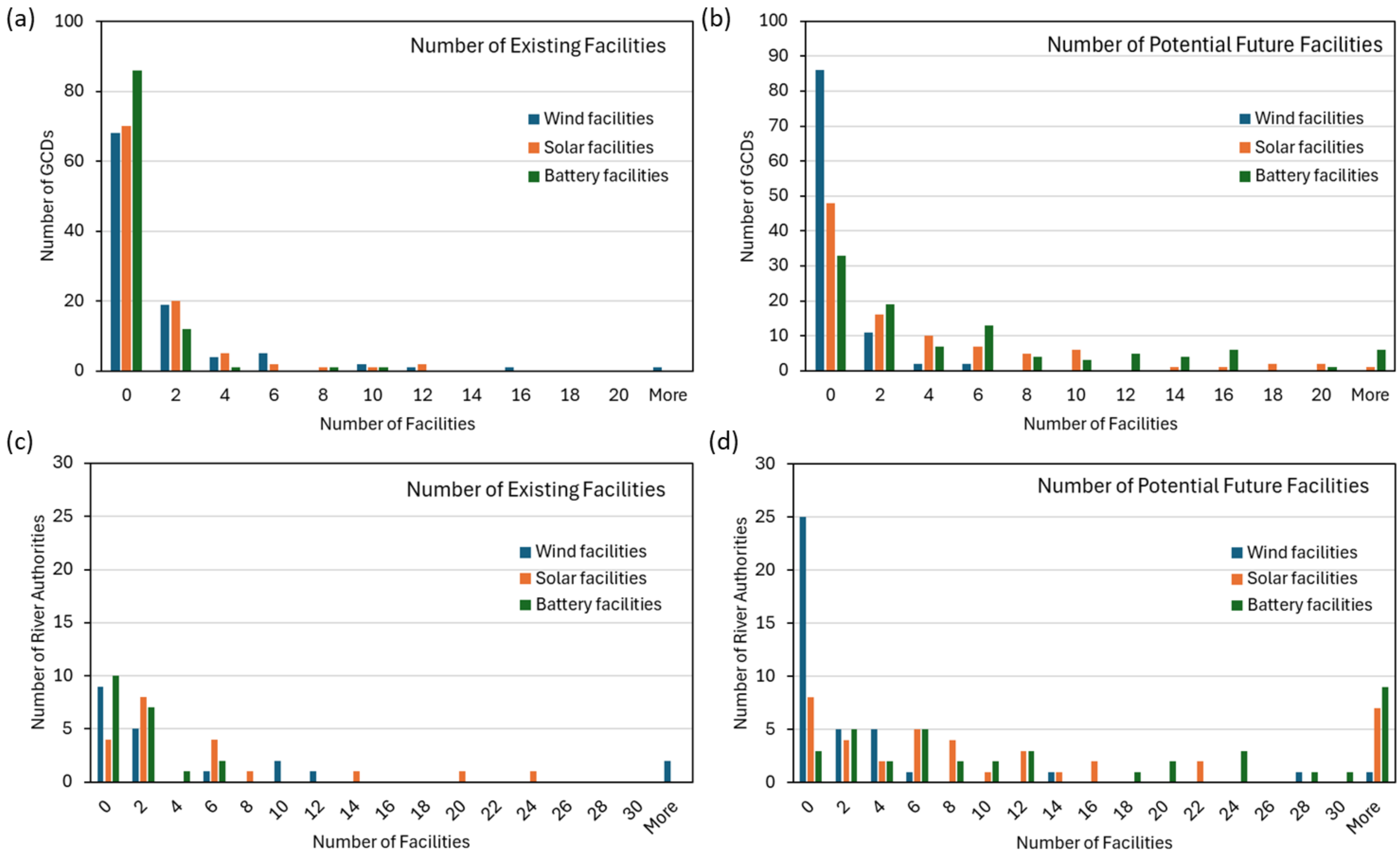


Figure 1. 2 The breadth of distribution of the wind, solar, and battery system for (a) existing facilities of GCDs, (b) potential future facilities of GCDs, (c) existing facilities of RAs, and (d) potential future facilities of RAs.

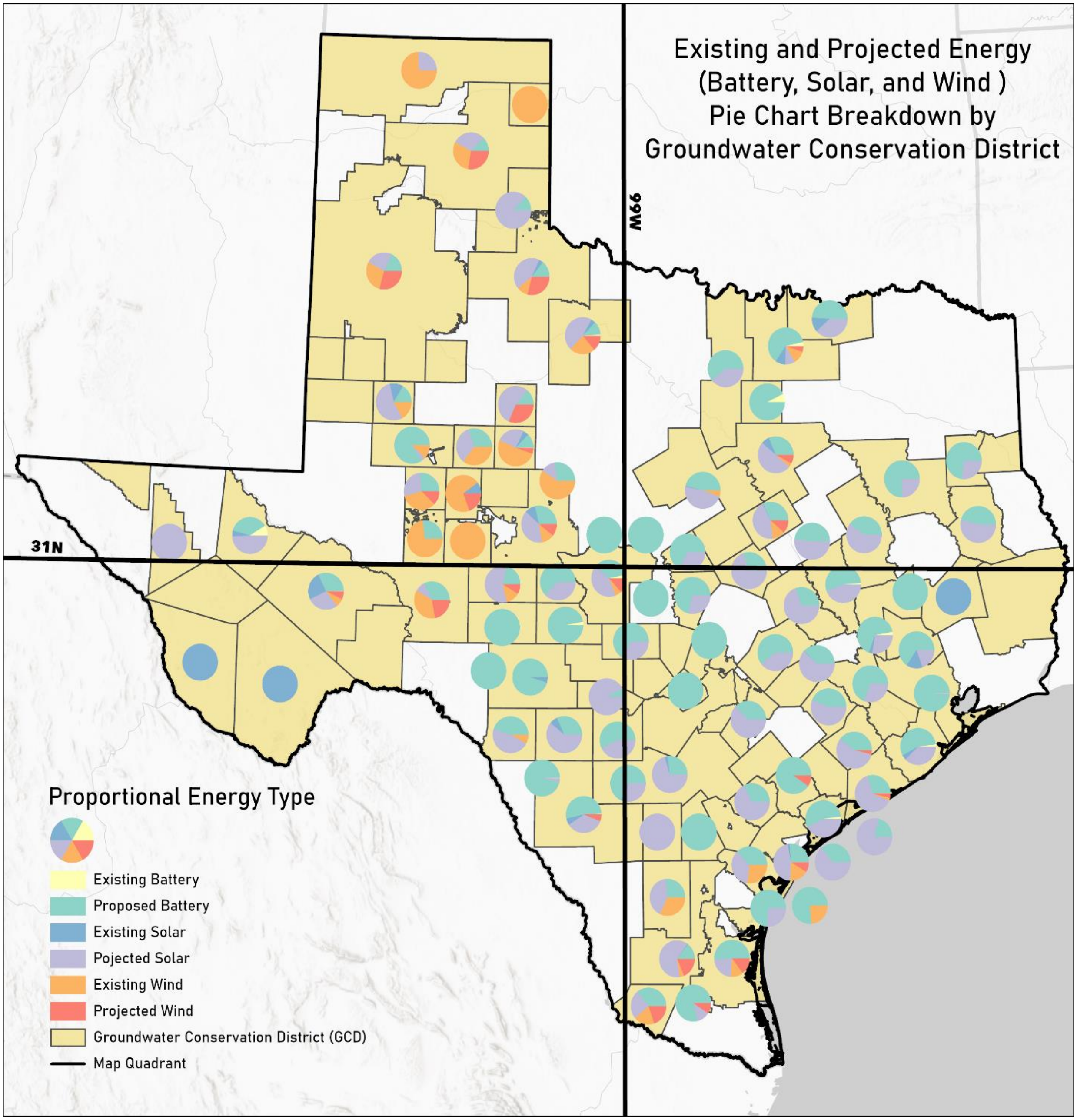


Figure 1.3 Current operational and projected capacities of solar, wind, and battery systems across Groundwater Conservation Districts (GCDs)

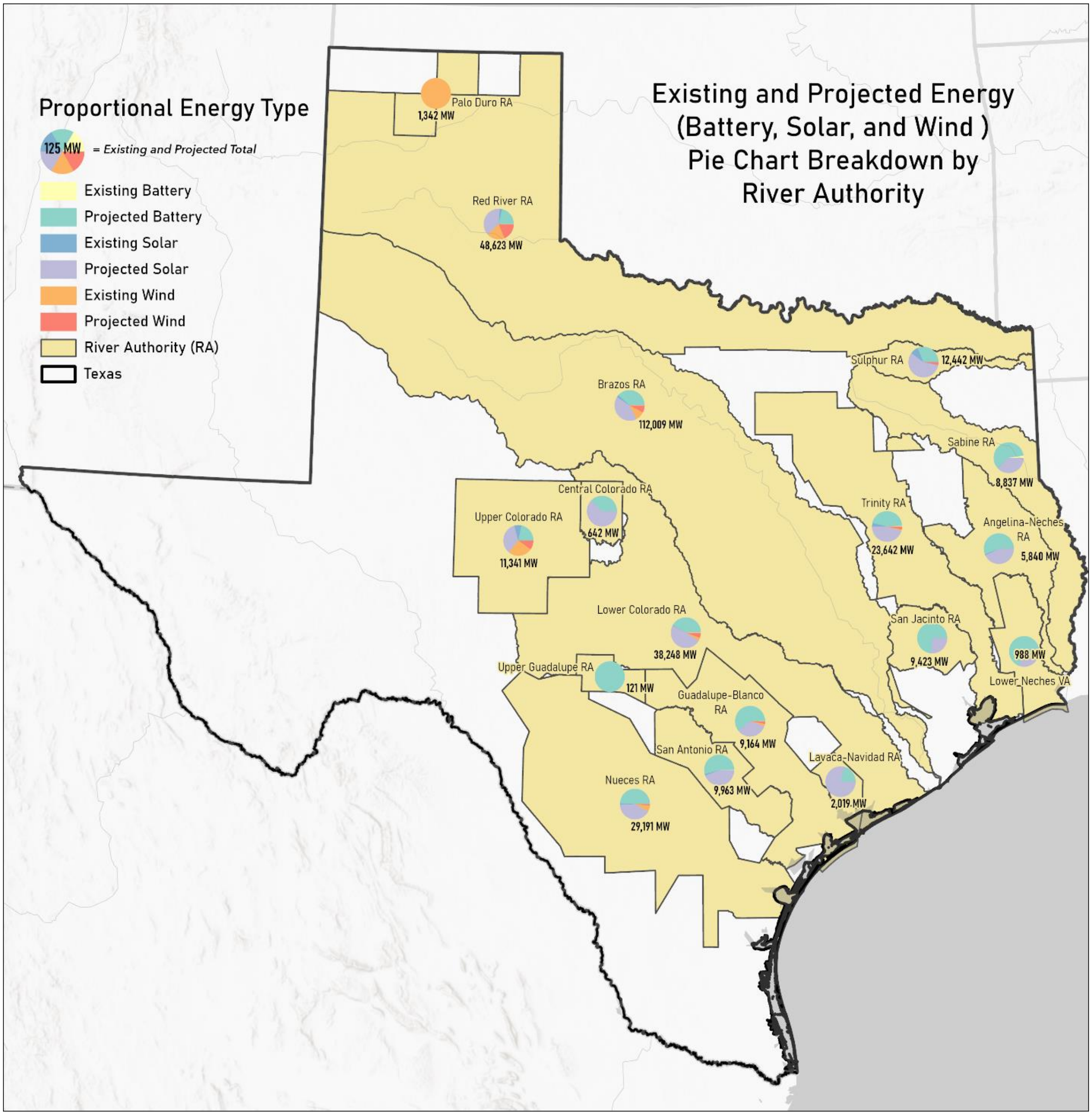


Figure 1.4 Current operational and projected capacities of solar, wind, and battery systems across Regional Authority (RAs)

2. Stakeholder Outreach and Input

The stakeholder engagement and feedback processes were crucial to the progress of our project. Through active involvement with a wide range of stakeholders, we have acquired important perspectives that have informed our project and ensured that we can properly contextualize the discussions. To broaden how data can be provided to our research team, we held public meetings, created and distributed a questionnaire, and held numerous other discussions with stakeholders. Methods of this engagement are listed in Table 2.1.

2.1 Direct Outreach to the Public and Project Coordination

These meetings (Table 2.1) were organized by TCEQ and other relevant participants to monitor progress and update the research team on action items.

Table 2 1 Summary of meetings with TCEQ and relevant parties

Date	Location	Participants	Agenda	Outcomes and Action Items
1/17/2024	Virtual	TCEQ representatives	Introductory meeting	
2/13/2024	Virtual	90+ participants	Research team presentation followed by questions from participants related to the scope and boundaries of study.	• Framework for study area
4/15/2024	Virtual	TCEQ and TAMU	Discussion on the boundaries of work within the UT workscope, and areas where TAMU could contribute to the study and report. Additional discussion on Li-ion batteries and materials contained therein, and utility-scale battery testing and other relevant topics.	• Defined boundaries of work. • Mentioned some references of representatives from companies involved in the installation, maintenance, and decommissioning of renewable energy systems.
6/24/2024	Virtual	TCEQ and TAMU	Updates provided by UT Austin research team and general discussions on other items to include in the final report (e.g., effect of innovation on solar, wind, and batteries EoL options, including ecosystem services, site specific and SWOT analyses of erosion potential, etc.).	• Finalized the report outline
8/2/2024	Virtual	TAMU	Discussion of the power-generating facilities in Texas	

			and heat map generation for the Groundwater Conservation Districts (GCDs) and River Authorities (RAs).	
8/23/2024	Virtual	TAMU	Updates on the heat map for showing facilities within GCDs and RAs of solar, wind, and battery.	

2.2 Questionnaires and Meetings with Industry

We developed an extensive questionnaire, distributed to installers and recyclers, for the purpose of understanding techniques and procedures when installing, operating, and disposing of solar panels, wind turbines, and batteries that have reached the end of their useful life. The details included existing methods and challenges. Questions were structured to cover key areas including expected lifespan, effects due to natural hazards, damage during installation, waste handling capacity, treatment methods, secondary material recovered from recycling, testing for hazardous materials, transportation of components, other methods of disposal, such as landfilling, repair, reuse, and other topics. Detailed questionnaires about solar facilities, wind turbine, and energy storage equipment were written individually, and are provided in Appendix C.

2.3 One-On-One Interviews with Industry Experts

We also held numerous meetings with energy companies, recycling companies, trade associations, and the like (Table 2.2), to understand, firsthand, the approaches used by companies to address and mitigate potential environmental impacts, when installing, operating, or disposing of equipment. We were able to engage with experts in the field to gain a deeper understanding of the overview of recycling technologies, challenges in scaling up these technologies, and potential for innovations to improve recycling rates, and to create avenues for reducing environmental impact.

Table 2.2 Summary of meetings held with industry experts

Date	Location	Participants	Key Discussion Points	Outcomes and Action Items
Initial: 2/20/2024 Follow up: 3/12/2024	Virtual	Wind turbine blade recyclers	Discussed location and transportation concerns of wind blade recycling. Highlighted tracking (with RFID) and documenting each process while recycling. Briefly discussed the initial recycling processes, including blade cutting, TCLP test, and EPA test.	• Better understanding of the method used for processing turbine blade waste. • Received some documents on the job hazard analysis, field operation flow, etc.
3/19/2024	Virtual	Composite recyclers	Discussed glass-to-glass (G2G) recycling, recovery of char and fibers, and	• Clearer understanding of the mechanical, chemical, and thermal

			their recovery rates, multi-stage pyrolysis (same gas compression), energy-efficient processes, repowering, disposal of wind turbine blades and its effect on land, economical modes of transportation, and how chemistries of turbine blade (PET vs. balsa wood) could affect recycling approaches.	recycling of wind turbines blades. • Recycling capacity of blades per day. • Questionnaire sent and response received.
3/25/2024 to 3/26/2024	Visit (In-person)	Solar recycler	Visited recycling facility and observed the handling and recycling of crystalline silicon panel, starting from tracking and documenting panel arrival to deframing, delamination and material recovery.	• Prepared visit report about recycling units. • Questionnaire sent and response received.
4/3/2024 (initial) 4/26/24 (follow-up)	Virtual	Battery recycler	This meeting was a one-to-one discussion about the study and inputs needed for the project. In a follow-up meeting, we discussed damaged, defective, and recalled (DDR) batteries, battery scrap and impurities within, and recovery of metals in battery recycling. Additionally, we discussed issues of recycling batteries with LFP chemistry, and secondary market of blacksand (Cu, Ni and Li).	• Letter sent to the company through email to provide details of the study for BESS. • Company's approach for recycling and recycling facility establishment. • Questionnaire sent and response received.
4/4/2024	Virtual	Solar, wind, and battery	Discussion of development planning, recycling, facility operation, and economic feasibility.	• Questionnaire sent but response not received.
4/17/2024	In-person	Solar manufacturing and recycling	We discussed presentation material provided by the company and discussed circular economy, zero landfill commitment, etc.	• Questionnaire sent but response not received. • Shared some information on stormwater erosion.

5/2/2024	Virtual	Battery manufacturer	The company is mainly on the deployment side and not on recycling. The company focused mainly on LFP batteries and less on NMC batteries. We discussed three aspects of after life: secondary life market (primary solution), recycling, and landfill. Highlighted the economic side of disposing of and recycling batteries. We also discussed the risk involved with site operations, and design of battery storage systems, particularly explosion risk, spacing between batteries, and design criteria that mitigate thermal runaways, overcharging and undercharging, and others.	• Questionnaire sent but response not received. • Shared some references of report and webinar and companies involved in battery recycling. • UL9540 and UL9540A methods for testing and the NFPA 855 report.
5/17/2024	Virtual	Solar recycler	Company presented material and discussed the recycling capacity of their facility, recovery of semiconductor material from recycling, ASTM standards additional to TCLP, EPEAT ecolabels, etc.	• Understanding the mechanical, chemical, and thermal recycling of CdTe solar panels. • Questionnaire sent and response received.
6/11/2024	Virtual	Legislative Director for Texas representative	Discussed soil and water erosion, effect of technology improvement on recycling, need for information for first responders to address fires stemming from battery fires and other issues, siting considerations, etc.	No other action items listed.
6/1/2024	Virtual	Recycling wind turbine blades	Swiss company specializing in recycling composite materials, beginning with watercraft	No other action items listed.

			and vehicles, but now also wind turbine blades. Their process, which needs to be upscaled, processes nearly 100% of all materials in the blade.	
6/18/2024	Virtual	Batteries	Technical discussion related to company's approach to addressing battery technology, recycling, and other issues. The company focuses mostly on mobile batteries, and less on BESS.	No other action items listed.
8/6/2024	Virtual	Wind turbine blade recycler	Discussion on the recycling methods and processes to ensure the quality of recycled materials. Comparative difference between glass fiber and carbon fiber recycling. The company focuses on the manufacturing of environmentally friendly secondary products.	No other action items listed.

2.3 Focus Groups

Discussions were held with certain stakeholder groups (Table 2.3) to further explore particular topics and to obtain additional insights.

Table 2.3 Summary of meetings with stakeholder groups

Date	Location	Participants	Key Discussion Points	Outcomes and Action Items
2/21/2024	Virtual	Texas Solar Energy Society (TXSES)	Discussion related to the warranties and lifetime of solar panel, difficulties in installing rooftop solar, and recycling responsibility of installers.	• Discussion of the preparation of the questionnaire used in the study. • Received responses from a few business partners that mainly work at utility scale.
4/3/2024	Virtual	Texas Energy Storage Coalition	Discussed innovation in technology and associated changes recycling, impact of	• Letter and questionnaire sent.

			new battery chemistries on recycling, etc.	• Questionnaire circulated across their network for more insight.
4/10/2024	Virtual	Advanced Power Alliance (APA)	Discussion of soil and water erosion due to technologies, environmental contribution from different panel types, effect of technology improvement recycling, opportunities for new recyclers, optimum location for generation sites, using criteria such as access to power, transmission lines, private land availability, neighboring landowner, technology dependence, and overall solar market.	• Questionnaire sent. • Received joint response from Advanced Power Alliance (APA), the Texas Solar Power Association (TSPA), and the Solar Energy Industries Association (SEIA).
5/17/2024	Virtual	Electric Power Research Institute (EPRI)	Discussed multiple working areas and ongoing research related to current study field.	• Multiple EoL related resources shared by EPRI representatives.
8/29/2024	Virtual	APA/ TSPA/ SEIA	Discussion of list of questions that is related to EoL and in-field (operations) management.	

3. Current Status of Associated Regulations and Legislation (outside of SB 1290)

Many aspects of installation, operation, and disposal of energy-related equipment—as for many other types of infrastructure—are regulated under existing federal and state regulations. These regulations cover many aspects of environmental protection, including land and water resources (both groundwater and surface water resources and quality) from various phases of solar, wind, and battery storage system deployments. Below is a list of existing regulations, with brief descriptions of their intent and their relevancy to the energy systems listed in SB 1290.

Not all regulations have long histories of applications to solar, wind, and battery storage. Utility-scale solar energy generation, for example, is a relatively new energy source that has only recently (in the last 10 years) become more significant as an electricity generation source in Texas. We are intentionally not including distributed generation, like rooftop installations, in this report because they are not considered to be utility-scale, which is generally assumed to be 1 MW or greater (US EIA, 2024). Battery energy storage systems are even newer, with less than 100 MW of storage across ERCOT as late as 2018 (ERCOT, 2020), and with around 7,700 MW in Texas as of mid-2024.

The list is subdivided by the environmental protection of surface water bodies from off-site discharge of pollutants; protection of soil and groundwater from release of pollutants onto ground surface; classification of waste material from industrial sources; and the required remediation of the environment from facilities and accidental releases.

It is important to note that discussions on applicable laws that might apply to wind, solar, and battery energy storage systems should describe generally that a waste generator is responsible for classifying the waste and transporting, processing, storing, and disposing of the waste according to its waste classification. No handling, storage, or disposal of solid waste may cause an unauthorized discharge into the environment; create a nuisance; or endanger public health and welfare. Those responsible for solid waste are required to assess and remediate unauthorized discharges into the environment from occurrences such as leaks, spills, seeps, unauthorized burials, and other activities.

3.1 National (Texas) Pollution Discharge Elimination System (NPDES/TPDES) – Controlling Discharges of Pollutants to Surface Water Bodies

The National Pollutant Discharge Elimination System (NPDES) regulates point source discharge of pollutants from industrial facilities and other point sources into waters of the United States. Texas has had delegated authority for administering the NPDES program since 1998, under the Texas Pollutant Discharge Elimination System (TPDES), with TCEQ administering the regulations for discharges from facilities to Texas surface waters. Below is a schematic of regulations and authorizations:

- Federal Regulations: 40 Code of Federal Regulations (CFR) Part 122
  - Subpart A: Definitions and General Program Requirements
    - Includes purpose and scope of regulations
  - Subpart B: Permit application and special NPDES program requirements

        - Section 122.26: Describes stormwater discharges subject to state NPDES (TPDES in Texas) program requirements, including construction, industrial, and municipal separate storm sewer systems (MS4s) regulations.
    - Subpart C: Permit Conditions
- State Authority: Texas Water Code Chapter 26
    - 26.027: authorizes the Commission to issue permits and amendments to permit discharge of waste or pollutants into or adjacent to water in the state of Texas.
    - 26.121: makes it unlawful to discharge pollutants into or adjacent to water in the state of Texas, except as authorized by a rule, permit, or order issued by TCEQ.
- State Regulations:
    - 30 TAC Chapter 205: General Permits for Waste Discharges
    - 30 TAC Chapter 305: Consolidated permits
    - 30 TAC Chapter 307: Texas Surface Water Quality Standards
    - 30 TAC Chapter 319: General Regulations Incorporated into Permits

3.2 Stormwater Pollution Prevention Plan (SWP3) for Construction General Permit

The development and implementation of a site-specific SWP3 is a requirement under the Construction General Permit (CGP, TXR150000) to reduce and eliminate the discharge of pollutants from stormwater runoff from construction and construction support activities that disturb areas greater than or equal to 1 acre. The purpose of the SWP3 is to identify and address potential sources of pollution that are expected to affect the quality of stormwater discharges from the construction site, including off-site material storage areas, overburden and stockpiles of dirt, and borrow areas. The CGP includes requirements for operators to develop and implement an SWP3 and best management practices (BMPs) and obtain authorization to discharge stormwater from TCEQ before commencement of construction activities. A Notice of Intent (NOI or application) to obtain stormwater CGP authorization is required for construction activities that disturb large construction sites (5 acres or greater), or part of a larger common plan of development that disturbs 5 acres or greater. The required contents of the SWP3 are based on federal Phase II rules related to stormwater permitting, as well as on current TPDES general permits for small and large construction sites based on federal Phase I rules.

- Federal Regulations:
    - 40 CFR Part 122: Subpart B: Permit application and Special NPDES program requirements
        - 122.26(b)(14)(x) and (b)(15): Includes stormwater program that covers the construction regulations
        - 122.28: General permits
    - 40 CFR Part 450: Subpart B: Construction and Development Effluent Guidelines
        - 450.21: Includes effluent limitations for erosion and sediment controls from construction sites
- State Regulations:
    - 30 TAC Chapter 205: General Permits for Waste Discharges
    - 30 TAC Chapter 305.541(a)(9): adopts by reference 40 CFR Part 450.

3.3 Use of Stormwater Best Management Practices

The Construction General Permit requires operators to develop and implement BMPs to minimize or prevent pollutants in stormwater runoff from construction sites. Stormwater BMPs are defined as schedules of activities, prohibited practices, maintenance procedures, and other management practices to prevent or reduce the discharge of pollutants. These BMPs include structural controls, erosion and sediment control, stabilization practices, and non-structural controls such as inspections, and maintenance and operating procedures. TCEQ requires operators to develop and implement BMPs before beginning construction activities that disturb the soil.

- Federal Regulations:
  - 40 CFR Part 122: Subpart B: Permit application and Special NPDES program requirements
    - 122.26(b)(14)(x) and (b)(15): Includes Stormwater program that covers the construction regulations
    - 122.26(c)(1)(ii)(C): operators shall provide BMPs to control pollutants in stormwater discharges during construction
    - 122.28: General permits
  - 40 CFR Part 450: Subpart B: Construction and Development Effluent Guidelines
    - 450.21: Includes effluent limitations for erosion and sediment controls from construction sites
- State Regulations:
  - 30 TAC Chapter 205: General Permits for Waste Discharges
  - 30 TAC Chapter 305.541(a)(9): adopts by reference 40 CFR Part 450.

3.4 Final Stabilization and Terminating Coverage

The stormwater CGP requires operators to meet final stabilization requirements before terminating coverage of their general permit authorization. The requirements of final stabilization are critical in the process of CGP authorization. Final stabilization requires that all soil-disturbing activities at the site be completed and that uniform cover of perennial vegetation, native to the area and with a density of at least 70%, has been established before termination. This does not apply to paved areas, permanent structures, or areas where equivalent permanent stabilization measures have been employed. Alternative requirements are available to sites in arid, semi-arid, and drought-stricken areas.

Site operators are then required to remove any temporary BMPs that have been implemented at the construction site, complete the site notice requirements as necessary, and submit a Notice of Termination if a Notice of Intent was submitted for a large construction site.

3.5 Industrial Hazardous Waste Related Rules

TCEQ oversees rules related to Industrial and Hazardous Waste (IHW) in Texas. These rules are relevant to varying degrees to the questions of operating and disposing of solar, wind, and battery storage systems in Texas, particularly when related to recycling of infrastructure, which may or may not generate waste that meets the criteria for hazardous material. These IHW rules specify for generators of waste streams classification protocols, according to state and federal requirements. Below are rules that are in place for classifying and managing material that falls under IHW rules, with short explanations, when relevant.

- 30 TAC Chapter 335 Subchapter A: Industrial Solid Waste and Municipal Hazardous Waste in General
    - Permit and Notification Requirements
    - Recordkeeping Requirements
    - Standards and Criteria for Variances
    - Recycling Requirements
- 30 TAC Chapter 335 Subchapter H:

  This rule addresses the management of "Universal Waste" that includes waste batteries. As recently as July 2024, TCEQ has been working to address "large format" batteries that include those used for electric vehicles (EVs). EV batteries more often use what are known as NMC (Nickel Manganese Cobalt) and NCA (Nickel Cobalt Aluminum) chemistries (see Chapters 5 and 6). All large format batteries are specifically prohibited from disposal in municipal landfills. TCEQ has articulated a process for recycling batteries that follows specific steps. While these steps (Figure 3.1) and the related website are specifically related to mobile, EV, batteries, they will also apply to utility-scale battery storage systems that use lithium-iron-phosphate (LFP) chemistry, which is the subject of this report. And, while LFP batteries are recycled less often than NMC and NCA batteries, given the lower value of metals contained in them, new and innovative strategies (e.g., da Silva Vasconcelos et al., 2023) could lead to more recycling in the future.
- 30 TAC Chapter 335 Subchapter O: Land Disposal Restrictions –
    - Subchapter O applies to waste that is classified as hazardous in accordance with 30 TAC Subchapter R - Waste Classification. Subchapter O identifies hazardous waste that is restricted from land disposal and defines limited circumstances under which an otherwise prohibited waste may continue to be land disposed. Subchapter O sets guidelines to ensure safe waste management practices.
- 30 TAC Chapter 335 Subchapter R: Waste Classification –
    - These rules provide requirements for classifying and coding industrial and hazardous waste in Texas, whether the waste is generated in Texas, or those generated outside of Texas but brought here for treatment, storage or disposal. If industrial waste (solar panels or wind turbines) fails the Toxicity Characteristic Leaching Procedure (TCLP) test and releases toxic materials to the environment, it is classified as hazardous waste. In such instances, waste recyclers and handlers are required to manage the waste in accordance with 30 TAC Chapter 335, based on its classification as Class I, II, III, or hazardous material. Industrial hazardous waste batteries are subject to management under Subchapter H – Universal Waste regulations, which provide specific requirements for their proper handling. For further details, please refer to TCEQ (2024b).
- 30 TAC Chapter 335 Subchapter V: Standards for Reclamation of Hazardous Secondary Materials –
    - These rules are relevant for recyclers who manage hazardous materials contained within solar panels (for example, cadmium, copper, lead (in older panels), and others), regardless of whether the panel passes the TCLP test. In

this case, TCEQ is notified that generators are sending the material to a processor and that receivers have received it for recycling. The secondary materials stemming from recycling are regulated under this subchapter, but they are not discussed further in this report, given that most secondary materials enter other industrial circuits as input inventory for new products.

Figure 3.1 TCEQ diagram that describes, graphically, the steps for end-of-life management of batteries (from TCEQ, 2024a).

3.6 Remediation Related Rules

- 30 TAC Chapter 350 Texas Risk Reduction Program:
  - This chapter addresses releases of chemicals of concern (COC) as defined by various programs subject to this chapter, as well as remedy standards, protective concentration levels, reporting requirements, and additional measures to protect public health and the environment.
- 30 TAC Chapter 335 Subchapter K: Hazardous Substance Facilities Assessment and Remediation:
  - This subchapter establishes an assessment and remediation program for facilities that may pose imminent and substantial danger to public health, safety, or the environment due to the release of hazardous substances.
  - Other relevant statutes are found under Texas Health and Safety Code, Chapter 361, Subchapter F, Registry and Cleanup of Certain Hazardous Waste Facilities.
- Several relevant statutes are also found in the Texas Water Code, specifically those found under Chapters 7 and 26. The cited statutes in Texas Water Code Chapter 7 address *criminal* liability. TCEQ also has authority for administrative and civil enforcement of TCEQ rules, statutes and permits, including injunctive authority to require a person to take certain actions or refrain from certain actions and to assess penalties:

- Sec. 7.145. Intentional or Knowing Unauthorized Discharge. (a) A person commits an offense if they intentionally or knowingly discharge or allow the discharge of waste or a pollutant.
- Sec. 7.147. Unauthorized Discharge. (a) A person commits an offense if they discharge or allow the discharge of any waste or pollutant into any water in the state that causes or threatens to cause water pollution
- Sec. 26.039. Accidental Discharges and Spills. Of particular importance is 26.039(c), which states "Activities which are inherently or potentially capable of causing or resulting in the spillage or accidental discharge of waste or other substances and which pose serious threats of pollution are subject to reasonable rules establishing safety and preventive measures which the commission [TCEQ] may adopt or issue. The safety and preventive measures which may be required shall be commensurate with the potential harm which could result from the escape of the waste or other substances." This rule pertains to surface runoff that could leave a facility and enter a surface water body, or spillage or deposition of material onto the ground that percolates downward toward the groundwater table. In both cases, operators are required by regulations to prevent or mitigate risks of off-site contamination.
- Sec. 26.041. "Health Hazards. The commission [TCEQ] may use any means provided by this chapter to prevent a discharge of waste that is injurious to public health."
- Section 26.121(c). "No person may cause, suffer, allow, or permit the discharge of any waste or the performance of any activity in violation of this chapter or of any permit or order of the commission."
- Texas Health and Safety Code, Chapter 361, The Solid Waste Disposal Act. The statutes in THSC Chapter 361 provide authority to TCEQ for regulation of solid waste (Sec. 361.017) and establish the liabilities and requirements for persons responsible for solid waste (Sec. 361.271).

3.7 Regulations Related to Wind and Solar Generation in Texas

3.7.1 HB 2845

House Bill 2845 (HB 2845) was passed into law by the 86th Texas legislative session in 2019. HB 2845 amended Title 6, Utilities Code, and added Chapter 301, which pertains to wind power facility agreements. The statute defines wind power facilities as including wind energy devices and ancillary equipment that supports the facility, including transmission lines, transformers, and battery storage facilities, among others. It identifies operators of wind power facilities as being responsible for removing equipment from the landowner's property, cleaning the property of infrastructure, roadways, etc., and returning the property to "tillable state," and/or as near as reasonably possible to the same condition as before the facility was installed. The statute specifies that the property be returned to original condition within 180 days of when the wind facility is no longer "generating electricity in commercial quantities" or after the facility operator notifies the landowner of the intent to decommission. The statute includes financial surety and related bonds that are sufficient to restore the land, with updated estimates available to the landowner every 5 to 10 years.

3.7.2 SB 760

Senate Bill 760 (SB 760) was passed into law by the 87th legislative session in 2021. It was written with similar stipulations to those for wind power generation. SB 760 amended Title 6, Utilities Code, and added Chapter 302, which pertains to solar power facility agreements. The statute defines solar power facilities as including solar energy devices and ancillary equipment that supports the facility, including transmission lines, transformers, and battery storage facilities, among others. It identifies operators of solar power facilities as being responsible for removing equipment from landowner's property, cleaning the property of infrastructure, roadways, etc., and returning the property to "tillable state," and/or as near as reasonably possible to the same condition as before the facility was installed. The statute specifies that the property be returned to original condition within 180 days of when the facility is no longer "generating electricity in commercial quantities" or after the facility operator notifies the landowner of the intent to decommission. The statute includes financial surety and related bonds that are sufficient to restore the land, with updated estimates available to the landowner every 5 to 10 years.

4. Topics Related to Installation and Operation of Solar, Wind, and Battery Systems

SB 1290 specified the need to assess the impacts of solar, wind, and energy storage systems during installation, operations, and disposal. In this chapter, we touch on the installation and operations phases of these systems, focusing mostly on land impacts (both positive and negative) and the potential impacts of weather and related events on the environmental performance of these systems. (Discussions about disposal are in subsequent chapters). This chapter does not address the question of impacts to viewshed, soundshed, etc., from the deployment of these systems. Our interpretation of SB 1290 is that the mandate of the bill is to focus more on potential impacts to the natural environment and watersheds.

We present this chapter by breaking down our understanding of positive and negative impacts for installation and operation life cycle phases, for each energy system studied (when appropriate). We approach this chapter in this way because some environmental impacts from solar and wind generation facilities are beneficial and others detrimental; mostly they are varied and often depend on preexisting conditions and the type of site work. Impacts can include biodiversity gain or loss, soil degradation from compaction, sealing, erosion, drying, improved crop yields, and habitat enhancement. Two critical factors influencing whether impacts from solar or wind development projects are positive or negative include site selection and project planning and management. We also pay special attention to the potential for battery fires (see section 4.3).

4.1 Installation

4.1.1 Positive Impacts

- None identified for installing either solar, wind, or battery storage system projects.

4.1.2 Negative Impacts

- Land erosion – (solar energy, wind energy, and energy storage) - Erosion during construction of any subject energy facility is addressed through the SWP3 that is developed and implemented before site construction begins. Facility operators are required to develop and implement an SWP3 before applying for SWP3 authorization under the Construction General Permit, TXR150000. During construction of solar facilities, more so than at wind energy facilities, disturbed land is more susceptible to flooding and erosion from substantial precipitation events. Therefore, companies are required by permit stipulations to control runoff and subsequent erosion before the eroded material leaves the regulated site. Construction of berms, stormwater detention structures, and other features to reduce runon and runoff are options available for complying with the stormwater construction SWP3.
- Land fragmentation – (solar energy, wind energy, and energy storage) - Choosing a site for solar, wind, or battery storage should account for the potential impacts of fragmenting and perforating intact landscapes on large-scale land quality and ecosystem function. Solar facilities, generally contiguous and occupying 100s to 1000s of acres of

land, can alter large areas, especially if the land is graded, cleared of vegetation, and grubbed of plant roots. Wind energy facilities are constructed differently, with large spacing between wind turbines, often spaced at some multiple of blade length. Each turbine site requires 3 to 4 acres of land (Denholm et al., 2009) for the turbine tower and support area, each requiring roadways. These pads and roadways perforate and subdivide intact landscapes, degrading landscape and ecosystem quality during construction and throughout the operation of the turbine (Arnett et al., 2007). With the existence of more than 15,000 turbines in Texas, the potential exists for large-scale ecosystem change in the windy areas where turbines are installed, even given that much of the original vegetation on these lands has already been converted to agricultural production, and that the spaces between the turbines are often used for various agricultural purposes. Avoiding sites proximal to fragile landscapes and using land-related BMP's can reduce impacts from land fragmentation.

4.2 Operations

4.2.1 Positive Impacts

- Reduced land erosion – agricultural or brownfield lands that are converted to solar with land stabilization (vegetation, berms, ripping, and reseeding) efforts could result in lower erosion. Although field data are sparse, modeling studies have shown that maintaining vegetation below the panels, using vegetation strips between solar modules resulted in reduced peak runoff and erosion, when compared with site conditions of either gravel or bare soil (Cook and McCuen, 2013). Mulla et al. (2024) monitored and simulated soil moisture conditions and drip-edge runoff at solar facilities located in several states (Colorado, Georgia, Minnesota, New York, and Oregon). They reported substantial infiltration between panel arrays, such that the facilities could be treated as disconnected impervious surfaces in stormwater permits. Field-scale monitoring data, which is lacking, could help validate these numerical modeling studies.
- Enhanced biodiversity and ecosystem services – large intact land areas used for solar energy generation that are reseeded to enhance vegetative covers can lead to a more diverse groundcover and biodiverse landscape that includes pollinators and other valuable vegetation.
    - Solar - Different studies of solar generation facilities have reported environmental gains and losses. Montag et al. (2016), in a technical report, studied habitats at solar generation facilities and similar undeveloped control and reclaimed cropland plots in the UK, finding that solar facilities were associated with greater or comparable ecological diversity. Different management practices (e.g., seeding, grazing, mowing routine, hedging, and non-use of herbicides) were implemented among the 11 studied solar generation facilities. Seeding, non-use of herbicides, and grazing were the most influential practices in enhancing biodiversity. These facilities, we note, were not part of any agrivoltaics programs, where agricultural production on operating solar facilities is intended and incorporated into the design of the facility itself.
    - Wind - Positive impacts have also been reported that include increased biodiversity and improved soil health, which also have occurred from wind development, especially if wind turbines are installed on already-converted land,

such as agricultural land or brownfields (Xu et al., 2019; Bennun et al., 2021). Research has also shown that the carbon opportunity costs of wind energy development on cropland and pastureland are well below those for peat or forestland (Albanito et al., 2022). Well-planned wind energy development on previously converted land can improve habitat health through revegetation and breaking up homogenous landscapes (Bennun et al., 2021). Turbines themselves introduce greater airflow to the surrounding area, mitigating fungus and bacterial growth and regulating air and soil processes that can increase crop yield (Nazir et al., 2020; Bennun et al., 2021; Liu et al., 2023). Crop impacts are likely location- and species-specific.

- Opportunities for Agrivoltaics – In addition to creating ground cover, some solar energy sites are designed for dual use of both energy development and agricultural production. These are promising opportunities for mitigating the environmental impact of solar energy development or even providing environmental benefits. Agricultural production in this sense often includes grazing and foraging but can include low-height, high-value crops. For example, Yavari et al. (2016) and Barron-Gafford et al. (2019) found that the soil environment below the panels (e.g., soil temperature, soil moisture, and plant evapotranspiration rates) were conducive to improved vegetative and soil health, even in arid settings. Studies (Taylor et al., 2019; Yavari et al., 2022) have shown that plant biodiversity and biomass can either increase or decrease at different solar generation facilities, highlighting the site-specific nature of the impacts. Vervloesem et al. (2022) studied negative land impacts of a solar facility and found they were lower than those of a wheat field; thus, converting intensive cropland to a solar facility provided environmental benefits through increased biodiversity. Federal programs (usually through US DOE and USDA) are being focused on developing efficient dual usage of lands for solar development and agricultural production (e.g., US DOE, 2024; OpenEI, 2024).

4.2.2 Negative Impacts

- Increased Land Erosion - Potential exists for increased erosion of soil, depending on the pre-operations land quality, soil type and conditions, land slope, and other factors that are site specific. Before construction, undisturbed lands converted to solar could become more erosive, although stormwater construction permits are required before any site work can begin and even before financing is available. The stormwater CGP is written to reduce the discharge of pollutants from soil disturbing activities related to a construction site by requiring preventive measures from construction site operators, such as the development and implementation of a SWP3, BMPs, and monitoring requirements to ensure compliance.
    - Solar Energy - In some cases, land altered through blading and devegetation and then covered with gravel before installation of the facility can notably reduce long-term soil and land quality. In addition to issues of land quality during and after construction, solar generation facilities in arid climates run the risk of disrupting hydrological connectivity across the facility, which may increase erosion and dust emission potential (Hernandez et al., 2014), depending on how geomorphic feedback is considered during the design (Liu et al., 2023). Moreover, construction that removes vegetation can increase the likelihood of

flooding and soil erosion by water (Dhar et al., 2020). Yavari et al. (2022) reported that most states do not recommend or mandate specific site-protection activities beyond those in the SWP3 that are required before construction can begin. They also indicated that some states recommend actions to (1) minimize site disturbance during construction, (2) ensure enough space between rows of solar modules to facilitate infiltration of stormwater, and (3) reduce surface runoff. By designing and deploying a vegetation-management program that is codesigned with the facility's staff, ecosystems and soil health can be improved, and surface runoff and erosion can be reduced.

  - Wind Energy - Adverse land impacts from wind generation facilities are generally categorized into two bins: direct impacts from land use change and those that account for edge effects, often calculated as multiple of turbine blade length. Direct impacts arise from direct change in land use from original condition into land that hosts infrastructure including turbine towers, platforms, roads and pavement, substations, and transmission lines. Previous land cover and land use, especially in West Texas, where wind energy density is the highest, often is occupied by native vegetation and used for agricultural activities like grazing, irrigated croplands, etc. Direct impacts that lead to soil degradation (e.g., drying, compaction, and erosion) have been documented widely in literature (e.g., Vaithiligam et al., 2023; Wang et al., 2023). Edge effect impacts are less tangible or quantifiable, but they include degradation of intact landscapes that promote habitats, animal migration routes, etc. (Harper et al., 2015; Pierre et al., 2020).

- Offsite flooding –
  - Solar Energy - Like the situation for land erosion, and the much larger spatial footprint needed for solar energy facilities (often 100s to 1000s of acres) offsite flooding can be an important consideration for industry as well as those downgradient of the solar facility who could experience impacts from surface runoff from facility.
  - Wind Energy and Energy Storage – Given the distributed nature of wind turbine placement, and the relatively small footprint for energy storage systems (which are probably similar in size to many commercial facilities), offsite sedimentation is less likely to be an issue.
- Impacts to wildlife –
  - Solar Energy - Given that solar power generation relies on infrastructure with no moving parts, animal harm from collisions is a lower concern. Some instances of bird fatalities from solar panels have been reported, though the rate of bird deaths is far below that from traditional power facilities (Walston et al., 2016; Nordberg et al., 2021). Mammalian wildlife displaced during construction probably will not return directly to the same land parcel, as these facilities are almost always protected by fencing. However, with available fencing to discourage predators, solar arrays can provide protection and structural habitat for nesting or perching, which are beneficial to birds and insects (Nordberg et al., 2021).
  - Wind Energy - The direct negative effects of wind generation facilities on animals, particularly avian species, can include death, injury, and displacement. Wind turbine blades impact birds and bats, known as bird strikes, and disrupt bird migration (Kikuchi, 2008; Vaithiligam et al., 2023). Although researchers have shown that the number of birds killed by wind turbines is smaller than

several other causes unrelated to the energy industry (Loss et al., 2013), researchers and industry have both noted that design changes to the wind turbine blades (e.g., by painting one blade black) can substantially reduce bird strikes, by as much as 70 percent (May et al., 2020). Other technologies used in wind turbine design, such as using monopoles rather than lattice poles (like those on cell phone towers), as is common today, can reduce bird nesting on the poles themselves and subsequent mortality through collision. The noise from wind turbines can also impact animals, which avoid atypical and loud acoustic signals by fragmenting populations, resulting in decreased genetic diversity as well as behavioral changes. Livestock, co-located under or proximal to wind generation facilities, are not generally affected by turbines (Adeyeye et al., 2020).

- Susceptibility to hazards – Each of the energy systems considered here can be susceptible to environmental hazards that stem from weather events, including hailstorms, tornados, hurricanes, and wildfires, and the flooding (or debris flows) that often accompany many of these events. Indeed, the weather events are not necessarily the issues themselves—except for the potential for equipment to become dislodged and relocated during a tornado or hurricane. Rather, the aftermath of the event is more important from the standpoint of environmental protection.
    - Solar Energy – Solar panels and modules are susceptible to damage from hailstorms and potentially from high winds from tornados or hurricanes. From the standpoint of hailstorms, one recent event in Texas (Fighting Jay's Solar Farm in Fort Bend County in March 2024) that damaged 1000s of panels was covered extensively in the media. This facility began construction in 2021 and occupies approximately 3,000 acres of land. The facility was reported to be back online in June 2024. The concern from events like that at Fighting Jay is that damaged equipment can become exposed to atmospheric conditions (sun and water) and leach metals from the electronic components in the panels. However, because the electronic equipment in the panel is encapsulated using ethylene vinyl acetate sheets and glass laminate (i.e., the top layer of silica glass), the risk of leaching metals from exposure to moisture is reduced. We are aware of one study (Sharma et al., 2021) that did show some leaching of lead from panels with encapsulation, using fluids that simulated the natural environment, which is known as the Synthetic Precipitation Leaching Procedure (SPLP) (USEPA, 1992); however, the SPLP test (similar to the TCLP) used in their experiment was designed to simulate uncontrolled disposal of panels over the moderate to long term (3–10 years; Kimmell and Friedman, 1986), rather than the impacts of damaged panels that are replaced after a reasonable amount of time. Thus, for the weather-related hazards considered here, the risks of leaching are minimal.
    - Wind Energy – Wind turbines are generally designed to withstand wind velocities of more than 100 mph without damage, although several online media reports and videos show crumpled wind turbine towers and damaged and missing blades resulting from tornados. To our knowledge, research reports have not considered whether damaged wind turbine blades pose an environmental hazard (e.g., from leaching of broken blades). Given the low leachability of materials that compose turbine blades and the relatively rapid cleanup efforts that can be expected around the facilities (i.e., to maintain good housekeeping but also to maintain income from electricity generation from the

facility), the risk of leaching and dispersion of materials is likely very low to zero. The research papers identified on this topic (e.g., Letson et al., 2020) focus more on the effects on turbine efficiency from hailstone impacts on the leading edge of the turbine blade. Thus, in general, other than physical impacts from falling material, impacts to the environment and watersheds are minimal.

- Energy Storage (Batteries) – For most weather-related events (hailstorms, hurricanes, and subsequent flooding), BESS facilities are less likely to be susceptible to damage, given that the battery packs are protected by reinforced physical structures like steel transportainers and other structures that are (or should be) designed to withstand design-basis events. Risks from floods can be further reduced through use of berms to protect from runon events and to provide secondary containment against the potential for chemical release or use of water to cool structures adjacent to an overheating or burning unit.

4.3 Issues Related to Battery Fires

Of notice and concern—and one worth a separate category—is the risk of a battery fire or a thermal runaway[1] (TR) that could create hazardous conditions for first responders, fire fighters, facility neighbors, and the environment. The Electric Power Research Institute (EPRI) has conducted research into the failure of BESS, tracking failure incidents in terms of number of incidents and incidents per GW of total storage per year (EPRI, 2024). The EPRI report lists a total of 86 events, dating from 2011, and a total of 4 events indicating a thermal runaway[1]. Failures per GW of storage capacity have fallen well below one incident per GW of storage, even though the number of total incidents hovers between 10 and 15 per year (EPRI, 2024).

Batteries and battery systems are subject to substantial design criteria, testing and certification before they can be deployed. These design criteria and installation criteria are generally required by municipal code before they can be permitted and installed. For example, UL 9540 (UL LLC, 2024) focuses on design criteria for batteries, whether a single battery cell, a module of cells, or a unit of modules. Test method 9540A (UL LLC, 2024) is the testing standard used in the U.S. and Canada for stationary batteries, such as those used in energy storage systems. UL 9540A is referenced in NFPA 855 (2023), which includes standards for installing stationary batteries. The UL 9540A testing methodology determines the potential for a particular battery technology or design to withstand a fire and to mitigate the potential for an explosion or TR. Tests are done at the cell, module, unit (also called packs), and installation levels and standards are created that are incorporated into municipal codes. When the cell design passes the testing standard, UL then tests the module (a collection of cells) and, after it passes with more complex safety measures, UL tests the units (or packs) (a collection of modules) and then proceeds to the full installation level. Throughout the process, UL tests the venting systems and ensures that the batteries are kept safe through ventilation. If the cell is shown not to vent flammable gases or is not driven to TR, then the cell is considered as safe as any electrical equipment. Module-level tests study the potential for TR propagation by measuring gas production, temperature increases, smoke release rate, and other criteria. If modules pass the test, then TR is assumed to be contained by the module design. Scaling up the tests to the installation (or facility) level, UL identifies design features that include gas detection, fire suppression, communication to first responders, and other safety measures. These systems must pass all criteria before they are certified, assuming the specific municipality adopts the UL standards.

[1] A thermal runaway is one of the primary risks related to lithium-ion batteries. It is a phenomenon in which the lithium-ion cell enters an uncontrollable, self-heating state (UL.org).

4.4 Use of Best Management Practices

Developers and builders of wind and solar generation projects can channel conservation and even benefit lands environmentally, given that conservation considerations are codesigned into the energy generation project. Choices that industry makes during the planning process can influence the impacts of wind and solar developments on land quality. For example, during pre-development, industry should create a plan for site decommissioning and reclamation to ensure compliance with state and federal regulations (e.g., stormwater pollution prevention) and follow best management practices throughout facility operations (Moore-O'Leary et al., 2017; Dhar et al., 2020). During construction of solar and wind generation facilities, developers can use rain, grey, or other forms of recycled water to reduce stress on the ecosystem (Dhar et al., 2020). Following the completion of soil disturbing activities, sites authorized to discharge stormwater from a construction site are required to meet final stabilization requirements prior to terminating their general permit authorization coverage. These requirements include completion of soil-disturbing activities, removal of any temporary BMPs, and a vegetative cover with at least 70% of coverage on areas that are not paved or are covered by permanent structures, or areas with equivalent permanent stabilization measures.

Dhar et al. (2020) reported on topsoil protection and other conservation practices during land reclamation that either restores developed land to its original state, if the land requires such intervention, or ensures that enhancements remain during decommissioning. Techniques recommended by Dhar et al. (2020) include reseeding, targeted fertilization, tilling, and mulching to preserve topsoil health and diversity throughout the lifetime of the wind and/or solar generation facility and during decommissioning. Proper soil management from the start of development to the end of reclamation can lessen impacts from wind and solar energy generation and can ultimately improve site conditions. We note also that Texas regulations (SB 760 – related to removal of solar power facilities [2021] and HB 2845 – related to removal of wind power facilities) already outline specific land reclamation goals that industry must meet when decommissioning lands used for wind and solar energy generation.

5. Literature Assessment of Potential End-of-Life Alternatives

5.1 Solar Energy Technology

Solar energy plays a major role in energy production in Texas, accounting for 6.26% of generation in 2024. Texas is among the top states with the highest capacity for solar power generation; according to the U.S. Energy Information Administration (EIA), Texas ranks second in solar power production in 2024 (SEIA, 2024), behind only California. Within the past decade, solar power capacity in Texas has grown much, and is expected to grow to around 40,000 MW at the end of 2025 (ERCOT, 2024a). Given the recent announcements by ERCOT that electricity demand is likely to increase by an additional 40,000 MW by 2030 (ERCOT, 2024b), we can anticipate a large increase in solar capacity as well. The ramp up of the construction of solar energy facilities means that, eventually, decisions will need to be made, to address questions about EoL options and to assess which are most efficient and environmentally protective pathways.

5.1.1 Recycling

Methods for recycling photovoltaic (PV) modules include mechanical, thermal, and/or chemical treatment processes (Camargo et al., 2023; Feng et al., 2023). In all three processes (Figure 5.1), the first step is manual or mechanical removal of the junction box and frame, followed by separating and recycling of the laminated structure, mostly using mechanical treatment (e.g., shredding, separation by hot knife or wire, or scraping glass or plastic layer) (Ko et al., 2023). Using a combination of thermal and chemical treatments, along with mechanical processes, recovered materials are sorted and sent to other facilities as secondary materials or products. These resulting materials are transported to other locations for additional handling, which could include landfilling or additional refining, including smelting, direct use in secondary markets, incineration, and so forth. For example, additional handling could include glass recycling (Ansanelli et al., 2021), reuse of ferrous and nonferrous metals in secondary markets, or the smelting of metals that were incorporated into crystalline silicon (c-Si) cells (e.g., Si, Ag, and Cu). Often, these metals are transported as Si cells without being separated and are later individually extracted and recycled as secondary materials.

Most recycling processes recover nonferrous metals, such as glass and aluminum frames, whereas certain recycling circuits also recover components from c-Si PV cells, mostly when combined with plastics and polymers (Ko et al., 2023). For thin-film photovoltaic modules, the semiconductor metals used in the PV cell can also be extracted from the glass (Chowdhury et al., 2020; Ko et al., 2023).

Although recycling PV panels offers substantial environmental and economic benefits, it also poses considerable obstacles that must be addressed. For example, recycling is beneficial for retrieving silicon from discarded panels, because it only requires one-third of the energy and cost compared to generating silicon from raw materials, thus decreasing resource utilization over the term (Choi and Fthenakis, 2010). At the same time, recycling is challenging, given the complicated composition of panels and separation of materials from the PV panels. Labor and technological obstacles are further exacerbated by the unpredictable prices and market values of the recovered materials, impacting overall viability. In addition, solar panels can also include heavy metals (e.g., lead, tin, and cadmium); careful handling is needed to reduce impacts on human and environmental health (Bakhiyi et al., 2014).

Recycling can help alleviate these concerns by lowering waste volumes and limiting environmental impacts caused by leaching of materials. An additional considerable obstacle is the technological diversity of solar modules (e.g., crystalline silicon versus cadmium-telluride) and the related recycling procedures. While recycling routes for these different panel chemistries are maturing, establishing standardized recycling techniques is more difficult, complicating efforts to optimize operations and save costs (Cucchiella et al., 2015). In the absence of established procedures, the costs associated with collecting, transporting, disassembling, and treating panels can exceed the value of recovered materials. Specific information on PV panel recycling routes can be found in Appendix D (Table D.1).

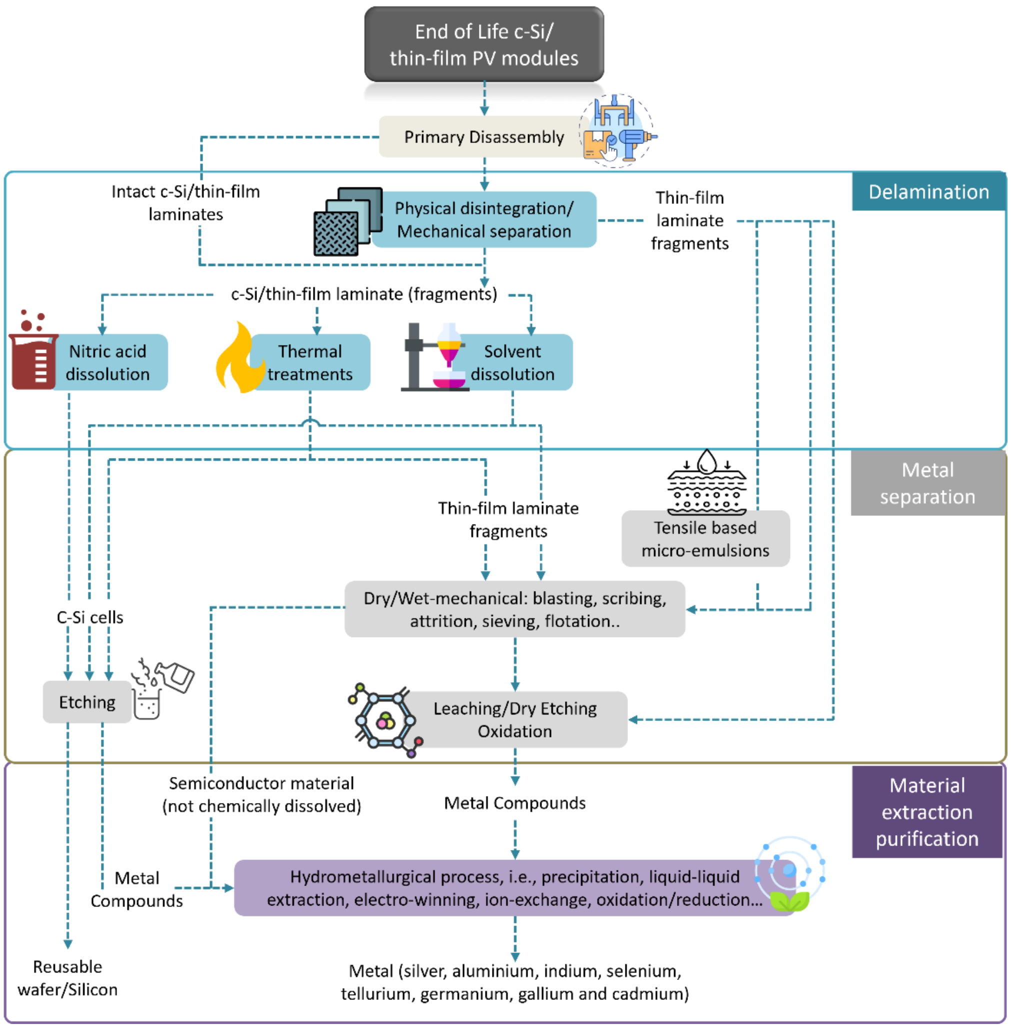


Figure 5.1 Various possible recycling routes considered in the literature (Ansanelli et al., 2021; Ko et al., 2023)

5.1.2 Reuse

Reuse is another approach for extending the life of solar panels, reducing waste volumes, optimizing resource efficiency, and promoting sustainability. One approach entails refurbishment and repair, during which modules undergo an evaluation to detect any faulty components and to ensure the module generates electricity according to a predetermined specification. Improved warranties for refurbished modules might also stimulate secondary markets (Salim et al., 2019). Other strategies to promote reuse could be “short term seeding,” which provides complementary modules and installation to some PV proprietors (Walzberg et al., 2021).

Engaging in collaborative efforts with local communities creates opportunities for reuse, either near the original deployment location or elsewhere. Solar panels no longer meeting utility-scale specification may be sufficient to provide energy for other community amenities (e.g., street lighting) and potentially for powering small-scale independent systems. The decentralized strategy used in these independent systems enables communities to use solar energy according to their individual requirements, thereby promoting resiliency and sustainability. For example, some panels could be used in countries where the average household electricity consumption can be just 500 kWh per year, or lower (IEA, 2022; Panos et al., 2023). In such locations, older panels can still power homes, devices, and machinery with lower electricity demands.

5.1.3 Disposal in Landfills

As indicated above in Chapter 3.5, Texas already has regulations (30 TAC Chapter 335 Subchapter O: Land Disposal Restrictions) that allow solar panels to be disposed in landfills. Specifically, operators must determine whether solar panels exhibit characteristics of a hazardous material, such as ignitability, corrosivity, reactivity, or toxicity. Often this is done using the TCLP test that assesses leachability of material from the panels in a landfill environment. Nevertheless, even with these regulations in place, landfilling of panels can take place, potentially contributing to a variety of issues. For example, studies have shown that metals (especially lead) in damaged and abandoned solar cells could eventually leach into soil, irrespective of the design innovation (Sharma et al., 2021). Zapf-Gottwick et al. (2015) reported that a landfilling period of only 56 days could result in the release of over 15% of lead from c-Si panels. Nover et al. (2017) documented that 1.4% of lead was released from a sample size measuring just 5×5 cm^2 of c-Si panel fragments, whereas 62% of cadmium was released from cadmium telluride (CdTe) pieces under low pH circumstances after 360 days.

To date, researchers have mostly focused on investigating the risk associated with exposure to lead and cadmium, owing to their potential carcinogenicity. According to research findings, the potential risk of heavy metals was generally below regulatory values, considering their present disposal rate. Nevertheless, research is limited to the conditions under which leaching of constituents from damaged panels could be problematic. This was noted by Nain and Kumar (2022), who highlighted uncertainties in exposure scenarios, module breaking rates, and estimates of exposure concentrations. Research could be done across a wider range of conditions expected in Texas, or guidelines can be created that limit the period during which damaged panels with exposed electronics are allowed to remain in the field.

5.2 Wind Energy Technology

Texas hosts the highest wind energy capacity in the United States, having an installed capacity of over 41,500 MW in 2023. The high contribution of wind energy generation stems from several factors, including favorable wind conditions, particularly in the Panhandle and West Texas, available transmission line infrastructure that allows electricity to be transported to load centers in the Dallas-San Antonio-Houston regions, and the rural and wide-open character of the region that facilitates installation and operation of wind turbines.

As described above, all infrastructure has a lifespan that can be expected under normal conditions, but that can be shortened by unplanned weather (e.g., hailstorms) or other events (e.g., repowering). When these wind turbines are no longer generating electricity at anticipated or required rates, they must be decommissioned and managed according to existing regulations (especially HB 2845), and in a manner that is economically viable and environmentally sustainable. In this chapter, we provide information on the options available, focusing on wind turbine blades; the other major components include the tower, nacelles, gearboxes, and other parts that are made of steel and other valuable materials that are recyclable.

5.2.1 Recycling

Recycling becomes important when wind turbines are retired or updated, also known as "repowered." For example, materials contained in a typical wind turbine can be broken down into specific materials with variable abilities to recycle (Figure 5.2, after Jensen, 2019). The problem arises in the handling, managing and transporting materials that are present in large quantities in wind turbines, such as fiberglass and steel. Other materials (i.e., iron, aluminum, copper, concrete) and electronic components of wind turbine foundations such as towers, and wiring can be completely recycled (Jensen, 2019).

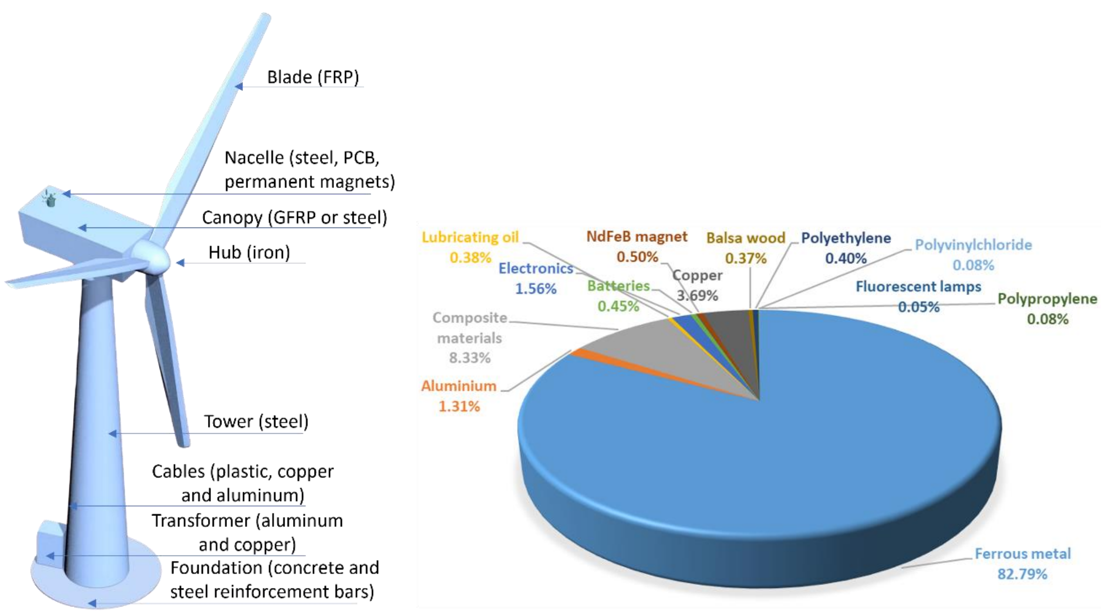


Figure 5. 2 Components of wind turbines with respective mass percentage distribution of material used. (Jensen, 2019).

The prevailing techniques for recycling wind turbine blades (composite materials) mostly consist of a series of steps that include mechanical recycling, thermal recycling, and chemical recycling (Figure 5.3). The mechanical recycling method uses on-site disassembly and either sawing of the blades into smaller units suitable for typical highway travel without an escort and/or the shredding of the blades with mechanical shredders. The selection of machinery, including shredders, crushers, mills, and grinders, depends on the intended final product (Cherrington et al., 2012) and the needs of off-takers who would create beneficial uses of the material. In general, the byproducts of mechanical recycling are used as basic materials, additives, and reinforcements, or in the production of new polymer products or cement with particulate matter emissions and dust due to the grinding of blades, and release of Volatile Organic

Compounds (VOCs) if the blades contain resin or other organic materials that can then contribute to smog formation and have health impacts (Chen et al., 2019).

The thermal recycling procedure enables the recovery of fibers, certain oil fractions, and depending on the specific method, energy via the combustion of the matrix material. The methods include pyrolysis, fluidized-bed pyrolysis, microwave-pyrolysis, and combustion with the operating temperature range of 450°C to 700°C (750°F to 1300°F) (Yang et al., 2022; Yousef et al., 2024). Chemical recycling, also referred to as solvolysis, is a favorable method in terms of the recoverable fibers from recycling wind turbine blades because of the minimal loss of fiber's original mechanical properties. This method uses solvents, with or without catalysts, to degrade and dissolve the resin in composites into monomers, oligomers, or other substances. Ultimately, useful chemicals are produced, and clean fibers are recovered. This is typically accomplished under moderate conditions using supercritical and subcritical fluids (Sokoli et al., 2017). A comparison of each technique, with its competitive advantage and disadvantage, is shown in Figure 5.4.

In addition to mechanical, chemical, and thermal recycling technologies that often are done separately, researchers are investigating hybrid methods to address constraints of individual processes, which can include surface defects, set-up cost, and other considerations. One of these hybrid approaches is microwave-assisted chemical recycling. According to Jani et al. (2022), this hybrid approach is seen as an ecologically sustainable, energy-efficient, and viable recycling solution in the long run. Although it is still in the first phases of investigation, microwave-assisted chemical recycling exhibits potential to reclaim fibers from discarded composite materials, thereby offering a resource for the manufacturing of new composites with a lower environmental footprint.

Other materials present in wind turbines include ferrous metals, mostly steel, which undergo a process of melting, purification, and solidification to be recycled (Stavridou et al., 2020). This procedure preserves raw material resources, lowers energy use (compared to creating primary steel), and minimizes potential environmental impacts linked to mining new materials. Recycled steel also has a well-established secondary market. Besides ferrous metals, copper and aluminum are economically important materials in wind turbines. The process of recycling copper, which can be recycled indefinitely without any degradation in quality (Jensen, 2019), results in energy savings with pyrometallurgical and hydrometallurgical recycling.

Many researchers have examined various recycling and recovery strategies for extracting glass fibers and carbon fibers, with the aim of finding viable secondary applications for these materials so that the material is not routed to landfills. Appendix D (Table D.2) represents such articles in brief.

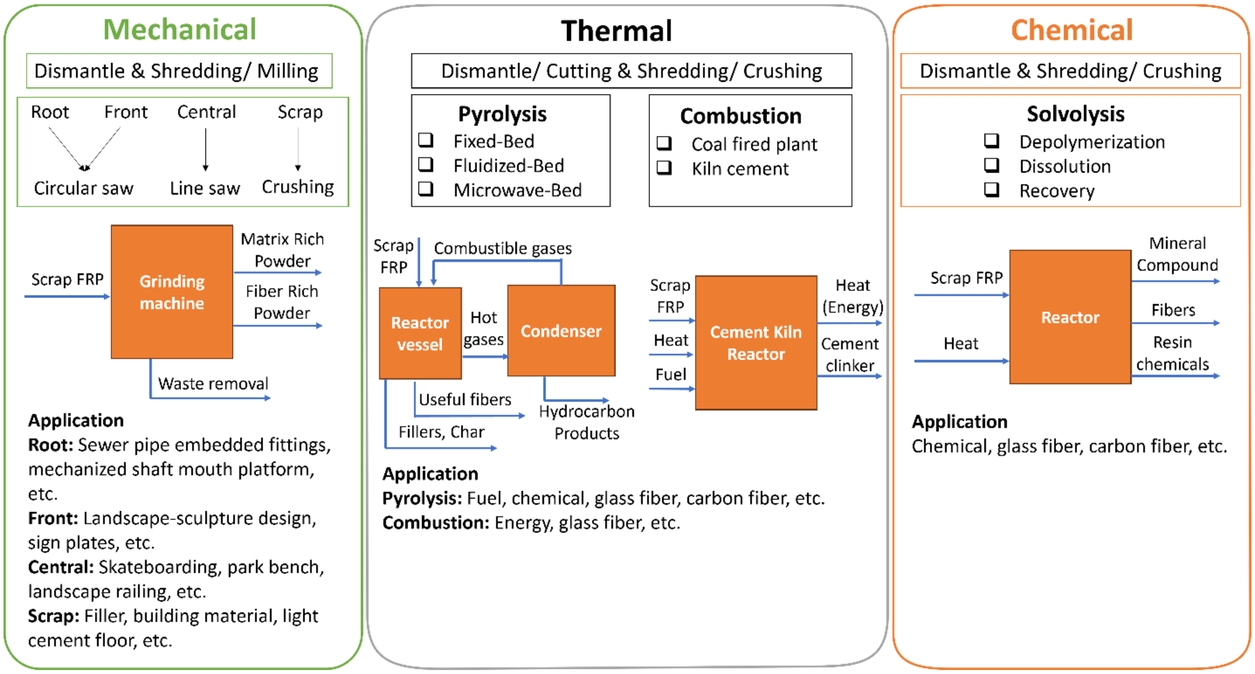


Figure 5.3 Different techniques for recycling wind turbine blades (WTBs)

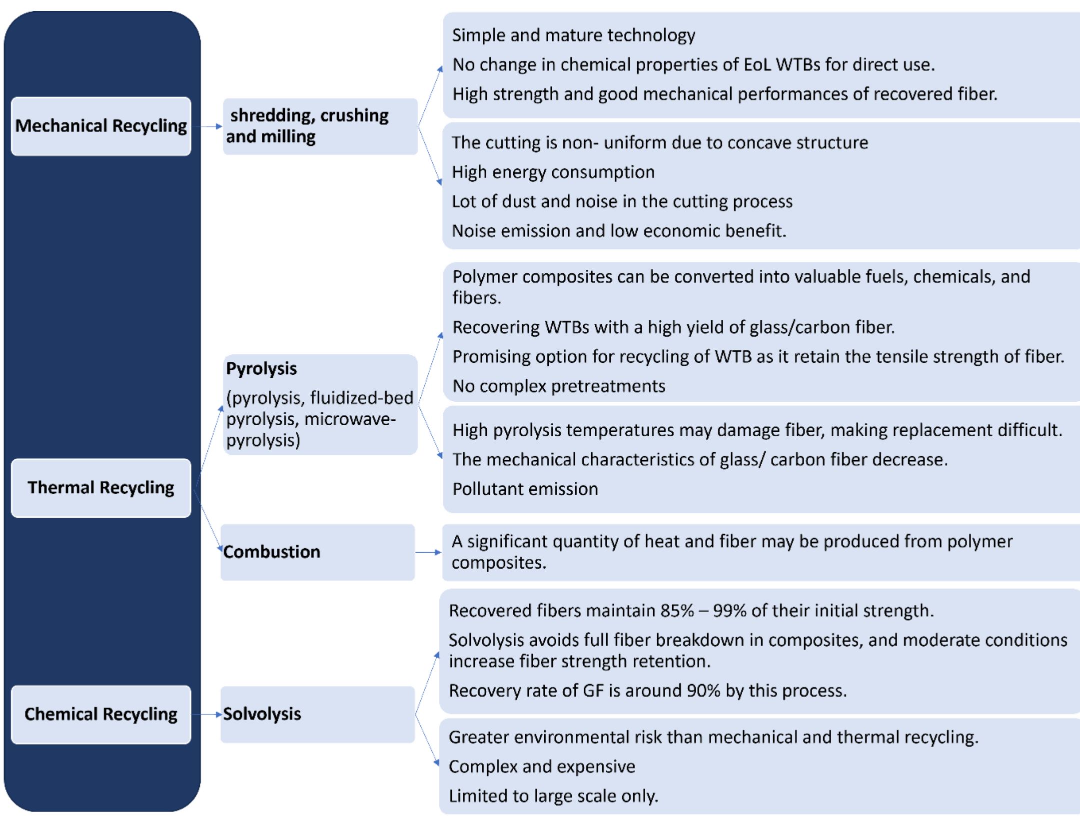


Figure 5.4 Comparison of recycling techniques (Shen et al., 2023)

5.2.2 Reuse

The reuse of wind turbine blades is an important waste management solution that reduces landfill waste. One approach for reusing turbine blades is to repair them after they have completed their initial operational lifespan, allowing them to be reused in wind energy applications (Fitzgerald and Mishnaevsky, 2023). For example, when the blades remain structurally sound, despite the need for maintenance, a process can be implemented to repair damage, fortify areas of weakness, and optimize aerodynamic performance. Commonly observed causes of damage and failure of wind turbine blades in the field include leading edge erosion, delamination in tapered sections and ply drops (a structural feature that is added to wind turbine blades), damage to adhesive connections, and buckling and collapse under bending and twisting, to name a few (Mishnaevsky, 2022). Under these conditions, the blades can be repaired and reused. Through the structural repair of wind turbine blades (Mischnaewski and Mishnaevsky, 2021), new wind turbine installations can incorporate refurbished blades, thereby prolonging their operational lifespan and avoiding accumulation of these blades in landfills. Additionally, discarded blades may be used for testing and experiments that could improve performance of the materials and possibly advance subsequent blade designs.

Also, incorporating older towers into new installations could decrease the need for new resources, provided that the structures are stable. Gearboxes and generators also could be refurbished and used in new turbines. By adopting this methodology, not only are the lifespans of critical components prolonged, but also the environmental impacts linked to the production of new components would be reduced. Upgrades to electronic systems, controllers, and wiring could be implemented to ensure that the efficiency of refurbished turbines is optimized.

5.2.3 Disposal in Landfills

Even given the large sizes of wind turbine blades and the need for optimizing existing landfill space, landfilling continues to be the prevailing EoL option. To improve transportation and handling, the blades, which frequently exceed a length of 50 meters, often are divided into smaller parts before transportation to a handling or recycling facility. However, even after undergoing segmentation, they still occupy too much space within landfills.

The inefficiency is further exacerbated by the materials used in the production of blades, which are specifically designed to withstand severe weather conditions, including high winds, harsh sunlight, and moisture, within extended periods of as much as several decades. According to Meira Castro et al. (2013), the epoxy resin that has undergone curing, which is a key constituent of the blades, has substantial impermeability to heat, UV radiation, and moisture. Consequently, conventional methods of mechanical compaction and natural decay will not effectively disintegrate these blades, given typical landfill environments. Nevertheless, it is worth noting that the organic constituents present in the blades, such as balsa wood, can biodegrade over time. Moreover, although the resins and chemical additives in the turbine blades have undergone curing that improves their resilience in the environment, we were unable to find laboratory leaching (TCLP) test results that would document the potential for long-term leachability, particularly for compounds such as Bisphenol A (BPA), which is found in most epoxy resins used in carbon fiber reinforced plastics found in wind turbine blades.

Furthermore, disposing of wind turbine blades in landfills incurs an opportunity cost in terms of the energy and materials contained within the blades that are not reclaimed. Although alternate techniques of disposal, such as recycling or energy recovery, could recover a portion of this value, the availability of land for disposal and the relatively low cost of landfilling make widespread use of this approach (Ramirez-Tejeda et al., 2017).

5.3 Battery Storage Systems

Large-scale energy storage has been increasing in Texas. According to ERCOT (2024a), 7,702 MW of battery storage capacity is currently deployed and operational in Texas, with capacity expected by ERCOT to grow to nearly 18 GW by November 2025, assuming that planned battery systems with financing in place are installed. The proper management of decommissioned batteries is likely to soon emerge as a major issue and will eventually need more organized EoL management.

5.3.1 Recycling

The recycling process for spent lithium-ion batteries (LIB) is divided into pre-processing or pre-treatment using three main methods: mechanical, hydrometallurgical, and pyrometallurgical (Figure 5.5). Pre-processing refers to procedures that do not modify the configuration of the LIB cells (e.g., discharge, battery disassembly and sorting) (Velázquez-Martínez et al., 2019). Discharging batteries is needed to avoid potential risks of explosions. Battery disassembly yields the battery core coil from the battery shell, which will be further manually separated into its constituent elements, including the cathode, anode, and organic diaphragm. Following pre-processing, mechanical processing (also known as physical processing) encompasses many methods for extracting, categorizing (magnetic separation to recover ferromagnetic material like steel, and density separation using flotation, air classification, etc.), and intensifying materials without modifying their chemical composition (Islam and Iyer-Raniga, 2022). Relative differences in the physical properties of materials (e.g., density, shape, and size) form the basis of these techniques. Mechanical methods are usually performed at mass scale, making it a most economically viable option. The final product of this treatment method is the "black mass" material consisting of anode and cathode materials from shredded lithium batteries, which can be sold to the secondary market.

After mechanical processing, pyrometallurgy, hydrometallurgy, and several combination methods are used to recycle and recover components of LIB cells. Pyrometallurgy is a method that uses high temperatures to decompose the materials in spent LIBs. Typically, this approach consists of two stages. First is the evaporation of the electrolyte during the initial stage in a furnace at a low temperature; second is the formation of slag and alloy, which is the result of the incineration of plastics and solvents at a higher temperature. Pyrometallurgy has been extensively used in the manufacturing sector due to the short process flow, low equipment requirements, mature technology, and strong operability; however, the process does have some downsides: its energy consumption is high, it potentially releases pollutants, and it is costly, among other disadvantages (Meshram et al., 2015).

Hydrometallurgy is another recycling method used for spent LIB batteries. This method uses aqueous chemistry to dissolve and recover valuable metals from the processed battery materials and consists of key steps like leaching, purification of leachate and recovery (Zanoletti et al., 2024). Acid or alkaline solutions are employed to dissolve metals (e.g., lithium, cobalt, nickel, and manganese) in crushed and separated battery materials. Acid leaching is the commonly used method for the recovery of metals, and hydrochloric acid and sulfuric acid are prevalent leaching agents (Fan et al., 2021). Alkali leaching agents are usually potassium hydroxide or sodium hydroxide. After the leaching process, the leachate, which is a solution containing dissolved metals, undergoes purification to eliminate contaminants using methods such as precipitation, solvent extraction, or ion exchange followed by recovery via precipitation, electrolysis or other chemical methods. Hydrometallurgy processes have the potential to achieve high rates of metal recovery. Additionally, if waste solutions are well handled, these processes may result in a reduced environmental impact. However, it is important to acknowledge that the use of chemicals in these processes is accompanied by potential hazards.

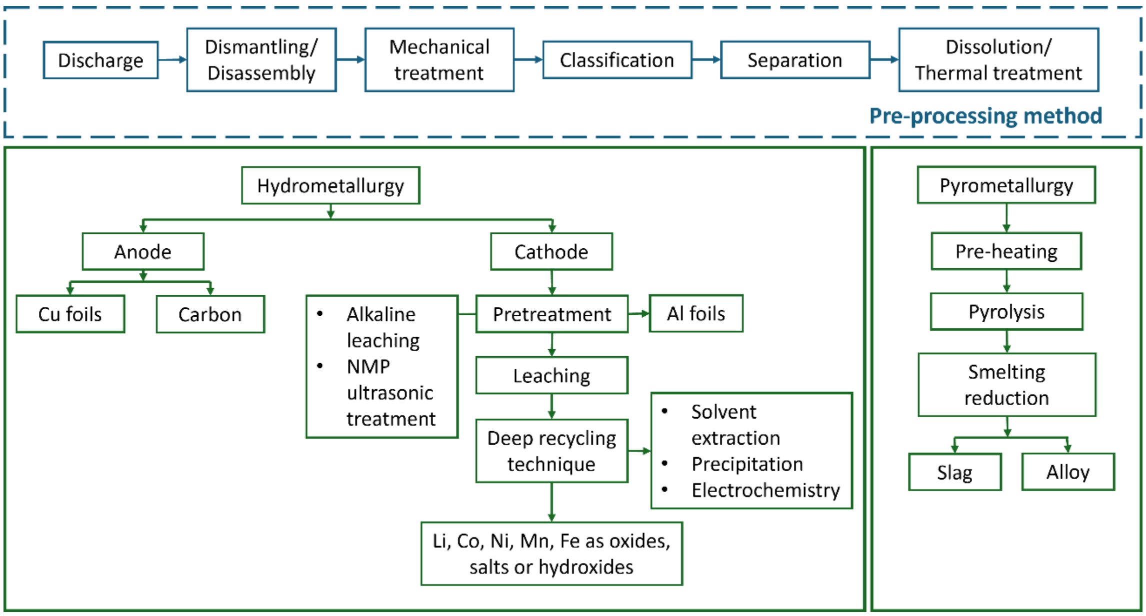


Figure 5.5 Different approaches used in the recycling of lithium ion spent batteries

Other recycling methods include bio-metallurgy (or bio-hydrometallurgy), that use microorganisms, including fungi, chemolithotrophic bacteria, and acidophilic bacteria, by acting as leaching agents to extract precious metals from a substrate. These microbes use ferrous iron and sulfur as energy sources to generate metabolites in the leaching media that enhance the extraction of metals (Moazzam et al., 2021). Another recent method is solvometallurgy, which is an alternative to hydrometallurgy that overcomes the disadvantage of disposing of and treating wastewater. Solvometallurgy uses ionic liquids and deep eutectic solvents (DESs) that are based on biodegradable and inexpensive components (Wang et al., 2023). State-of-the-art information on different recycling methods appears in Appendix D (Table D.3).

5.3.2 Reuse

Reuse extends the battery lifespan by allowing batteries to be used for a secondary function or for less resource-intensive tasks such as electricity supply, household services, and renewable energy sources (Cusenza et al., 2019). Reuse should be prioritized above recycling and disposal of batteries, as it can maximize economic value and reduce environmental demand.

The best way to reuse batteries is through remanufacturing or reconditioning, which involves repairing or refurbishing that restores battery capacity and performance. Remanufacturing often entails testing to identify defective cells and components and replacing faulty components, which require partial disassembly and subsequent reassembly (Rohr et al., 2017). As reported by Foster et al. (2014), although remanufacturing offers a cost-saving advantage of around 40% compared to new goods, industry lacks large-scale remanufacturing applications. Lastly, when it is not feasible to reuse the complete battery, individual components (mostly cathode and anode materials) can be recovered and potentially incorporated into new batteries.

Repurposing refers to the process of reconfiguring decommissioned LIBs for secondary usage in applications that are less demanding, such as grid-connected storage, backup power supply, supplementary services, and electrical equipment. Repurposing can sometimes require disassembly, removal, testing, etc. (Chen et al., 2019). The potential uses of repurposed batteries may be classified based on their energy levels (industrial, commercial, and residential applications), intended function, and degree of mobility (stationary-such as wind power storage systems; quasi-stationary such as energy supply for construction sites, and mobile scenarios such as power sources in forklifts) (Richter et al., 2016).

5.3.3 Disposal in Landfills

As mentioned in Chapter 3.5, large format batteries are classified as "universal waste" and are thus prohibited by rule (30 TAC Chapter 335 Subchapter H) from being disposed in municipal landfills.

The current rules in Texas are generally related to mobile batteries, not to stationary batteries that are used in utility-scale energy storage, which is the specific topic listed in SB 1290. These types of batteries have different chemistries. Mobile batteries generally contain various amounts of lithium, nickel, manganese, cobalt, or aluminum (known as NMC or NCA chemistry), whereas stationary batteries more often contain lithium, iron, and phosphate (known as LFP). NMC and NCA chemistries contain valuable constituents that promote recycling and discourage disposal. Batteries with LFP chemistry are less likely to be recycled because the metals contained therein are not as valuable, although innovative techniques are being pursued (e.g., Vasconcelos et al., 2023).

6. Life-Cycle Assessment of EoL Alternatives

6.1 General background on LCA methods

Life Cycle Assessment (LCA) is a systematic method used to assess the environmental impacts caused by a product, process, or service, from its inception to its completion. For example, when considering a manufactured product, the evaluation of its environmental effects begins with the extraction and processing of raw materials (cradle), continues through the manufacturing, distribution, and use of the product, and concludes with the recycling or ultimate disposal of the materials from which it is made (grave) (ISO, 2020a). We are discussing LCA in this report, because different EoL options will lead to potentially different impacts on the environment and watersheds. By studying the different routes, we can highlight advantages and disadvantages appropriately, although LCA analysis does not account for the current landfilling or recycling capacity that might be needed for future anticipated waste volumes. By combining LCA results with capacities, industry can better understand where innovation would benefit EoL management and how those management decisions will impact the environment.

6.1.1 Short history of LCA and energy systems

The origins of LCA modeling can be traced from the 1960s, and LCA has undergone substantial evolution since then. In the past, LCA was referred to as Resource and Environmental Profile Analysis (REPA) or Ecobalances, before the term LCA became widely used in the 1990s. Early pioneering research on LCA was presented at the World Energy Conference in 1963, when a study was presented on the energy needs to produce chemical intermediates and products (Hauschild et al., 2018). In 1969, the Coca-Cola company conducted an analysis of the use of resources and the environmental effects of beverage containers. The first public and peer-reviewed LCA research, titled “Resource and Environmental Profile Analysis of Nine Beverage Container Alternatives,” was first published in 1974. The initial version of GaBi, the first commercially available LCA software, was published in 1989, and subsequently, SimaPro, another popular commercial LCA software, was introduced in 1990 (Hauschild et al., 2018).

In the 1990s, the term “life cycle assessment” was coined, and distinct life cycle inventory (LCI) databases were created and managed by various institutions. The Society of Environmental Toxicology and Chemistry (SETAC) played a leading role in the standardization of LCA techniques and in arranging workshops and conferences with the goal of standardizing LCA methodology. During this time, multinational companies and researchers carried out more extensive LCA assessments, which went beyond only examining energy use to also include a wider range of environmental effects (Finnveden et al., 2009). The growing intricacy of industrial processes required a more rigorous method for evaluating the environment, paving the way for more progress. The International Organization for Standardization (ISO) in the late 1990s released the ISO 14040 series, which established a standardized framework for performing LCA studies (Simonen, 2014). During this time, LCA was used in a range of sectors such as automotive, electronics, and packaging to better understand the environmental impacts of various decisions on supply chains, industrial processes, and others. The use of standardized methodologies has played a crucial role in ensuring uniformity and comparability in LCA outcomes, promoting wider acceptance and applications across various industries. In 2003, LCA methodology advanced with the release of version 1.01 of the LCI database known as “Ecoinvent.” This complete life cycle inventory database enhanced the uniformity and comprehensiveness of LCA findings.

Throughout the years, energy systems have been the focus of more than a thousand LCA studies. According to Chen et al. (2014), a total of 7500 scientific articles and conference papers were published in LCA between 1998 and 2013. Of them, 1067 publications fell under the category of "Energy and Fuels." Within a span of 10 years (2014—2024), a total of 72,184 scientific papers were identified in the Web of Science database when combining keywords "energy system," "LCA," and "Life cycle assessment." The increased publishing rate related to energy systems is likely due to the focus on greenhouse gas (GHG) emissions.

6.1.2 LCA Methodology - System Boundaries, LCI, LCIA, and others

ISO 14040 (2020a) provides a comprehensive guide for conducting LCA, including defining the objectives and boundaries, analyzing life cycle inventories, assessing impacts, and interpreting results. The document offers instructions for conducting LCA analyses, although it does not recommend specific methodologies. ISO 14044 (2020b) builds on ISO 14040 by specifying requirements for carrying out LCA. ISO 14044 encompasses guidelines for selecting impact categories, category indicators, and characterization models, ensuring that LCA studies are carried out consistently. The four-phase framework for LCA appears in more detail below (Figure 6.1):

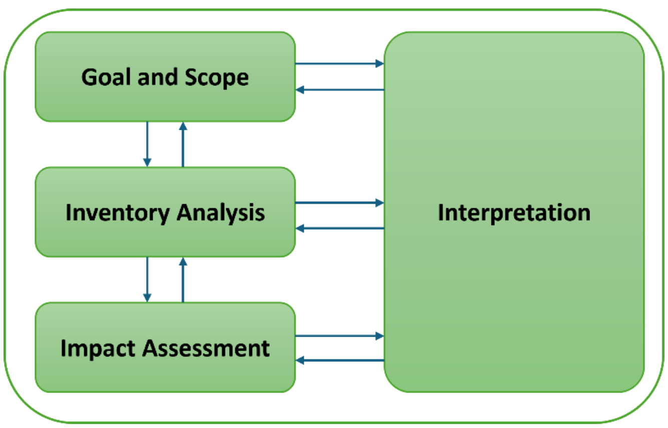


Figure 6.1 LCA framework as defined by ISO 14044 (ISO 14040:2006, 2020a)

Phase 1: Goal and Scope - In this phase, the LCA study is designed and articulated, ensuring that the goals and objective are specified and in line with the planned use of the results. The process of goal definition involves determining the intended application (i.e., marketing or product development), the purpose (i.e., internal use or publication), the intended audience (i.e., shareholders or consumers), and whether the results will be used for comparative analysis, which requires a thorough evaluation. The scope definition encompasses a comprehensive description of the product or process system, including specific assumptions and methodologies. This description covers various aspects, including product function, the functional unit, reference flow, system description and boundaries, allocation procedures, impact categories, data requirements and assumptions, limitations, data quality, peer-review process, the reporting type. Applications of this study are included below for context.

Functional Unit - The functional unit (FU) refers to the precise and quantifiable description of a product purpose or function. One aspect of this description is the reference flow, which quantifies the components and materials required to perform a specific function. All inventory phase data are scaled based on this reference flow, maintaining consistency in the LCA. For example, the functional unit in this study nominally will be 1 ton (1000 kg) of solar PV panels, wind turbine blades, or spent batteries that are decommissioned from the field, transported to a facility (e.g., a landfill or a recycling center), and managed accordingly.

System Boundaries - The system boundary delineates the processes that are encompassed in or omitted from the evaluation. The four primary system boundary options are: (1) cradle-to-grave, which encompasses the entire life cycle from raw material extraction to EoL treatment; (2) cradle-to-gate, which includes raw material extraction to the production phase; (3) gate-to-grave, which covers the operations phase to EoL; and (4) gate-to-gate, which can include any of the internal steps. In this study, we focus on (3) gate-to-grave (i.e., from the operations phase to EoL). This study did not review the supply chain needed to build the solar, wind, or battery facilities, nor did it review what happens to the secondary products that are made available after the recycling processes are complete.

Phase 2: Life Cycle Inventory - A life cycle inventory (LCI) entails collecting and analyzing the inputs and outputs of a specific product system or individual process across its system boundary. The LCI involves gathering and organizing data into LCI tables, generally within a modeling platform. The quantitative and qualitative data collected for each unit process are classified as: energy inputs, raw material inputs, co-products, wastes, ancillary inputs, emissions, and other physical inputs. For example, if wind turbine blades are being recycled, all the steps and the materials needed for recycling are considered (e.g., transportation to recycling center, electricity needed for mechanical processing, chemicals and/or heat needed for chemical and thermal processing, any waste materials that need to be landfilled [including those impacts]). In this phase, detailed and quantitative information and data provide a more thorough and accurate comparison of different EoL options, whether that includes landfilling, recycling, reuse, or other alternatives.

Phase 3: Life Cycle Impact Assessment - The Life Cycle Impact Assessment (LCIA) phase involves converting the input and output data gathered in the LCI phase into probable environmental impacts. This phase also evaluates the magnitude of these impacts to better understand their environmental consequences. Various methodologies, such as TRACI (Bare, 2011) or ReCiPe 2016 (Huijbregts et al., 2017; Rybaczewska-Błażejowska and Jezierski, 2024), can be applied to assess impacts. In these methods, two main approaches are used to characterize and classify environmental impacts: the problem-oriented approach (midpoint) and the damage-oriented approach (endpoint). In our study, we use the ReCiPe 2016 Midpoint H approach of Huijbregts et al. (2017), which is a *de facto* global standard in the LCA community.

Phase 4: Interpretation - During the interpretation phase, the results are examined and assessed to ensure that they align with the defined purpose and scope, and that the research is comprehensive. This phase comprises two main steps: (1) identification of key concerns and (2) evaluation (completeness, sensitivity, and consistency checks). In our study, we compare the different EoL options to better understand where environmental impacts are more likely to manifest, which can help in decision-making with smaller environmental footprints and/or in showing industry how and where innovation can reduce footprints further.

6.1.3 Impact Pathways – List and Description

Impact pathways in LCA are the series of cause-and-effect interactions that connect certain activities or emissions during the relevant life phases of a product or process to their ultimate environmental consequences. These pathways play important roles in understanding how various phases contribute to either environmental damage or advantages. The 16 different impact pathways under the ReCiPe 2016 midpoint (H) method (Huijbregts et al., 2017; Table 6.1) were used here.

Table 6.1 Description of impact categories used in this study.

Impact category	**Unit**	**Abbr.**	**Description**
Fine particulate matter formation	kg PM2.5 eq	PMFP	This determines the influence of emissions of fine particulate matter (PM) on human health, specifically focusing on respiratory and cardiovascular problems.
Freshwater ecotoxicity	kg 1,4-DCB	FETP	This quantifies the effects of harmful compounds on freshwater ecosystems, specifically on aquatic animals.
Freshwater eutrophication potential	kg P eq	FEP	This indicator evaluates the nutrient enrichment of freshwater bodies, resulting in the excessive proliferation of algae and aquatic plants, which can deteriorate water quality and cause harm to aquatic life.
Global warming potential	kg CO_2 eq	GWP	It refers to the analysis of the impact of GHGs on the Earth's atmosphere, resulting in a rise in global temperatures.
Human carcinogenic toxicity	kg 1,4-DCB	HTPc	Human carcinogenicity is a classification used to evaluate and measure the likelihood of acquiring cancer as a result of being exposed to chemicals or pollutants that have the potential to cause cancer.
Human non-carcinogenic toxicity	kg 1,4-DCB	HTPnc	It is an impact category used to assess the risk of various toxic effects, such as organ damage, reproductive harm, or developmental issues, due to exposure to non-carcinogenic chemicals or pollutants.
Ionizing radiation	kBq Co-60 eq	IRP	This evaluates the effects of ionizing radiation on human well-being, focusing on the consequences of exposure to radioactive substances. It quantifies the radiative effects of emissions in comparison to uranium-235.
Land use	m^2a crop eq	LOP	This category evaluates the effects of land occupation and alteration, encompassing deforestation, urbanization, and agriculture. It takes into consideration problems such as soil erosion, biodiversity loss, and changes in land productivity.
Marine ecotoxicity	kg 1,4-DCB	METP	This assesses the possible harm to marine ecosystems caused by harmful chemicals.
Marine eutrophication	kg N eq	MEP	This evaluates the enrichment of nutrients in marine habitats, which leads to comparable problems such as eutrophication in freshwater systems.
Ozone formation, Human health	kg NOx eq	OFHH	Depletion of the ozone layer results in an elevation of UV radiation that reaches the Earth's surface, hence increasing

			the likelihood of skin cancer, eye damage, and suppression of the immune system.
Ozone formation, Terrestrial ecosystems	kg NOx eq	OFTE	This category assesses the environmental impact of ground-level ozone creation, which can harm respiratory health and damage crops, vegetation, and ecosystems.
Stratospheric ozone depletion	kg CFC11 eq	ODP	It refers to the capacity of compounds to degrade the ozone layer in the stratosphere, which shields life on Earth from detrimental ultraviolet (UV) radiation.
Terrestrial acidification potential	kg SO_2 eq	TAP	This measures the acidification caused by pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and ammonia (NH_3) on soils and ecosystems.
Terrestrial ecotoxicity	kg 1,B	TETP	This evaluates the possible damage to land-based ecosystems caused by the discharge of toxic substances into the environment.
Water depletion potential	m^3	WDP	This assesses the influence of water consumption on the accessibility of freshwater resources and gauges the amount of freshwater utilized.

6.2 LCA Study of EoL of Energy Systems

The EoL phase encompasses the processes from decommissioning to disposal or recycling. This phase considers potential pollution, resource recovery, and waste management implications. Hence, the goal of the present study is to assess EoL alternatives of solar panels, wind turbines, and battery systems to identify environmental impacts associated with the disposal phase of their life cycles. The various disposal routes considered are landfilling (Route 1), mechanical recycling (Route 2), thermal recycling (Route 3), and chemical recycling (Route 4).

For solar panels, the c-Si PV modules are mechanically separated, yielding bulk materials that include glass cullets, aluminum scrap, and copper scrap. Processes include shredding, pre-sorting, and crushing. Thermal processing involves removing encapsulant material, typically a polymer layer that holds together and protects the solar cell from environmental degradation. The chemical method consists of reverse electroplating followed by two-stage etching processes.

For wind turbines, the mechanical process mostly entails crushing and cutting wind turbine blades that can maximize production of secondary products. Pyrolysis, the primary technique in thermal recycling, involves the thermal decomposition of polymers at high temperatures, typically between 450°C and 700°C (750°F to 1300°F) (Yang et al., 2022; Yousef et al., 2024), in the absence of oxygen or with a controlled flow of oxygen. To break down the polymer resin and separate it from fiber, the chemical recycling procedure requires liquid solvents, including water, acid, or alcohol.

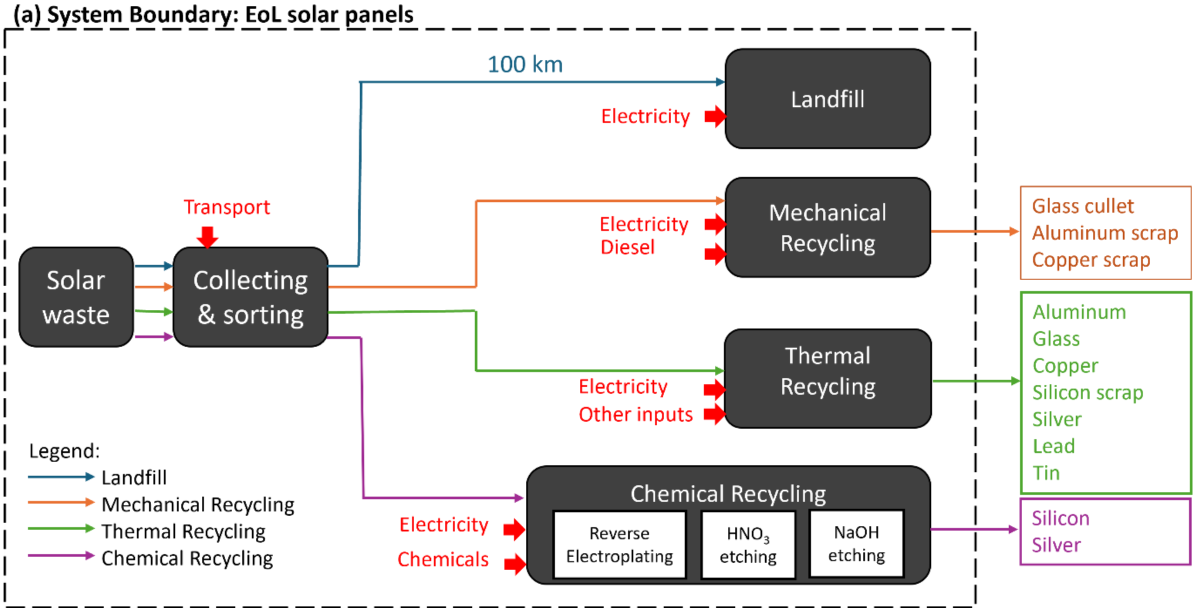
For NMC and NCA batteries, which we are using as surrogates for LFP batteries, the mechanical recycling process includes collecting, discharging, sorting, and dismantling of batteries (pre-treatment processes) before the shredding process (see also Figure 6.2). Batteries undergoing a pyrometallurgy recycling route are first crushed before being neutralized and processed; for batteries being recycled using hydrometallurgy, waste batteries are first shredded under inert gas and then chemically treated.

We analyzed and intercompared the environmental effects of these routes, to identify those with the least environmental impact. The system boundaries are shown in detail (Figure 6.2a for solar panels, Figure 6.2b for wind turbine blades, and Figure 6.2c for BESS). The below-mentioned assumptions highlight the different conditions applied to the LCA analysis.

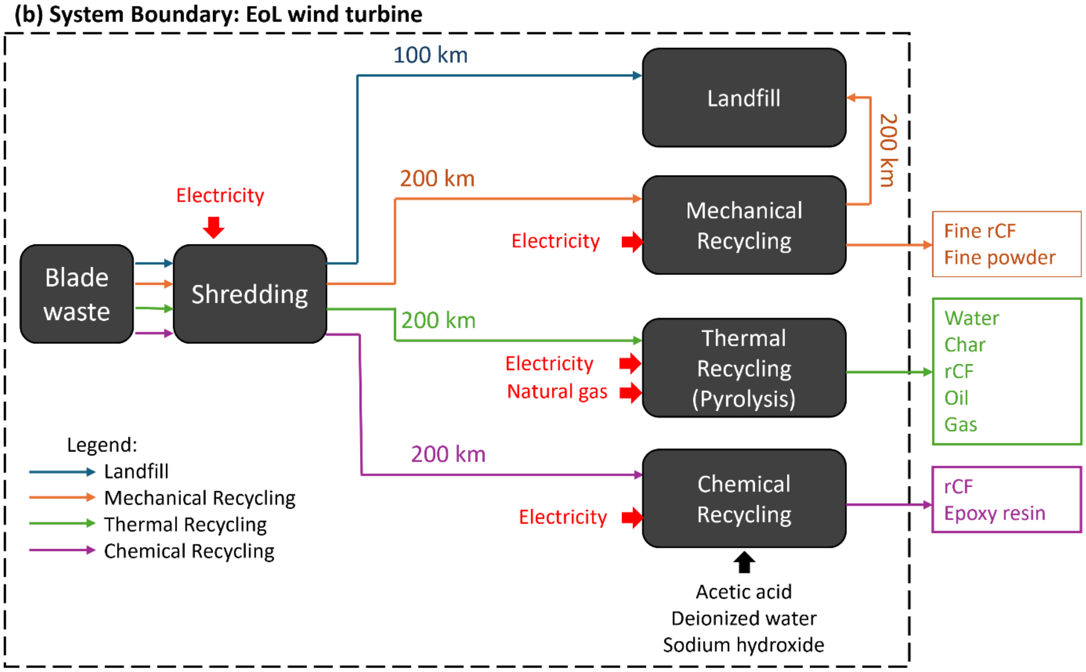
Assumptions:

- We assumed that solar panels, wind turbine blades, and battery waste are readily available as feedstock, without any pre-existing environmental burdens being attributed to them.
- For EoL analysis of solar panels, we selected crystalline silicon technology, given the big market share for the technology and the associated future waste stream, when compared to cadmium-telluride (CdTe) and other thin-film technologies.
- For wind turbine blades, we assume that they are composed of carbon fiber-reinforced plastic, or CFRP because of the higher recycling complexity of CFRP compared to glass fiber-reinforced plastic (GFRP). Although the process is comparatively more energy intensive, CFRP can recover more quality fibers with higher mechanical properties than GFRP.
- The model does not track or account for any secondary products (e.g., production of energy, fuels, and new materials) as possible outcomes of waste treatment processes. This means that avoided burdens due to material/energy recovery were not considered.
- The transportation distance was assumed to be 60 miles (100 km) from the decommissioning site to the landfill, or 120 miles (200 km) to the recycling facility. If the waste was generated from the recycling process and disposed of in a landfill, we assumed this distance as 120 miles (200 km) (see Figure 6.2).
- The entire energy mix was assumed to flow from and within Texas.
- All waste created in Texas was assumed to be managed within Texas boundaries (i.e., no waste streams leave the state) and no waste generated outside Texas was imported into Texas, although we note that both assumptions are stringent.
- Life cycle inventory data were collected from the best available literature and LCI databases (e.g., Ecoinvent).
- The LCA was done only for recycling and landfilling options; it was not done for reuse specifically, given that the equipment eventually would be routed toward final EoL options.

(a) System Boundary: EoL solar panels



(b) System Boundary: EoL wind turbine



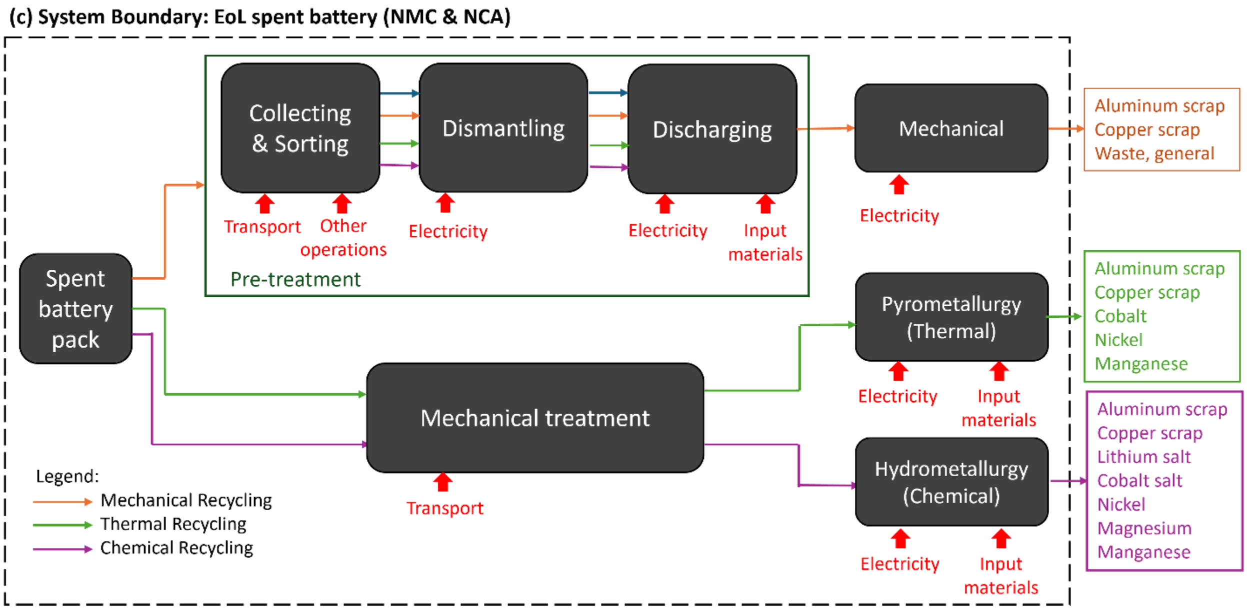


Figure 6.2 System boundary showing material and energy flow for EoL of (a) solar panels, (b) wind turbine blades, and (c) BESS.

6.3 Results and Discussion

6.3.1 Solar Energy Technology

As indicated above, we focus the LCA analysis on disposal routes that include landfilling and recycling (mechanical, thermal, and chemical). We assess and compare the environmental impacts of these 4 EoL options across 16 key categories (Table 6.2). This analysis will assist with the trade-offs that are associated with various end-of-life management strategies for solar modules.

Recycling (mechanical, thermal, and chemical): The recycling of solar panels generally uses three methods: mechanical, thermal, and chemical processes, each having specific environmental effects. Comparing different recycling methods, for PMFP, consumption of excessive amounts of nitric acid causes high impacts (6 kg PM 2.5 eq /ton solar panel) for chemical recycling. Although this study does not consider any benefit in environmental impacts from the recovery of silver in chemical recycling, but the analysis does include electricity consumption and material as process inputs for the recovery. Where the contribution is maximum (in PMFP), they contribute 65.71% and 28.9%, respectively (Figure 6.3).

The mechanical recycling process emits 504 kg CO_2 /ton solar panels, with most emissions stemming from the disposal of plastic waste in municipal waste incineration plants and inert material landfills (70.10%), transportation of decommissioned panels to recycling facilities and transportation of waste from recycling center to landfill (17.65%), and electricity consumption during the recycling process (11.06%) (IEA-PVPS Task 12, 2018). The thermal recycling process emits 587 kg CO_2 /ton solar panels, with maximum contribution in the impact indicator being from electricity consumption (64.27%), because thermal recycling process typically requires high temperatures to break down materials, which requires a greater amount of electricity, and transportation (27.73%). Among the mechanical, thermal, and chemical recycling processes, the maximum CO_2 emission can be observed from the chemical recycling route (1,998 kg CO_2 / ton solar panels), where the contribution is maximum from the electricity consumption (48.20%) and input materials (40.97%). The reason for such a high CO_2 emission is that the chemical process used here is an advance-treatment method that is mainly geared toward retrieval of silver, a precious and limited resource in the production of solar cells, as well as for retrieving greater amounts of aluminum and silicon (Deng et al., 2019).

Table 6.2 Environmental impacts of various disposal routes, "per ton" of solar panel. Green shading indicates the lowest environmental burden for the specific pathway; tan shading indicates the highest environmental burden.

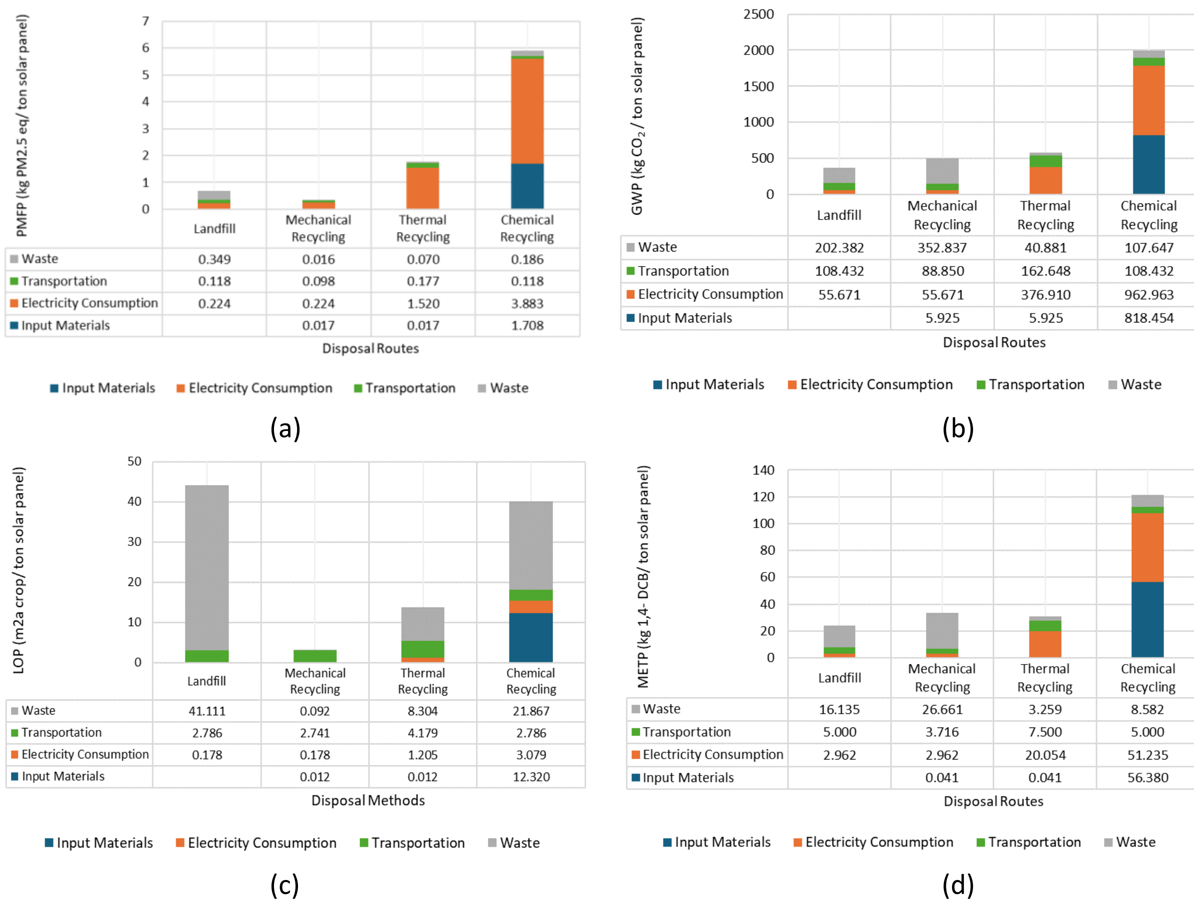
Impact	Unit	Landfill (Route 1)	Recycling		
			Mechanical (Route 2)	Thermal (Route 3)	Chemical (Route 4)
Fine particulate matter formation	kg PM2.5 eq	6.92E-01	3.55E-01	1.78E+00	5.91E+00
Freshwater ecotoxicity	kg 1,4-DCB	1.69E+01	2.46E+01	2.23E+01	9.07E+01
Freshwater eutrophication	kg P eq	1.58E-01	7.03E-02	4.47E-01	1.48E+00
Global warming	kg CO_2 eq	3.66E+02	5.03E+02	5.86E+02	2.00E+03
Human carcinogenic toxicity	kg 1,4-DCB	9.95E+01	1.42E+01	5.17E+01	1.65E+02
Human non-carcinogenic toxicity	kg 1,4-DCB	3.13E+02	4.97E+02	6.24E+02	2.27E+03
Ionizing radiation	kBq Co-60 eq	1.45E+01	1.01E+01	6.10E+01	2.34E+02
Land use	m^2a crop eq	4.41E+01	3.02E+00	1.37E+01	4.01E+01
Marine ecotoxicity	kg 1,4-DCB	2.41E+01	3.34E+01	3.09E+01	1.21E+02
Marine eutrophication	kg N eq	1.21E-02	5.42E-02	2.98E-02	1.14E-01
Ozone formation, Human health	kg NO_x eq	8.58E-01	4.69E-01	9.04E-01	3.42E+00
Ozone formation, Terrestrial ecosystems	kg NO_x eq	9.08E-01	4.79E-01	9.35E-01	3.49E+00
Stratospheric ozone depletion	kg CFC11 eq	1.34E-04	2.34E-04	2.55E-04	2.60E-03
Terrestrial acidification	kg SO_2 eq	9.15E-01	4.09E-01	1.28E+00	5.58E+00
Terrestrial ecotoxicity	kg 1,4-DCB	1.60E+03	1.43E+03	2.14E+03	5.51E+03
Water depletion potential	m^3	1.75E+00	8.55E-01	1.69E+00	2.42E+01

The ecotoxicity impact categories (marine and terrestrial) also have higher values for chemical recycling with values of 122 kg 1,4-DCB/ton solar panel and 5513 kg 1,4-DCB/ton solar panel, respectively. The impacts stem largely from the hazardous input materials used in the process. Also, the chemical recycling process requires large amounts of water to dilute chemicals, wash materials, and neutralize acids, which leads to higher impact from the Water depletion potential impact category (25 m^3) compared to other disposal methods (Figure 6.3).

Disposal in landfill: Landfilling is generally seen as a preferred method of waste disposal because of financial considerations. On the environmental front, this disposal route leads to the lowest CO_2

emissions compared to other methods of waste disposal (367 kg CO_2/ton solar panel). The limited CO_2 emission related to landfill disposal is mostly attributed to its passive nature, in contrast to the energy-intensive processes involved in recycling methods, such as thermal or chemical treatments, which greatly contribute to GHG emissions. However, for the land use impact category, landfilling produces the maximum impact of 44 m^2a crop eq/ton solar panel in comparison to mechanical (3 m^2a crop eq/ton solar panel), thermal (13.7 m^2a crop eq / ton solar panel) and chemical (40 m^2a crop eq / ton solar panel) (Figure 6.3). This is due to the permanent land occupation for very long durations, reducing the land's availability for other productive uses such as agriculture. The result for the land use impact category for chemical recycling process is also comparable to the landfill impact; this is due to the need for facilities to store and process the chemicals and waste, as well as the potential for environmental impacts that could affect land productivity (Figure 6.3).

To provide a more precise interpretation of the findings, we selected six ReCiPe midpoint environmental impact categories that have been identified as the most pertinent for solar panel EoL recycling procedures. These impacts capture the most critical environmental and health impacts associated with solar panel recycling and landfilling. They address key concerns like human health risks, climate change, resource usage, and ecological contamination, providing a comprehensive overview of the environmental implications of different end-of-life management strategies for solar panels. Further, to gain a more comprehensive understanding of the contributions from each input category, we categorized these selected impacts in accordance with the process inventory. This allowed us to evaluate the impact of each input on the overall impact within these key categories (Figure 6.3).



(a)

	Landfill	Mechanical Recycling	Thermal Recycling	Chemical Recycling
Waste	0.349	0.016	0.070	0.186
Transportation	0.118	0.098	0.177	0.118
Electricity Consumption	0.224	0.224	1.520	3.883
Input Materials		0.017	0.017	1.708

(b)

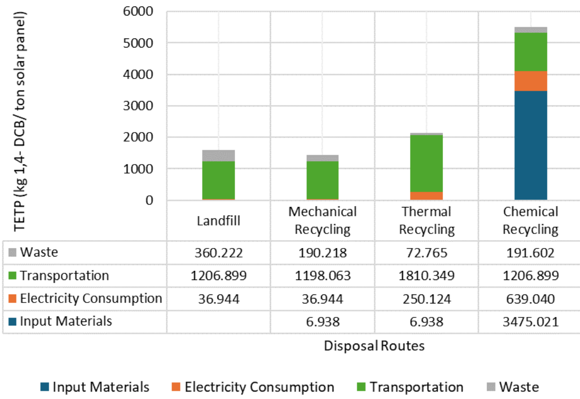
	Landfill	Mechanical Recycling	Thermal Recycling	Chemical Recycling
Waste	202.382	352.837	40.881	107.647
Transportation	108.432	88.850	162.648	108.432
Electricity Consumption	55.671	55.671	376.910	962.963
Input Materials		5.925	5.925	818.454

(c)

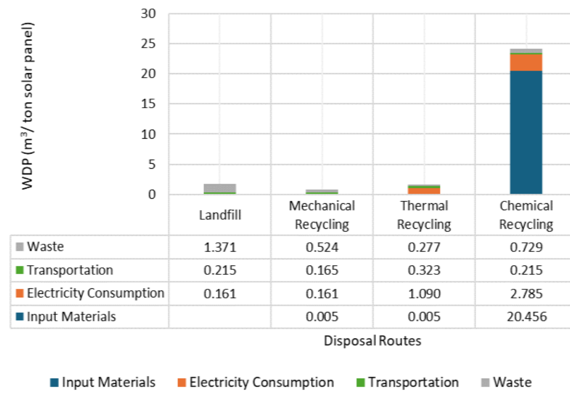
	Landfill	Mechanical Recycling	Thermal Recycling	Chemical Recycling
Waste	41.111	0.092	8.304	21.867
Transportation	2.786	2.741	4.179	2.786
Electricity Consumption	0.178	0.178	1.205	3.079
Input Materials		0.012	0.012	12.320

(d)

	Landfill	Mechanical Recycling	Thermal Recycling	Chemical Recycling
Waste	16.135	26.661	3.259	8.582
Transportation	5.000	3.716	7.500	5.000
Electricity Consumption	2.962	2.962	20.054	51.235
Input Materials		0.041	0.041	56.380



(e)



(f)

Figure 6.3 Contribution from landfill, mechanical, thermal, and chemical disposal methods of solar panels in (a) Fine particulate matter formation (PMFP), (b) CO_2 eq emissions (global warming potential, GWP), (c) Land use (LOP), (d) Marine ecotoxicity (METP), (e) Terrestrial ecotoxicity (TETP), and (f) Water depletion potential (WDP).

6.3.2 Wind Energy Technology

This chapter is subdivided into landfilling and recycling (mechanical, thermal, and chemical) for wind turbine blades (reuse was not assessed specifically, as it simply delays other EoL activities). For each route, the 16 environmental impact category results using the LCIA method and excluding recycling credits for recovered materials (or product) by each route, are given in Table 6.3.

Recycling (Mechanical, Thermal, and Chemical): In addition to the benefits of energy recovery and the reuse of recovered fibers and other materials, recycling procedures for CFRP wastes require additional energy inputs. These inputs contribute to the analysis of several environmental aspects (Table 6.3). The results suggest that thermal recycling has a greater PMFP impact than mechanical and chemical recycling. This increased impact is mostly caused by sulfur dioxide emissions, which account for 975 kg PM2.5 eq/per ton of waste, from the 982 kg PM2.5 eq per ton total produced by thermal recycling.

When considering CO_2 emissions, mechanical recycling, which involves disposing of the residual coarse fraction (570 kg/ton of waste blade) in landfills, leads to comparatively modest emissions of 490 kg CO_2 eq/per ton of waste blade. As a result of the higher energy inputs needed, thermal recycling (pyrolysis) and chemical recycling generate much more CO_2 eq emissions. Pyrolysis emits 2,017 kg of CO_2 eq, whereas chemical recycling creates 1,744 kg of CO_2 eq per ton of waste blade, mostly because of combustion in pyrolysis and additional inputs (chemicals) in chemical recycling. The results are consistent with the investigation carried out by Meng et al. (2018). The contribution of CO_2 eq from different processes (e.g., electricity consumption, sanitary landfill operations, etc.) and other energy inputs for landfilling and recycling routes (mechanical, thermal, and chemical) are shown in Figure 6.4. For recycling methods, most CO_2 eq emissions stem from electricity consumption, emission rates which are much higher when compared to landfilling. In chemical and thermal recycling processes, the land use impact is primarily driven by the input materials and electricity consumption. These processes focus on material recovery, meaning no waste is sent to landfills, thus eliminating land use impacts associated with disposal. Instead, the impact comes from the land required for producing and supplying the necessary chemicals and energy. Since the recycling processes do not, or only negligibly, generate landfill waste, the land use burden shifts to the resources needed to carry out the recycling.

Table 6.3 Environmental impacts of various disposal routes for "per ton" of wind turbine blades. Green shading indicates the lowest environmental burden for the specific pathway, and tan shading indicates the highest environmental burden.

Impact	Unit	Landfill (Route 1)	Recycling		
			Mechanical (Route 2)	Thermal (Route 3)	Chemical (Route 4)
Fine particulate matter formation	kg PM2.5 eq	7.91E-02	2.19E-01	9.82E+02	5.21E+00
Freshwater ecotoxicity	kg 1,4-DCB	4.33E+02	2.48E+02	7.41E+01	7.30E+01
Freshwater eutrophication	kg P eq	2.23E-02	5.74E-02	2.01E+00	1.28E+00
Global warming	kg CO_2 eq	7.69E+02	4.90E+02	2.02E+03	1.74E+03
Human carcinogenic toxicity	kg 1,4-DCB	1.67E+01	1.24E+01	1.16E+02	1.00E+02
Human non-carcinogenic toxicity	kg 1,4-DCB	9.30E+03	5.36E+03	2.19E+03	1.85E+03
Ionizing radiation	kBq Co-60 eq	2.06E+00	7.43E+00	2.79E+02	2.03E+02
Land use	m^2a crop eq	9.16E-01	1.09E+00	7.22E+00	1.40E+01
Marine ecotoxicity	kg 1,4-DCB	5.67E+02	3.26E+02	9.87E+01	9.69E+01
Marine eutrophication	kg N eq	8.29E-01	4.76E-01	1.30E-01	8.57E-02
Ozone formation, Human health	kg NOx eq	1.26E-01	1.37E-01	8.08E+02	2.69E+00
Ozone formation, Terrestrial ecosystems	kg Nox eq	1.28E-01	1.40E-01	1.30E+03	2.84E+00
Stratospheric ozone depletion	kg CFC11 eq	5.65E-05	5.50E-05	6.90E-04	7.70E-04
Terrestrial acidification	kg SO_2 eq	1.32E-01	1.81E-01	3.36E+03	4.76E+00
Terrestrial ecotoxicity	kg 1,4-DCB	1.15E+02	2.87E+02	1.81E+03	3.81E+03
Water depletion potential	m^3	3.35E-01	3.25E-01	6.87E+00	2.53E+01

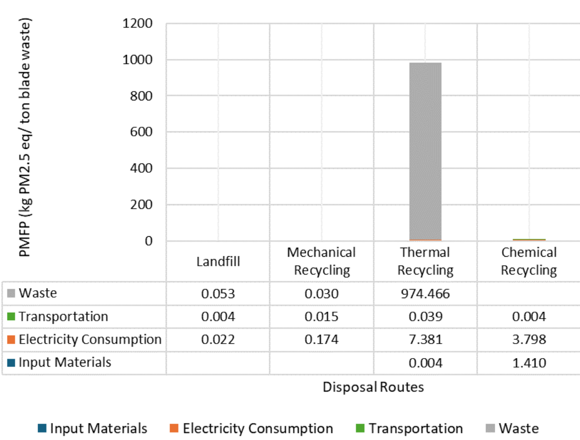
In the context of terrestrial ecotoxicity, chemical recycling stands out as the most influential procedure, demonstrated by a quantified value of 3,809 kg 1,4-DCB/ton of waste blade that is treated. The main factor responsible for this increased effect is the material input employed in the process, which account for a share of 82% of the overall TETP impact. Although less predominant, electricity usage still contributes 16.4% to the overall effect. The substantial contribution of input materials to the TETP impact category is mostly attributed to the release of copper into the atmosphere during the recycling procedure. Copper, an essential component in nearly all chemical recycling processes, is renowned for its ecotoxicity, especially when it is discharged into the environment as airborne particles. These emissions have the potential to cause pollution of soil and water, which can have a negative impact on terrestrial ecosystems and contribute to the aggregate burden of ecotoxicity. Chemical recycling also has the greatest impact on the Water depletion potential impact category, with a total usage of 25 m^3/ton of waste blade. The input materials are responsible for most of this Water depletion potential —89.24%

(Figure 6.4). This is likely due to the water-intensive process of producing and refining the compounds necessary for the recycling process.

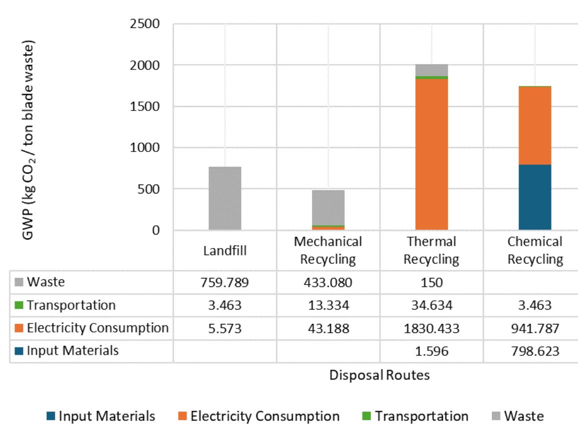
Disposal in Landfill: The landfill option for disposing of wind turbine blades generates relatively minor CO_2 equivalent emissions, with a value of 769 kg CO_2 eq per ton of waste, as determined by the GWP impact indicator (Table 6.3). The disposal process in sanitary landfills is the primary source of these emissions, accounting for 98.82% of the total. Electricity and transportation contribute only minimally. The U.S, Department of Energy (2024) noted that landfilling, despite being one of the most prevalent disposal methods, presents challenges due to the size of the blades, which have an average length of more than 50 meters and are now even longer. Due to the blades' length, they are difficult to stack and compress, which results in inefficient use of landfill space and the necessity for additional pre-processing stages, including pulverizing and cutting. These processes necessitate additional energy inputs, which directly contribute to emissions. Additionally, on-site shredding of wind turbine blades for compaction is particularly tough to do due to the need for specialized equipment, such as mobile shredding units and containment and filtration systems designed to prevent the spread of potentially harmful particles.

The impact of landfilling on land use is negligible, with only 1 m²a crop eq/ton of waste blade. These factors are negligible in the context of landfilling, in contrast to thermal and chemical recycling, where electricity consumption and input materials substantially influence the impact. Rather, the waste category is responsible for the primary land use impact, accounting for 83.39% of the total. Conversely, the impact of the waste category on other disposal routes is either nonexistent or negligible (Figure 6.4). Furthermore, the LOP impact of landfilling is further diminished by negative land occupation (associated with waste sites) and land transformation (to shrubland) values, resulting in a reduction in the overall Impact. Moreover, landfilling has the most substantial effect on marine ecotoxicity of all disposal routes, with a value of 567 kg 1,4-DCB/ton of waste blade. The primary cause of this increased impact is the waterborne emissions of copper ions (234 kg 1,4-DCB per ton) and zinc ions (323 kg 1,4-DCB per ton).

Figure 6.4 focuses on the six environmental impact categories that are most relevant to EoL management of wind turbine blades due to associated environmental impact. By categorizing the total impacts based on the process inventory, we were able to assess the contribution of each input category to the overall impact to understand how each input influences the overall environmental impact.



(a)



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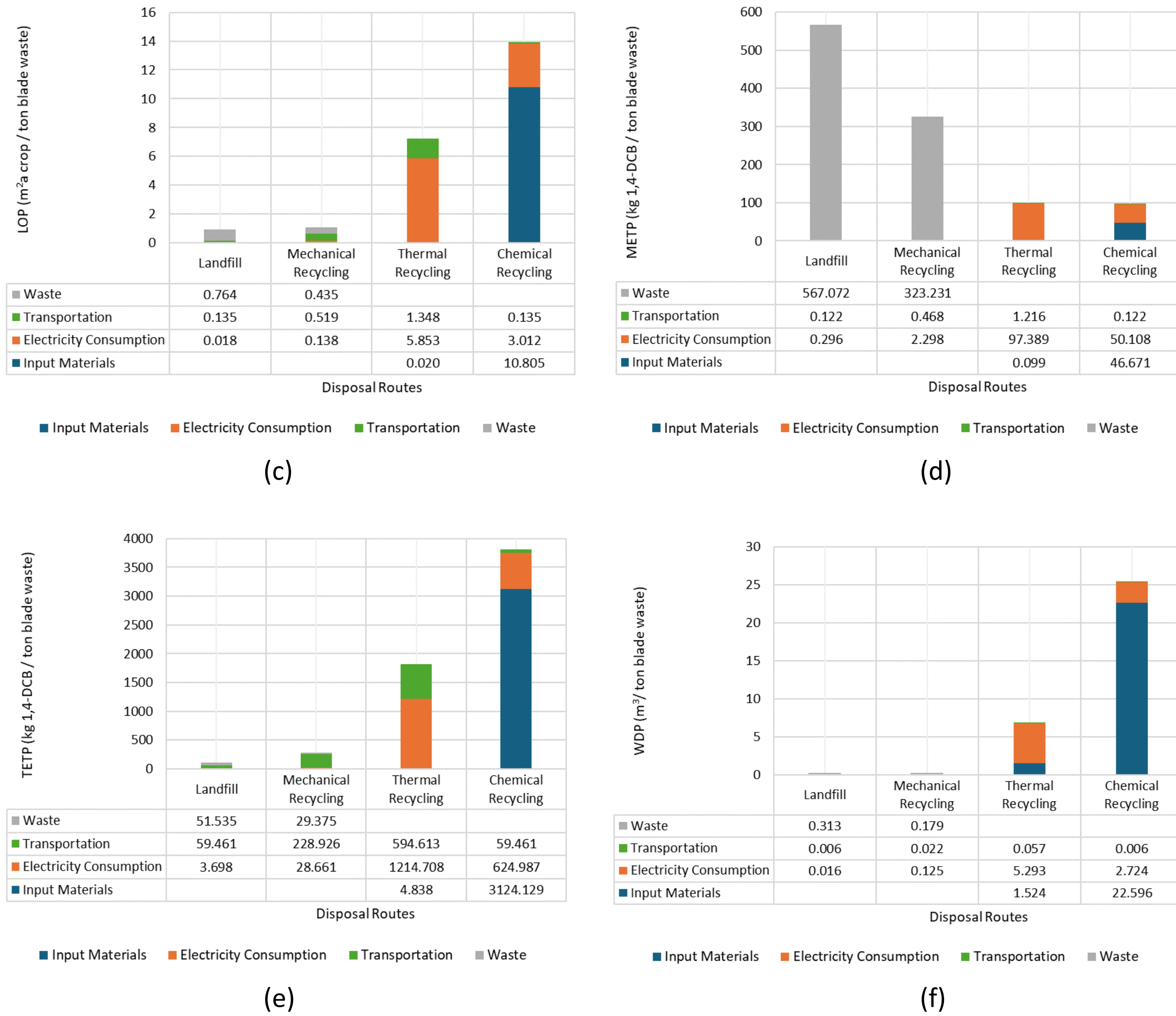

Figure 6.4 Contribution from landfill, mechanical, thermal. and chemical disposal methods of wind turbine blades in (a) Fine particulate matter formation (PMFP), (b) CO_2 eq emissions (global warming potential, GWP), (c) Land use (LOP), (d) Marine ecotoxicity (METP), (e) Terrestrial ecotoxicity (TETP), and (f) Water depletion potential (WDP).

6.3.3 Battery Electric Storage Systems

Due to the limited availability of specific inventory data on LFP batteries in the literature and given that the recycling processes detailed in existing studies are largely consistent, we have opted to use NMC (Nickel Manganese Cobalt) and NCA (Nickel Cobalt Aluminum) batteries as surrogates for LFP. By analyzing the LCA results for these battery types, we aim to derive a comparable understanding of the environmental impacts associated with LFP recycling.

Hence, this chapter presents an interpretation of the LCA conducted for the different EoL management routes for NMC and NCA batteries. It evaluates the efficacy of the different routes, emphasizing the trade-offs and advantages in energy demand, resource conservation, transportation, waste produce, etc. Table 6.4 shows the environmental impacts of each recycling pathway (mechanical, pyrometallurgy, and hydrometallurgy) for 16 different impact categories for the two battery types. The LCA results present the impacts on recycling methods and do not include any credits that would be expected given recovery of recycled materials. Discussion of landfilling route is done separately later in the chapter. We note that the inventories for NMC and NCA are similar, with the only difference in the process inventory of emissions and waste produced. Mechanical treatment of NMC and NCA batteries is usually pre-treatment, before pyrometallurgy and hydrometallurgy processes, which is treated separately with black mass as the final output product. The process inventory for mechanical treatment of both NMC and NCA is identical, leading to the same associated environmental impacts (Table 6.4).

Table 6.4 Environmental impacts of various disposal routes for "per ton" of NMC and NCA batteries. Green shading indicates the lowest environmental burden for the specific pathway, and tan shading indicates the highest environmental burden.

Impact	Unit	NMC/NCA	NMC	NCA	NMC	NCA
		Mechanical	Thermal Pyro-metallurgy	Thermal Pyro-metallurgy	Chemical Hydrometallurgy	Chemical Hydrometallurgy
Fine particulate matter formation	kg PM2.5 eq	6.42E-01	2.45E+00	2.46E+00	3.47E+00	3.47E+00
Freshwater ecotoxicity	kg 1,4-DCB	7.65E+00	4.00E+01	4.77E+01	7.30E+01	8.07E+01
Freshwater eutrophication	kg P eq	1.44E-01	5.77E-01	5.77E-01	1.69E-01	1.69E-01
Global warming	kg CO_2 eq	2.30E+02	7.40E+02	7.46E+02	3.34E+02	3.40E+02
Human carcinogenic toxicity	kg 1,4-DCB	2.26E+01	4.98E+01	5.00E+01	2.73E+01	2.75E+01
Human non-carcinogenic toxicity	kg 1,4-DCB	1.94E+02	1.04E+03	1.25E+03	1.61E+03	1.81E+03
Ionizing radiation	kBq Co-60 eq	1.95E+01	9.26E+01	9.26E+01	1.80E+01	1.80E+01
Land use	m^2a crop eq	6.94E+00	8.29E+00	8.32E+00	6.37E+00	6.40E+00
Marine ecotoxicity	kg 1,4-DCB	1.05E+01	5.33E+01	6.37E+01	9.61E+01	1.07E+02
Marine eutrophication	kg N eq	1.01E-02	1.30E-01	2.19E-01	9.89E-02	1.88E-01
Ozone formation, Human health	kg NOx eq	7.42E-01	1.53E+00	1.54E+00	1.05E+00	1.05E+00
Ozone formation,	kg NOx eq	7.64E-01	1.56E+00	1.56E+00	1.06E+00	1.07E+00

Terrestrial ecosystems						
Stratospheric ozone depletion	kg CFC11 eq	8.45E-05	4.71E-04	4.72E-04	2.86E-04	2.87E-04
Terrestrial acidification	kg SO_2 eq	6.66E-01	2.15E+00	2.16E+00	1.07E+01	1.07E+01
Terrestrial ecotoxicity	kg 1,4-DCB	7.05E+02	1.99E+03	1.99E+03	6.66E+03	6.66E+03
Water depletion potential	m^3	1.32E+00	9.54E+00	9.55E+00	5.29E+00	5.30E+00

Recycling (mechanical, pyrometallurgy, and hydrometallurgy): Among the recycling methods evaluated in this study, the PMFP value is minimum for mechanical recycling (0.6 kg PM2.5 eq /ton of spent batteries) and maximum in case of hydrometallurgy process (3.46 kg PM2.5 eq /ton of spent batteries for NMC and 3.47 kg PM2.5 eq /ton of spent batteries for NCA). The reason for high PMFP in the hydrometallurgy process is because of the emission of sulfur dioxide and particulates (<2.5 µm) in air, which together contributes to more than 95% for high PMFP impact. In terms of CO_2 emission for both NMC and NCA batteries, mechanical recycling exhibits the lowest environmental impact (230 kg CO_2 eq/ ton of spent batteries), followed by the hydrometallurgy processing (334 kg CO_2 eq/ton of spent batteries for NMC and 340 kg CO_2 eq/ton of spent batteries for NCA), whereas the pyrometallurgical recycling has substantially higher CO_2 eq emission rates (740 kg CO_2 eq /ton of spent batteries for NMC and 745 kg CO_2 eq/ton of spent batteries for NCA). The substantial energy requirements associated with the high-temperature processing characteristic of pyrometallurgy are the primary cause of this elevated CO_2 emissions (Mohr et al., 2020). In contrast, CO_2 emissions rates for mechanical treatment are lowest for both cell types, the reason being the reduced processing complexity and lower energy consumption. Among the cell types examined, NMC demonstrates the lowest production impacts and consequently the lowest net CO_2 emission compared to NCA. This advantage is attributed to NMC's higher energy density. This increased energy density necessitates the production of a reduced amount of cell mass to accomplish the same capacity, thereby reducing the amount of production energy required.

Other noticeable higher impacts from Table 6.4 can be seen in the marine ecotoxicity impact category. From the results, the hydrometallurgy process emits higher METP impact for both NMC and NCA batteries (96 kg 1,4- DCB/ton of spent batteries and 106 kg 1,4- DCB/ton of spent batteries, respectively) with the least from mechanical processing (10 kg 1,4- DCB/ton of spent batteries). Contribution of high METP for NMC is mostly from the use of sulfuric acid (65.67%), followed by treatment of plastic waste (10.55%). Similarly, for NCA, the highest contributions due to sulfuric acid and treatment of plastic waste are 59.27% and 19.28%, respectively. For terrestrial ecotoxicity also, the hydrometallurgy route gives a higher impact over mechanical and thermal pyrometallurgy (6,659 kg 1,4- DCB/ton of spent batteries for NMC and 6,661 kg 1,4- DCB/ton of spent batteries for NCA). Such high TETP impact is attributed to used process material inputs. For stronger interpretation of results and to identify the contribution of various process inventories—electricity consumption, transportation, input materials, and waste management in the four environmental impact categories for different recycling routes (mechanical, thermal, and chemical)—see Figure 6.5.

For LFP batteries, Mohr et al. (2020) highlighted several key points regarding the GWP of lithium iron phosphate (LFP) batteries compared to nickel manganese cobalt (NMC) batteries. The authors noted that LFP batteries exhibit a higher CO_2 emission impact during recycling, primarily due to the lower energy density of LFP chemistry. Additionally, the recycling benefits of LFP cells are comparatively lower than those of NMC and nickel cobalt aluminum (NCA) batteries, especially from an economic standpoint. However, the study also emphasized that data provided for hydrometallurgical processing do not adequately represent a suitable treatment method for LFP batteries. Quan et al. (2022) also compared NMC and LFP batteries and found that the NMC battery had overall better comprehensive environmental performance than the LFP, but shorter service life across all life cycle phases (cradle to grave).

Landfill disposal: According to TCEQ results, large-format lithium-ion batteries are classified as hazardous waste at EoL, and they can be managed under the streamlined universal waste management standards until they reach a destination facility for recycling or discard (see Chapter 3.5). TCEQ regulations prohibit the disposal of batteries that are considered universal wastes in conventional municipal solid waste landfills. Instead, these products must be transported to authorized hazardous waste treatment, storage, and disposal facilities or managed as universal waste at a destination facility under Universal Waste Management rules (30 TAC Chapter 335 Subchapter H). A universal waste handler can collect and store EV batteries, for example, for a maximum of 1 year. Moreover, although universal waste standards prohibit the disposal of hazardous waste without a permit, they do allow certain processing operations, including the dismantling of battery packs and the electrical discharge of batteries. The final disposition of batteries that are considered as universal wastes may occur at a permitted destination facility.

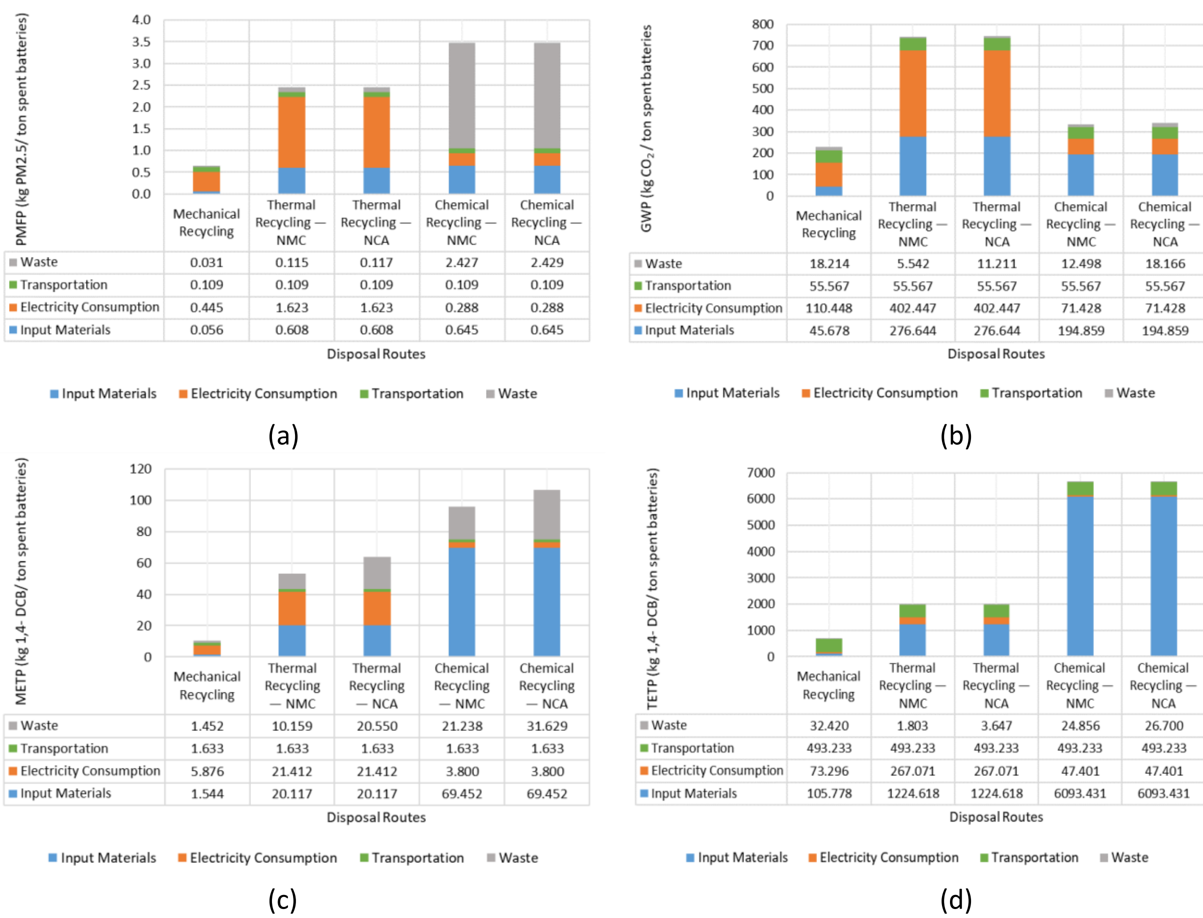

Figure 6.5 Contribution from landfill, mechanical, thermal, and chemical disposal methods of spent batteries (NMC and NCA) in (a) Fine particulate matter formation (PMFP), (b) CO_2 eq emissions (global warming potential, GWP), (c) Marine ecotoxicity (METP), and (d) Terrestrial ecotoxicity (TETP).

6.4 Observations from Reuse

When assessing disposal options for solar, wind, and energy storage equipment, it is essential to consider another alternative disposal option that is not discussed above, namely reuse, which is beyond the mandate of SB 1290. Although life cycle assessments for reuse were not conducted, key points from the literature can be used to consider and understand the associated environmental impacts from this route and to help to formulate more sustainable strategies for managing the EoL phase in the solar and wind energy sector.

Reuse is not disposal per se, but it can help prolong equipment life and minimize waste generation rate, thereby reducing the pressure on “disposal” options that include landfilling and recycling. Researchers have investigated factors related to reusing, refurbishing, and repowering wind turbine blades and other parts. Chiesura et al. (2020) examined the possible environmental benefits of using a new, reusable resin in glass fiber-reinforced polymer (GFRP) components. They reported that this method might decrease CO_2 emissions by 28%, mainly because of the capacity to reuse the resin. Korey et al. (2023) reported that blades undergoing repowering after 7 to 9 years of use have the potential to retain their value for a further 10 to 20 years, although the blades will probably be relocated to a new area. Reusing these blades might be viable if it is both economically competitive and logistically feasible to transfer them. Regarding refurbishing the blades for reuse in wind energy applications, Fitzgerald and Mishnaevsky (2023) showed that, where the blades remain structurally sound despite the need for maintenance, a repair process can be implemented to repair damage, fortify areas of weakness, and optimize aerodynamic performance. Commonly observed causes of damage and failure of wind turbine blades in the field include leading edge erosion, delamination in tapered sections, damage to adhesive connections in spar/cap, trailing and sometimes leading edges, and buckling and collapse under bending and twisting (Mishnaevsky, 2022). In many cases, the blades can be repaired and reused, potentially in new wind turbine installations, thereby prolonging their operational lifespan.

Related to reuse of solar panels, Panos et al. (2023) proposed the reuse and re-installation of outdated solar panels in other locations with lower energy demands, hence improving their usefulness and prolonging their lives. Faria et al. (2019) reported on reusing decommissioned power batteries by echelon utilization. This approach is expected to decrease battery waste and provide additional energy storage capacity for various applications. Casals et al. (2019) investigated the feasibility of reusing decommissioned batteries for energy storage in communication stations and low-speed electric vehicles (EVs).

7. Other Important Factors

7.1 Limitation of Study

7.1.1 Lack of Availability of Data and Previous Experience Produce a Range of Values

Conducting LCA for the EoL management of solar, wind, and battery technologies is substantially impeded by the absence of specific and dependable data. LCAs are essential for understanding the potential environmental impacts of installing, operating, and assessing EoL options of/for these technologies, particularly as they approach the end of their useful lifetimes. The quality and specificity of the underlying data are strongly correlated with the accuracy and robustness of LCA—and any—model results. Two areas of notable data issues include:

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- *Dependency on literature and assumptions:* The data used in LCA modeling of the EoL stages are derived from publicly available literature. Although literature-based data can serve as an important foundation in any research study, the data are frequently outdated, generalized, or in some cases not directly applicable to the specific study at hand. In this study, because many of the EoL management options either have undergone only cursory study, or the company-specific data for specific options were not available to us, we based the model on the data we could find. This required us either to make some assumptions based on professional experience and judgment, or to apply results from one technology to a related technology (see next bullet, below). These assumptions can introduce uncertainty about the LCA results.
- *Limited recycling method inventory for LFP batteries:* LFP batteries are gaining popularity for battery electric storage systems due to their extended cycle life and safety. However, the inventory data for recycling LFP batteries is nearly nonexistent, especially when compared with battery cathodes that contain various proportions of nickel and cobalt (NMC and NCA batteries). Thus, the recycling processes of LFP batteries are often assumed to be similar to those of NMC and NCA batteries. The lack of experience with, and data for, LFP recycling methods represents a gap in knowledge. The available LCA inventories frequently regard various lithium-ion battery types as if they undergo identical recycling processes, despite their unique material compositions and recycling requirements. The extent to which inventories for LFP versus NMC/NCA chemistries are alike or different is unclear, which means that comparisons of environmental impacts are difficult to make.

7.2 Role of Innovation

Innovation is a fundamental component of equitable growth. Progress in solar, wind, and battery technologies is transforming the energy industry by reducing GHGs and fostering a more diverse energy grid. Together with innovation that extends the lifespan of infield assets, revolutionizes recycling technologies, reduces landfill volumes, and minimizes the overall environmental impact, these technologies can pave the way toward a more sustainable future.

7.2.1 Advancing Recycling Technology

In addition to traditional recycling techniques such as mechanical, chemical, and thermal recycling methods, for advancing solar panels, wind turbines, and BESS recycling, continuous innovation has been identified in the literature from around the world (Table 7.1).

In repurposing and recycling, methods for prolonging the lifespan of solar panels, wind turbine blades, and batteries include regular maintenance (repair or refurbishment) to ensure optimal performance and to address minor issues before they escalate into major failures that require premature EoL decisions. A more detailed discussion of regular maintenance, which includes repair and refurbishment of faulty components and enables them for reuse, can be found in Chapters 5.1.2, 5.2.2, and 5.3.2.

Table 7.1 Technological innovations in solar panels, wind turbine blades, and battery energy storage systems for effective EoL management.

Equipment	Project	Technology	Details	Reference
Solar panels	Apollon Solar	NICE technology	The NICE technology uses a polyisobutylene (PIB) material (alternative for EVA encapsulation, which is the most difficult component to recycle) that has been extensively tested and verified in the insulating glass sector and has sealing qualities that provide exceptional and enduring airtightness and resistance to humidity and strong mechanical contact between the various components of the module. Additionally, the NICE architecture allows for easy and manual dismantling of modules, allowing the recovery of components as whole parts.	(Dupuis et al., 2012)
	TPedge	Encapsulant free module design	TPedge uses edge-sealing techniques, such as silicon, to remove the encapsulant from the surface of the cells.	(Fraunhofer, 2017)
		Design innovation	• Silver (Ag) metal can be replaced with copper/nickel (Cu/Ni) metal in solar modules, for introducing recycling trade-offs. • Tin (Sn) may be used as a substitute for Pb during manufacturing to ease recycling processes. • Ethylene vinyl acetate (EVA), an encapsulant, could be substituted for another durable material characterized by low vaporization temperatures, nonhazardous in vapor phase, and resilient to environmental conditions, thus representing a prospective resolution to the EVA recycling dilemma. Thermoplastics olefin resin filler sheets show potential in terms of	(Grandell and Höök, 2015; Hernández et al., 2012; Louwen et al., 2016; Norgren et al., 2020)

			both the functioning and recyclability of PV modules. • Frameless designs for PV modules ease the initial recycling process by completely avoiding the deframing process.	
Wind Turbine blades	Makeen Power (Denmark)	Advance prototype of pyrolysis facility	To recover fiberglass by blasting blades with heat and reuse it, rather than crushing it, as done in other technologies.	(Telsnig, 2022)
		Microwave-assisted chemical recycling	Fully reclaim fibers with minimum surface defects. The recovered fiber length is also long enough to provide better mechanical properties to distribute loads and to better impact resistance.	(Jani et al., 2022)
	Siemens Gamesa		The company modified the chemical composition of the blades to include a ”cleavage point“ that facilitates the separation of substances using a gentle process involving acetic acid and temperatures reaching 200°F during the recycling process, as compared to employing excessive heat.	(Fitzgerald and Mishnaevsky, 2023)
	CETEC (circular economy for thermoset epoxy composites) and Vestas	Chemcycling technology	A new recycling technique for epoxy/glass composites in 2022–2023. The method separates materials during recycling of the blade using “commoditized chemicals” under ambient temperature and pressure, then converts epoxy back to its fundamental components, which is hard to recover otherwise.	(Vestas, 2023)
		Novel materials	Improved feasibility of recycling CFRP by combining a green epoxy resin with a biodegradable polyamine ether (Recyclamine® 301) during design and manufacturing phases, thereby attaining recyclability, and recovering clean carbon fiber and a thermoplastic polymer from thermoset composites.	(Beg and Pickering, 2008; La Rosa et al., 2016)
	ENEL		The firm uses a process of shredding wind turbine blades, then separating the metal and fiberglass components from the foam and wood. These materials are then combined for cement manufacturing. Approximately 66% of the mixture substitutes cement sand and clay, while the remaining portion is incinerated to provide heat for cement kilns, hence decreasing the need for coal.	(Oliveira et al., 2020)

	Ireland's Gaoth Wind Energy, Japan's Mitsubishi Heavy Industries, and American Cyclics Inc.	Design innovation	These organizations collaborated to use glass-fiber reinforced cyclic butylene terephthalate resin (flowable thermoplastic resins) in creating the world's first 12.6 m recyclable wind turbine blades.	(Chen et al., 2019)
Battery energy storage system (BESS)			Replacing polymeric organic binders in batteries with water-soluble binders that can effortlessly eliminate them during the recycling process by washing with water.	(Zanoletti et al., 2024)
			Nanostructured hybrid materials composed of carbon and metal oxides have shown potential in enhancing the efficiency of charge transfer and reducing structural strain during charge/discharge cycles, which is important during the disposal stage.	(Liang et al., 2019)
Solar/ Wind/ Battery		Hybrid system	Due to the complexity of disassembly methods, self-learning robots cannot completely automate them; hence hybrid systems, wherein humans work with robotic arms to disassemble components, are more practical.	

7.2.2 Minimizing Landfill Impact and Extending Lifespan

One way to minimize landfill volumes and extend lifespans of these technologies is to contribute to the circular economy by potentially delaying the disposal of substantial quantities of materials by repurposing materials into another application (Table 7.2). In this way, the waste stream from solar, wind, and batteries considered in this study can be a valuable input to other products, thereby reducing their environmental footprint. This can benefit the broader economy overall.

Table 7.2 Repurposing application of solar panels, wind turbine blades, and battery energy storage systems.

Equipment	Country	Application	Industry	Details	Reference
Solar panel		Creative use		Solar panels can be transformed into art displays, furniture, or architectural components. Due to their sturdy and weather-resistant characteristics, they are well-suited for creative design initiatives.	(Pandey et al., 2016)
		Testing and prototyping		Used solar panels may be used for research endeavors, aiding in the testing of novel technologies,	(Pandey et al., 2016)

				strategies for enhancing efficacy, or more advanced recycling methodologies.	
Wind turbine blades	United States	Turbine blade park benches	Ohio-based firm known as Canvus	The organization generates a large quantity of 11 distinct items with these blades. For example, their “deborah” bench not only offers shelter but also has a swing. An alternative form, known as the “beacon,” can function as a seat, planter, or fountain.	(Bolin et al., 2023)
		Utility poles	Wind Team at Georgia Tech	They created a patented application to reuse EoL blades as vertical tower structures in future high-voltage transmission lines, contributing to the circular economy, specifically for future U.S. electrical system expansion. Reusing blades instead of steel and concrete in the electrical grid reduces the carbon footprint and avoids landfilling millions of tons of composite material.	(Al-Haddad et al., 2022; Alshannaq et al., 2023)
	Ireland	Turbine-blade bridges	BladeBridge	A pedestrian bridge 18 ft long was constructed in Cork City, using two retired turbine blades, each measuring 42 ft in length, as a substitute for steel. Their bridge yielded a 17% reduction in emissions compared to conventional steel bridges over a span of 60 years.	
	Denmark	Turbine-blade bike shelter		A distinctively designed bicycle shelter with a swooping curve lies in the main parking lot at the Port of Aalborg in Denmark. It has a canopy to keep bikes and riders dry and wind protected.	(Nagle et al., 2022)
Battery Energy Storage System	South America and Africa	Backup power		Backup power systems are strategically installed in urban areas to mitigate frequent power outages and provide electricity to essential facilities like hospitals, schools, and streetlights.	(Falk et al., 2020)

8. Conclusions and Final Thoughts

This study, conducted to satisfy SB 1290, identified several important findings related to the installation, operation, and disposal of solar, wind, and energy storage equipment. These include:

- The State of Texas has a regulatory framework in place to manage environmental and watershed impacts associated with these solar, wind and—to some extent—energy storage systems. In some cases, the regulations are Federal and are being implemented by TCEQ through primacy; in other cases, the statutes were developed and signed into law by the Texas Legislature and Governor; these include Senate Bill 760 (SB 760) and House Bill 2845 (HB 2845) for solar and wind energy.
    - The Federal rules identified herein center on protection of the environment to aid in reducing and preventing the discharge of pollutants from stormwater runoff, characterizing certain energy technologies as industrial waste that cannot be disposed of in municipal landfills, and ensuring that equipment that is damaged in the field cannot be allowed to leach chemicals into the soil and/or groundwater.
    - SB 760 and HB 2845 provide protection for landowners who agree to allow solar and wind energy generation on their lands. These protections include requirements for returning decommissioned lands to original conditions (to the extent possible) when electricity is no longer being generated, and financial surety that guarantees that the facility operator will have the resources needed for full decommissioning, among other things. These measures, along with existing federal rules, provide a reasonable framework for protection of the environment and watersheds from solar and wind energy generation.
    - Of particular importance is that both SB 760 and HB 2845 include energy storage systems (batteries) in their definition of the "facility." This means that energy storage systems that are paired with generation facilities are already being regulated from the standpoint of decommissioning, financial surety, etc. However, although large-format battery designs can be rigorously tested using UL procedures and installed using guidelines standardized by the National Fire Protection Association, it is unclear whether unincorporated counties, where many new systems are deployed, can require industry to follow these design and installation guidelines. Moreover, many energy storage deployments are no longer paired with generation facilities; rather, they are standalone facilities that provide services to ERCOT. It is unclear where these facilities fit in the regulatory landscape.

- Chapter 6 presents result from the LCA analyses and compares different EoL options, including landfilling and three recycling routes (mechanical, thermal, and chemical) for solar and wind technologies, and recycling only for battery technologies (landfilling was not considered for battery EoL). The LCA approach used herein, which follows international standards, includes 16 different environmental impact factors or pathways. Because data on recycling lithium-iron-phosphate (LFP) batteries, used mostly in energy storage systems, are missing or preliminary, we substituted more commonly understood and deployed battery chemistries (nickel-manganese-cobalt [NMC] and nickel-cobalt-aluminum [NCA]) in the analyses. The results show that landfilling and mechanical recycling (shredding, crushing, etc.) are generally more favorable for most of the environmental impacts for solar panel recycling; but the results are mixed for recycling wind turbine blades, where thermal processing of composites has the potential for higher CO_2 eq and air-related emissions. Maintaining strict environmental controls on these processes would further reduce the environmental impacts of these EoL options. Moreover, our analyses do not account for the (environmental and economic) benefits of building secondary markets for the outcomes of recycling routes. Building a circular economy around the secondary products would reduce the overall environmental impacts of solar, wind, and battery technologies, as it would for nearly any other industrial process.

- Overall, our study was limited by the data available to our research team at the time the study was conducted. In some cases, companies would not disclose proprietary data to us, and in other cases, data is apparently not available overall. For example, long-term exposure of stored or abandoned wind turbine blades to UV light and abrasion from wind and sand, will likely lead to degradation of the composite material that is composed of resin, glass, or carbon fibers and either PVC or balsa wood. The resins that reinforce these wind turbine blades are used because they are resilient against environmental exposure; nonetheless, the lack of any leachability data (using either TCLP or SPLP) opens the question to the potential long-term risks of disposing blades in landfills. As mentioned above, we are unaware of LCA data on the recycling of LFP batteries, so we did our best to find suitable surrogates. As the recycling (or overall EoL) industry builds up to meet the demand over the next 10 years, we hope and expect more data to become available, so that thorough analyses of potential environmental impacts can be conducted.

- Peer-reviewed literature has shown that intact solar panels (especially crystalline silicon type panels) are resistant to leaching of electronic components, but some studies have reported low-level release of lead and other constituents using two types of leachability tests developed by EPA: the TCLP and SPLP tests. Both tests assume exposure of material to last between 3 and 10 years. Panels left on site with damaged glass laminate (e.g., from hail) have garnered noteworthy media attention, given the concern that damaged laminate could expose electronic components to dust and moisture, accelerating corrosion. Thus, swift action by industry to remove damaged panels from the field will not only reduce exposure of components and minimize the potential for leaching, but also will provide some reassurance for neighbors of solar generation facilities and show that industry is taking measures to protect local land and water resources.

- In addition to recycling methods, Chapter 6 also presents a discussion of landfill disposal routes.
    - Because utility-scale solar energy is relatively new in Texas (capacity has increased from nearly negligible amounts in 2014 to over 7,000 MW today), most panels are well within their design life and decisions regarding landfilling have not yet been needed; however, those decisions will soon be upon industry. And, although the volumes of solar panels that could be authorized to go to an MSW landfill is very small compared to the total waste being generated across the state (i.e., less than 1% of the volume), recycling solar panels and recovering the aluminum, silica and other valuable materials should be considered as a first option. By some estimates, recycling solar panels recovers over 95% of the volume, which would significantly reduce landfilling volumes.
    - Landfilling is a commonly used method of waste disposal for wind turbine blades. However, landfilling of these bulky objects, which can surpass many 10s of meters in length, can present considerable difficulties. For example, the size of these objects and the resiliency of the resin-reinforced glass or carbon fiber material mean that the blades will not decay or compress, which are commonly relied upon for enhancing longevity of landfill operations. Additional energy-intensive pre-processing, such as cutting and crushing, requires specialized equipment, which further complicates the process. In addition, the pre-processing activities can lead to airborne particulate matter that could pose a worker-safety issue.
    - Disposal and Recycling of Energy Storage Systems - The disposal of large-format lithium-ion batteries in municipal solid waste landfills is prohibited under federal and state regulations.

Instead, these batteries need to be handled according to specified hazardous waste management methods until handlers determine whether the units can be shredded and further recycled. The widespread recycling of utility-scale energy storage systems needs to overcome two major issues.

- First, lithium-iron-phosphate (LFP) batteries that are used for stationary energy storage, as opposed to those used for electric vehicles, are generally not economically recyclable, because the batteries do not contain enough high-value metals to encourage their recovery. Hence, recyclers are not as enthusiastic about accepting these batteries into their recycling circuits, as they are with EV batteries that contain valuable metal material.
- Second, even if spent LFP batteries were sought-after commodities, the number of currently operating recycling facilities is not sufficient to handle future volumes of batteries expected when they are decommissioned from the field. Because the expected lifespan for these batteries could reach 10 years or longer (depending on operating conditions and number of full cycles; Preger et al., 2020) and that, at least in Texas, nearly all utility-scale batteries were deployed in the last few years, industry has some available time to innovate methods for recycling LFP batteries and to ramp up operations before large numbers of battery packs are decommissioned.

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10. Appendix

Appendix A: S.B. No. 1290 (without signature blocks)

AN ACT

relating to a study of the effects of the installation, operation, removal, and disposal of solar, wind turbine, and energy storage equipment.

BE IT ENACTED BY THE LEGISLATURE OF THE STATE OF TEXAS:

SECTION 1. DEFINITION. In this Act, "commission" means the Texas Commission on Environmental Quality.

SECTION 2. STUDY ON EFFECTS OF INSTALLATION, OPERATION, REMOVAL, AND DISPOSAL OF CERTAIN EQUIPMENT. (a) The commission shall conduct a study on the current and potential effects of the installation, operation, removal, and disposal of solar, wind turbine, and energy storage equipment on the environment and watersheds.

(b) In conducting the study under this section, the commission shall consult with:

(1) the Department of Agriculture;

(2) the Texas A&M Forest Service;

(3) the Texas A&M AgriLife Extension Service;

(4) the Texas A&M Engineering Extension Service;

(5) groundwater conservation districts; and

(6) river authorities.

(c) The commission may enter into a memorandum of understanding with a university or foundation to assist with the study.

(d) Not later than December 1, 2024, the commission shall submit to the governor, lieutenant governor, and speaker of the house of representatives a report that includes the findings of the study conducted under this section.

SECTION 3. EXPIRATION. This Act expires January 1, 2025.

SECTION 4. EFFECTIVE DATE. This Act takes effect immediately if it receives a vote of two-thirds of all the members elected to each house, as provided by Section 39, Article III, Texas Constitution. If this Act does not receive the vote necessary for immediate effect, this Act takes effect September 1, 2023.

Appendix B: Energy Generation and Projected Capacity within Groundwater Conservation Districts and River Authorities

- **Fields description used in Table B.1 and Table B.2:**

winCnt, winMw: Count and capacity of existing wind generation sites

solCnt, solMw: Count and capacity of existing solar generation sites

batCnt, batMw: Count and capacity of existing battery sites

totCnt, totMw: Sum of the count and capacity fields for existing sites.

pWinCnt, pWinMw: Count and capacity of wind generation sites in the interconnect queue

pSolCnt, pSolMw: Count and capacity of solar generation sites in the interconnect queue

pBatCnt, pBatMw: Count and capacity of battery sites in the interconnect queue

pTotCnt, pTotMw: Sum of the count and capacity fields for sites in the interconnect queue

Table B.1 Geospatial dataset on energy generation and projected capacity within Groundwater Conservation Districts.

S. No	Name	DistName	Counties	winCnt	winMw	solCnt	solMw	batCnt	batMw	totCnt	totMw	pWinCnt	pWinMw	pSolCnt	pSolMw	pBatCnt	pBatMw	pTotCnt	pTotMw
1	Uvalde County UWCD	Uvalde County Underground Water Conservation District	Uvalde	0	0	1	100	0	0	1	100	0	0	4	834.66	5	436	0	0
2	Real-Edwards C and R District	Real-Edwards Conservation and	Edwards, Real	0	0	1	1.5	0	0	1	1.5	0	0	0	0	0	0	0	0

		Reclamation District																	
3	Brewster County GCD	Brewster County Groundwater Conservation District	Brewster	0	0	1	50	0	0	1	50	0	0	0	0	0	0	0	0
4	Fayette County GCD	Fayette County Groundwater Conservation District	Fayette	0	0	0	0	0	0	0	0	0	0	2	440.63	2	411.88	0	0
5	Middle Pecos GCD	Middle Pecos Groundwater Conservation District	Pecos	5	542.2	11	1772	2	17.4	18	2331.6	6	500.26	9	2022.05	16	2281.57	31	4803.88
6	Texana GCD	Texana Groundwater Conservation District	Jackson	0	0	0	0	0	0	0	0	0	0	7	1592.56	5	426.22	0	0
7	Refugio GCD	Refugio Groundwater Conservation District	Refugio	1	220	0	0	0	0	1	220	0	0	3		3	711.75	0	0
8	Goliad County GCD	Goliad County Groundwater Conservation District	Goliad	0	0	0	0	0	0	0	0	0	0	7	1553.04	7	745.94	0	0
9	Evergreen UWCD	Evergreen Underground Water	Atascosa, Frio, Karnes, Wilson	0	0	9	147	0	0	9	147	0	0	20	3756.59	15	1437.82	0	0

		Conservation District																	
10	Brazos Valley GCD	Brazos Valley Groundwater Conservation District	Brazos, Robertson	0	0	0	0	1	50	1	50	0	0	0	0	14	2102.69	0	0
11	Brazoria County GCD	Brazoria County Groundwater Conservation District	Brazoria	0	0	4	598.1	8	249.5	12	847.6	2		19	5145.19	48	7711.08	69	
12	Clear Fork GCD	Clear Fork Groundwater Conservation District	Fisher	0	0	0	0	0	0	0	0	1	418.9	2	726.3	3	180	6	1325.2
13	Pineywoods GCD	Pineywoods Groundwater Conservation District	Angelina, Nacogdoches	0	0	0	0	0	0	0	0	0	0	6	1344.52	7	1139.72	0	0
14	Post Oak Savannah GCD	Post Oak Savannah Groundwater Conservation District	Burleson, Milam	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	Northern Trinity GCD	Northern Trinity Groundwater Conservation District	Tarrant	0	0	1	1.1	1	100	2	101.1	0	0	0	0	6	1272.58	0	0

16	Wes-Tex GCD	Wes-Tex Groundwater Conservation District	Nolan	12	2080.6	1	200	0	9.9	13	2290.5	6	217.41	3	1032.36	1	509	10	1758.77
17	Wintergarden GCD	Wintergarden Groundwater Conservation District	Dimmit, La Salle, Zavala	0	0	1	200	2	19.8	3	219.8	0	0	7	1164.81	12	1771.75	0	0
18	Coastal Plains GCD	Coastal Plains Groundwater Conservation District	Matagorda	1	151.2	0	0	1	10	2	161.2	1	241.2	18	3932.81	16	1822.54	35	5996.55
19	Kinney County GCD	Kinney County Groundwater Conservation District	Kinney	1	99.8	0	0	0	0	1	99.8	0	0	3	590.23	6	563.48	0	0
20	Lone Star GCD	Lone Star Groundwater Conservation District	Montgomery	0	0	0	0	0	0	0	0	0	0	0	0	2	367.16	0	0
21	Pecan Valley GCD	Pecan Valley Groundwater Conservation District	DeWitt	0	0	0	0	0	0	0	0	0	0	4	868.4	3	489.67	0	0
22	Lost Pines GCD	Lost Pines Groundwater Conservation District	Bastrop Lee	0	0	0	0	0	0	0	0	0	0	5	666.66	7	1029.22	0	0
23	McMullen GCD	McMullen Groundwater	McMullen	0	0	0	0	0	0	0	0	0	0	1	261.42	0	0	0	0

		Conservation District																	
24	Mesa UWCD	Mesa Underground Water Conservation District	Dawson	1	211.2	2	150	0	0	3	361.2	0	0	2	673.6	3	203.1	0	0
25	Presidio County UWCD	Presidio County Underground Water Conservation District	Presidio	0	0	1	10	0	0	1	10	0	0	0	0	0	0	0	0
26	Sandy Land UWCD	Sandy Land Underground Water Conservation District	Yoakum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	Saratoga UWCD	Saratoga Underground Water Conservation District	Lampasas	0	0	0	0	0	0	0	0	0	0	2	300	4	615.73	0	0
28	Glasscock GCD	Glasscock Groundwater Conservation District	Glasscoc, Reagan	5	910.2	0	0	0	0	5	910.2	0	0	0	0	0	716.21	0	0
29	Red Sands GCD	Red Sands Groundwater Conservation District	Hidalgo	0	0	0	0	0	0	0	0	2	468.4	3	575.9	30	3937.79	35	4982.09

30	Bee GCD	Bee Groundwater Conservation District	Bee	2	507.8	1	50.7	0	0	3	558.5	1	268.2	6	1383.27	8	794.42	15	2445.89
31	Blanco-Pedernales GCD	Blanco-Pedernales Groundwater Conservation District	Blanco	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	Victoria County GCD	Victoria County Groundwater Conservation District	Victoria	0	0	0	0	1	9.9	1	9.9	1	253.29	9		12	2358.45	22	
33	Coke County UWCD	Coke County Underground Water Conservation District	Coke	2	674.6	0	0	0	0	2	674.6	0	0	1	150	3	315.09	0	0
34	Clearwater UWCD	Clearwater Underground Water Conservation District	Bell	0	0	0	0	0	0	0	0	0	0	9	1911.9	6	834.74	0	0
35	Fort Bend Subsidence District	Fort Bend Subsidence District	Fort Bend	0	0	4	588.4	0	0	4	588.4	0	0	2	790.04	14	2636.95	0	0
36	Headwaters UWCD	Headwaters Groundwater Conservation District	Kerr	0	0	0	0	0	0	0	0	0	0	0	0	1	120.96	0	0

37	Gateway GCD	Gateway Groundwater Conservation District	Childress, Cottle, Foard, Hardema, King, Motley	3	649.9	1	240	0	0	4	889.9	0	0	0	0	0	0	0	0
38	Hemphill County UWCD	Hemphill County Underground Water Conservation District	Hemphill	1	288.6	0	0	0	0	1	288.6	0	0	0	0	0	0	0	0
39	Hill Country UWCD	Hill Country Underground Water Conservation District	Gillespie	0	0	0	0	0	0	0	0	0	0	1	150	2	298.61	0	0
40	Live Oak UWCD	Live Oak Underground Water Conservation District	Live Oak	0	0	0	0	0	0	0	0	0	0	0	0	1	60.4	0	0
41	Llano Estacado	Llano Estacado Underground Water Conservation District	Gaines	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	Lone Wolf GCD	Lone Wolf Groundwater Conservation District	Mitchell	2	357.5	0	0	0	0	2	357.5	0	0	2	348.86	2	301.5	0	0

43	Southern Trinity GCD	Southern Trinity Groundwater Conservation District	McLennan	1	300	2	15	0	0	3	315	1	300	8	1163.89	5	831.31	14	2295.2
44	North Plains GCD	North Plains Groundwater Conservation District	Dallam, Hansford, Hartley, Hutchinson Lipscomb, Moore, Ochiltree, Sherman	16	1632	0	0	0	0	16	1632	0	0	0	0	0	0	0	0
45	Cow Creek GCD	Cow Creek Groundwater Conservation District	Kendall	0	0	0	0	0	0	0	0	0	0	0	0	2	351.62	0	0
46	Middle Trinity GCD	Middle Trinity Groundwater Conservation District	Bosque, Comanche, Coryell, Erath	2	300.6	4	35.3	0	0	6	335.9	0	0	13	2583.02	15	2491	0	0
47	Red River GCD	Red River Groundwater Conservation District	Fannin, Grayson	0	0	7	236.4	0	0	7	236.4	0	0	0	0	5	905.63	0	0
48	Kenedy County GCD	Kenedy County Groundwater Conservation District	Brooks, Hidalgo, Jim Wells, Kenedy, Kleberg,	5	1075.4	0	0	0	0	5	1075.4	0	0	0	0	0	0	0	0

			Nueces, Willacy																
49	Brush Country GCD	Brush Country Groundwater Conservation District	Brooks, Hidalgo, Jim Hogg, Jim Wells	1	78	1	9.5	0	0	2	87.5	0	0	0	0	0	0	0	0
50	North Texas GCD	North Texas Groundwater Conservation District	Collin, Cooke, Denton	3	417.6	5	347.1	0	125	8	889.7	0	0	0	0	16	2290.37	0	0
51	Prairielands GCD	Prairielands Groundwater Conservation District	Ellis, Hill, Johnson, Somervell	1	300	5	632.1	0	0	6	932.1	0	0	22		0	0	0	0
52	Garza County UWCD	Garza County Underground Conservation District	Garza	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0
53	Hudspeth County UWCD No. 1	Hudspeth County Underground Water Conservation District No. 1	Hudspeth	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
54	Corpus Christi ASRCD	Corpus Christi Aquifer Storage & Recovery Conservation District	Nueces, San Patricio	0	0	0	0	0	0	0	0	0	0	9	2201.28	26	3773.11	0	0

55	South Plains UWCD	South Plains Underground Water Conservation District	Hockley, Terry	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
56	Santa Rita UWCD	Santa Rita Underground Water Conservation District	Reagan	1	300	0	0	0	0	1	300	0	0	0	0	2	110.41	0	0
57	Sterling County UWCD	Sterling County Underground Water Conservation District	Sterling, Tom Green	3	1018.2	2	145	0	0	5	1163.2	4	461	0	0	0	0	0	0
58	Crockett County GCD	Crockett County Groundwater Conservation District	Crockett	2	800.6	0	0	0	0	2	800.6	2	489.32	2	204.88	5	711.52	9	1405.72
59	Permian Basin UWCD	Permian Basin Underground Water Conservation District	Howard, Martin	4	355.6	0	0	1	2	5	357.6	0	0	0	0	13	2428.13	0	0
60	Neches & Trinity Valleys GCD	Neches & Trinity Valleys Groundwater Conservation District	Anderson, Cherokee, Henderson	0	0	0	0	0	0	0	0	0	0	0	0	12	1939.1	0	0

61	Menard County UWCD	Menard County Underground Water District	Menard	0	0	0	0	0	0	0	0	0	0	2	152.33	1	254.58	0	0
62	Rusk County GCD	Rusk County Groundwater Conservation District	Rusk	0	0	0	0	0	0	0	0	0	0	1	201.06	2	557.15	0	0
63	Bluebonnet GCD	Bluebonnet Groundwater Conservation District	Austin, Grimes, Walker, Waller	0	0	3	221.2	0	210	3	431.2	0	0	0	0	0	0	0	0
64	Trinity Glen Rose GCD	Trinity-Glen Rose Groundwater Conservation District	Bexar, Kendall	0	0	0	0	1	9.9	1	9.9	0	0	0	0	21	3964.74	0	0
65	Sutton County UWCD	Sutton County Underground Water Conservation District	Sutton	0	0	0	0	0	0	0	0	0	0			1	102.98	0	0
66	Coastal Bend GCD	Coastal Bend Groundwater Conservation District	Wharton	0	0	1	10	0	0	1	10	2	362.7	16	5584.22	20	3884.92	38	9831.84
67	High Plains UWCD No.1	High Plains Underground Water Conservation District No. 1	Armstrong, Bailey, Castro, Cochran, Crosby, Deaf Smith,	21	3619.4	1	4.4	0	0	22	3623.8	0	0	0	0	0	0	0	0

			Floyd, Hale, Hockley, Lamb, Lubbock, Lynn, Parmer, Potter, Randall, Swisher																
68	Central Texas GCD	Central Texas Groundwater Conservation District	Burnet	0	0	0	0	0	0	0	0	0	0	1	82.55	2	204.73	0	0
69	Starr County GCD	Starr County Groundwater Conservation District	Starr	5	947.6	0	0	0	0	5	947.6	4	1005.6	7	1272.72	13	1819.08	24	4097.4
70	Southeast Texas GCD	Southeast Texas Groundwater Conservation District	Hardin, Jasper, Newton, Tyler	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
71	San Patricio County GCD	San Patricio Groundwater Conservation District	San Patricio	5	1044.1	0	0	0	0	5	1044.1	2		6	1384.13	10	1451.81	18	
72	Panhandle GCD	Panhandle Groundwater Conservation District	Armstrong, Carson, Donley, Gray, Hutchinson, Potter,	10	1385.5	0	0	0	0	10	1385.5	0	0	0	0	0	0	0	0

			Roberts, Wheeler																
73	Irion County WCD	Irion County Water Conservation District	Irion, Tom Green	1	302 .4	0	0	0	0	1	302 .4	0	0	0	0	0	0	0	0
74	Jeff Davis County UWCD	Jeff Davis County Underground Water Conservation District	Jeff Davis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
75	Plum Creek CD	Plum Creek Conservation District	Caldwell, Hays	0	0	0	0	0	0	0	0	0	0	0	0	6	693 .45	0	0
76	Lower Trinity GCD	Lower Trinity Groundwater Conservation District	Polk, San Jacinto	0	0	1	150	0	0	1	150	0	0	0	0	0	0	0	0
77	Barton Springs/E dwards Aquifer CD	Barton Springs/Edward s Aquifer Conservation District	Caldwell, Hays, Travis	0	0	0	0	0	0	0	0	0	0	0	0	11	110 7.2 3	0	0
78	Upper Trinity GCD	Upper Trinity Groundwater Conservation District	Hood, Montague, Parker, Wise	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

79	Guadalupe County GCD	Guadalupe County Groundwater Conservation District	Guadalupe	0	0	1	4.9	0	0	1	4.9	0	0	4	831.22	2	509.13	0	0
80	Gonzales County UWCD	Gonzales County Underground Water Conservation District	Caldwell, Gonzales	0	0	0	0	0	0	0	0	0	0	10	1253.81	9	764.85	0	0
81	Edwards Aquifer Authority	Edwards Aquifer Authority	Atascosa, Bexar, Caldwell, Comal, Guadalupe, Hays, Medina, Uvalde	0	0	12	241.8	2	19.9	14	261.7	0	0	0	0	37	5741.98	0	0
82	Culberson County GCD	Culberson County Groundwater Conservation District	Culberson	0	0	0	0	0	0	0	0	0	0	3	570.76	0	0	0	0
83	Duval County GCD	Duval County Groundwater Conservation District	Duval	1	300	0	0	0	0	1	300	0	0	3	391.98	3	247.78	0	0
84	Mesquite GCD	Mesquite Groundwater	Briscoe, Childress,	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

		Conservation District	Collingsworth, Hall																
85	Panola County GCD	Panola County Underground Water Conservation District	Panola	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
86	Colorado County GCD	Colorado County Underground Water Conservation District	Colorado	0	0	0	0	0	0	0	0	0	0	5	1520.86	10	1194.88	0	0
87	Terrell County GCD	Terrell Groundwater Conservation District	Terrell	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
88	Calhoun County GCD	Calhoun Groundwater Conservation District	Calhoun, Refugio	0	0	0	0	1	9.9	1	9.9	0	0	4		5	963.25	0	0
89	Reeves County GGD	Reeves County Groundwater Conservation District	Reeves	0	0	1	100	9	172.3	10	272.3	0	0	5	947.55	6	704.12	0	0
90	Comal Trinity GCD	Comal Trinity Groundwater Conservation District	Comal	0	0	0	0	0	0	0	0	0	0	0	0	1	5	0	0

91	Hays Trinity GCD	Hays Trinity Groundwater Conservation District	Hays	0	0	0	0	0	0	0	0	0	0	0	0	1	75.38	0	0
92	Southwestern Travis County GCD	Southwestern Travis County Groundwater Conservation District	Travis	0	0	0	0	0	0	0	0	0	0	1	-53.3	5	413.78	0	0
93	Mid-East Texas GCD	Mid-East Texas Groundwater Conservation District	Freestone, Leon, Madison	0	0	0	0	0	0	0	0	0	0	17	3743.61	16	2503.77	0	0
94	Plateau UWC and Supply District	Plateau Underground Water Conservation And Supply District	Schleicher	2	349.5	0	0	0	0	2	349.5	1	241.13	6	1602	5	589.54	12	2432.67
95	Harris-Galveston Coastal Subsidence District	Harris-Galveston Coastal Subsidence District	Galveston, Harris	0	0	0	0	3	29.7	3	29.7	0	0	0	0	43	8987.38	0	0
96	Medina County GCD	Medina County Groundwater Conservation District	Medina	0	0	0	0	0	0	0	0	0	0	2	210.9	2	281.8	0	0
97	Lipan-Kickapoo WCD	Lipan-Kickapoo Water	Concho, Runnels, Tom Green	2	640	3	519.8	0	0	5	1159.8	0	0	9	2150.06	11	1576.92	0	0

		Conservation District																	
98	Hickory UWCD No. 1	Hickory Underground Water Conservation District No. 1	Concho, Kimble, Mason, McCulloch, Menard, San Saba	1	180	1	7.5	1	100	3	287.5	0	0	0	0	0	0	0	0
99	Bandera County River Authority & Ground Water District	Bandera County River Authority	Bandera	0	0	0	0	0	0	0	0	0	0	1	124.65	1	9.8	0	0
100	Kimble County GCD	Kimble County Groundwater Conservation District	Kimble	0	0	0	0	1	9.9	1	9.9	0	0	0	0	2	316.3	0	0
101	Rolling Plains GCD	Rolling Plains Groundwater Conservation District	Baylor, Haskell, Knox	9	1915.6	2	325	0	77.6	11	2318.2	0	0	0	0	0	0	0	0

Table B.2 Geospatial dataset on energy generation and projected capacity within River Authorities.

S. No	Name	Counties	winCnt	winMw	solCnt	solMw	batCnt	batMw	totCnt	totMw	pWinCnt	pWinMw	pSolCnt	pSolMw	pBatCnt	pBatMw	pTotCnt	pTotMw

1	West Central Texas MWD	Taylor, Jones, Shackelford, Stephens									3	236.4	11	2649.88	11	2303.01	25	5189.29
2	Mackenzie MWA	Briscoe									1	658.8	2	903.3	1	410.94	4	1973.04
3	Lower Colorado River Authority	Edwards, Fayette, Bastrop, Sutton, Menard, Kimble, Taylor, Gillespie, Mason, Blanco, Llano, Burnet, McCulloch, San Saba, Lampasas, Mills, Travis, Lee, Brown, Callahan, Comanche, Eastland, Matagorda, Wharton, Colorado, Real, Kerr, Kendall, Hays, Caldwell, Schleicher, Concho, Runnels, Coleman	5	1171.2	6	196	5	221.4	16	1588.6	14	2407.35	80	19480.98	118	17590.13	212	39478.46

4	Canadian River MWA	Dawson, Terry, Lynn, Hockley, Lamb, Randall, Potter, Hutchinson, Gray, Lubbock, Hale	1	3	0	0	0	0	1	3	3	1283.92	8	2878.16	7	1186.64	18	5348.72
5	Franklin County WD	Franklin	0	0	1	250	0	0	1	250	0	0	6	1162.4	6	479.41	12	1641.81
6	Lower Neches Valley Authority	Liberty, Jefferson, Hardin, Tyler, Chambers									0	0	2	300.6	3	687.46	5	988.06
7	Gulf Coast WA	Galveston	0	0	0	0	3	29.7	3	29.7	0	0	0	0	11	2476.83	11	2476.83
8	Central Colorado River Authority	Coleman									0	0	1	400.58	2	241.92	3	642.5
9	Palo Duro River Authority	Moore, Hansford	11	1342.1	0	0	0	0	11	1342.1	0	0	0	0	0	0	0	0
10	Trinity River Authority	Ellis, Tarrant, Dallas, Liberty, Chambers, Walker, San Jacinto, Leon, Madison, Freestone, Houston, Trinity, Polk,	1	299.2	8	892.2	1	150	10	1341.4	3	772.2	54	10724.37	70	10803.71	127	22300.28

		Navarro, Anderson, Henderson, Kaufman															
11	Bistone MWSD	Limestone									0	0	8	141 0.57	4	204. 22	12	161 4.79
12	Angelina-Neches River Authority	Orange, Houston, Trinity, Polk, Jasper, Newton, Angelina, Nacogdoches, Sabine, San Augustine, Van Zandt, Rusk, Shelby	0	0	1	59	0	0	1	59	0	0	12	250 4.98	19	327 5.95	31	578 0.93
13	Sulphur River Authority	Hunt, Hopkins, Morris, Cass, Delta, Franklin, Titus, Fannin, Lamar, Bowie, Red River	0	0	6	107 2.1	0	0	6	107 2.1	1	396. 8	39	707 4.93	29	389 8.55	69	113 70.2 8
14	Upper Colorado River Authority	Schleicher, Irion, Tom Green, Concho, Sterling, Coke, Runnels	10	298 4.7	6	864. 8	0	0	16	384 9.5	6	110 7.53	16	390 2.06	19	248 1.55	41	749 1.14
15	Bexar Metro Water District	Medina, Atascosa, Bexar, Comal	0	0	1	10.6	0	0	1	10.6	0	0	6	790. 59	24	410 3.4	30	489 3.99

16	Lubbock County WCID 1	Lubbock	2	11.7	1	4.4	0	0	3	16.1	0	0	0	0	2	479.8	2	479.8
17	Northeast Texas MWD	Upshur, Camp, Morris, Marion, Cass									0	0	0	0	0	0	0	0
18	Nueces River Authority	Dimmit, Kinney, Maverick, Zavala, Uvalde, Edwards, Real, Duval, La Salle, McMullen, Jim Wells, Nueces, San Patricio, Live Oak, Bee, Medina, Frio, Atascosa, Bandera, Karnes, Wilson, Bexar	9	1887.2	5	442.1	2	19.8	16	2349.1	4	465.21	61	12047.64	108	14328.89	173	26841.74
19	Guadalupe-Blanco River Authority	Refugio, Comal, Kendall, Victoria, DeWitt, Guadalupe, Gonzales, Hays, Caldwell, Calhoun	1	220	1	4.9	2	19.8	4	244.7	1	253.29	31	3148.43	35	5517.35	67	8919.07
20	Red River Authority	Parmer, Crosby, Castro, Floyd, Swisher, Briscoe, Dickens, Knox,	57	9486.1	14	1239.1	1	30	72	10755.2	27	9146.7	75	18317.92	60	10402.95	162	37867.57

		King,Motley,Hall,Cottle,Foard,Hardeman,Childress,Oldham,Deaf Smith,Randall,Armstrong,Potter,Carson,Hartley,Hutchinson,Gray,Donley,Collingsworth,Wheeler,Roberts,Hemphill,Baylor,Archer,Clay,Wilbarger,Wichita,Montague,Cooke,Grayson,Lipscomb,Fannin,Lamar,Bowie,Red River,Hale																
21	Brazos River Authority	Cochran,Bailey,Dawson,Terry,Borden,Lynn,Garza,Nolan,Taylor,Scurry,Kent,Fisher,Jones,Stonewall,Haskell,Mills,Williamson,Lee,Milam,Bell,Coryell,Hamilton,McLennan,Falls,Brown,Callahan,Comanche,Eastland,Era	56	10898.2	23	2555.8	6	596.2	85	14050.2	45	8526.45	203	49113.97	255	44089.25	503	101729.7

		th,Shackelford,Throckmorton,Stephens,Palo Pinto,Young,Bosque,Hood,Somervell,Hill,Johnson,Parker,Hockley,Lamb,Jack,Brazoria,Austin,Waller,Fort Bend,Washington,Burleson,Grimes,Brazos,Robertson,Limestone,Bastrop,Parmer,Burnet,Lampasas,Crosby,Lubbock,Castro,Hale,Floyd,Swisher,Dickens,Knox,King,Baylor,Archer																
22	Upper Neches River MWA	Anderson,Cherokee									0	0	2	338.18	5	536.39	7	874.57
23	Lavaca-Navidad River Authority	Jackson									0	0	7	1592.56	5	426.22	12	2018.78
24	Sabine River Authority	Orange,Jasper,Newton,Sabine,San Augustine,Smit	0	0	2	20	1	190	3	210	0	0	22	3378.78	33	5248.52	55	8627.3

		h,Kaufman,Rockwall,Collin,Hunt,Van Zandt,Wood,Hopkins,Rains,Rusk,Shelby,Panola,Gregg,Upshur,Harrison																
25	San Antonio River Authority	Goliad,Bexar,Karnes,Wilson	0	0	19	158.8	2	19.9	21	178.7	0	0	21	4392.08	38	5392.27	59	9784.35
26	Titus County FWSD 1	Titus									0	0	0	0	0	0	0	0
27	CCWID #10	Cameron									1	300	6	1141.14	17	2558.76	24	3999.9
28	San Jacinto River Authority	Waller,Fort Bend,Liberty,Grimes,Montgomery,Walker,San Jacinto									0	0	9	2469.3	31	6953.3	40	9422.6
29	Colorado River MWD	Ector,Howard,Scurry	1	120	0	0	1	9.9	2	129.9	4	573.82	11	2995.69	24	4410.05	39	7979.56
30	Tarrant Regional WD and WCID	Tarrant	0	0	1	1.1	0	0	1	1.1	0	0	0	0	6	1272.58	6	1272.58
31	Dallas Co. U&RD	Dallas									0	0	0	0	11	1886.38	11	1886.38

32	White River MWD	Garza,Crosby,Dickens									0	0	3	603.4	5	1057.93	8	1661.33
33	North Central Texas Municipal Water Auth	Haskell,Knox									1	225.6	14	3777.33	9	976.63	24	4979.56
34	Palo Pinto County MWD 1	Palo Pinto									0	0	3	365.03	1	120.68	4	485.71
35	Bexar-Medina-Atascosa Counties Water Imp	Medina,Atascosa,Bexar									0	0	6	790.59	23	4098.4	29	4888.99
36	Upper Guadalupe River Authority	Kerr									0	0	0	0	1	120.96	1	120.96
37	Sulphur Springs WD	Hopkins									0	0	8	1418.69	7	1185.41	15	2604.1
38	Sulphur River MWD	Hunt,Hopkins,Delta									0	0	16	2415.91	10	1518.24	26	3934.15
39	North Texas MWD	Denton,Rockwall,Collin,Dallas,Kaufman	0	0	1	5.9	0	0	1	5.9	0	0	6	996.41	27	4090.05	33	5086.46

Appendix C: Questionnaire related to "a study of the effects of the installation, operation, removal, and disposal of solar, wind turbine, and energy storage equipment."– SB 1290

Table C.1 Questionnaire for solar photovoltaic installers

	Answers
Name of the organization (optional)	
Date	
What types of solar PV systems are commonly installed?	• Residential • Com/Industrial • Utility-scale
What is the expected lifespan of the solar panels you install?	
How often is routine maintenance for your solar PV systems recommended?	
How do you monitor the performance of your installed solar PV systems?	
What steps do you take to assess and mitigate potential risks, such as extreme weather events or natural disasters, that could impact the solar installation?	
How do you handle panels damaged during installation?	
Is your company responsible for the end-of-life decisions for the solar PV components that you install?	• Yes • No
If yes, how do you handle the disposal and/or recycling of solar PV components at the end of their life cycle or at premature failure (including shipping to an off-site facility, disassembly, etc.)? In particular, do you partner with recyclers?	

Table C.2 Questionnaire for solar photovoltaic recyclers

	Answers
Name of the organization (optional)	
Date	
From which sources do you expect to collect your PV panels?	• Residential • Com/Industrial • Utility-scale
On average, how many metric tons of photovoltaic waste does the facility handle annually? How do you expect this volume to change in the future?	
If your facility conducts mechanical recycling, what are the sorting and shredding practices?	
If your facility conducts thermal recycling, do you use incineration, pyrolysis, or some other process?	
If your facility conducts chemical recycling, what sort of chemical treatments do you use to breakdown the materials into elemental or molecular forms?	
What percentage of the given materials is recovered from solar panels?	• Silicon _______ • Glass _______ • Aluminium ___ • Copper _______ • Silver ________ • Plastic _______ • Other ________
How are decommissioned PV panels tested to determine if they are hazardous waste under RCRA? Are specific chemicals or elements targeted during testing for hazardous waste classification?	
Does your organization incorporate recycled materials into new products or processes?	
What mode of transportation do you use for moving photovoltaic waste?	
How does transportation cost (distances) impact your recycling economics?	

What percentage of photovoltaic waste generated at the recycling facility is currently directed to landfills?	
Do the services provided by your organization also include repair, refurbishment, or re-manufacturing?	
What other factors influence the decision between recycling and other disposal methods?	

Table C.3 Questionnaire for wind turbine recyclers

	Answers
Name of the organization (optional)	
Date	
What is the volume of wind turbine components or materials that the recycling facility typically handles annually?	
What are transportation organization of heavy wind turbine blades and components to the recycling facility, considering their size and weight? What is the mode of transportation?	
How do the inspection and sorting take place at the recycling facility?	
If facility conducts mechanical recycling, please outline the specific steps involved in the process, including mechanical separation of material and recovery of valuable components.	
If facility handles thermal recycling, please provide an overview of thermal recycling processes from collection to material recovery. Please elaborate on the methods, including pyrolysis or gasification for the recovery of fiber and, alternatively, cement kiln method for the recovery of heat (energy).	
If facility handles chemical recycling, please outline steps involved? For example, solvolysis, etc.	
If facility uses other hybrid recycling methods than mechanical, chemical, and thermal, please outline the steps.	
Does the facility handle recycling of other wind turbine components? If yes, how?	
How are recycled materials tracked and documented?	

Is the facility involved in initiatives to promote a circular economy within the wind energy sector, such as repurposing, reuse, etc?	

Table C.4 Questionnaire for battery recyclers

	Answers
Name of the organization:	
Date:	
What is the annual volume of materials that your recycling facility processes?	
What types of batteries does your recycling facility accept?	
Are there any restrictions on the types or quantities of batteries your facility can accept for recycling?	
How do you collect and transport the batteries from the point of generation to the recycling facility? What mode of transportation do you use?	
Describe the steps involved in your battery recycling process (e.g. details on the sorting, discharge, pre-processing, shredding, and separation of materials)? Could you provide details on material inputs and outputs of each process?	
What methods do you use to recover end materials (cobalt, nickel, lithium, etc.)? What is the recovery percentage of these material?	
Are end materials further purified before leaving the facility and entering secondary market? If yes, how?	
Are there any by-products or waste generated during processing? If so, how are they managed?	
Are hazardous substances created during recycling processes and what is the approach for managing that waste stream?	
How much recycled material is produced from the feedstock?	

Does your facility provide options other than recycling for batteries that have reached the end of their life cycle? (e.g., reuse, refurbishment, etc.)	
What is the throughput goal typical for your facility?	

Appendix D: Literature review for the recycling of wind turbines, solar panels, and batteries.

Table D.1 Literature review for the recycling of solar panels.

Reference	**Technology/ Process/ Technique used**	**Details**
(Latunussa et al., 2016)	Pyrolysis/ Prototype induction system	Pyrolysis-based processes allowed to separate 80% for the wafers and almost 100% of the glass sheets and the glass sheet from displays screen and PV panels.
(De-wen et al., 2004)	Pyrolysis process of EVA (different heating rates & oxidising atmosphere)	The pyrolysis behaviour of EVA (e.g., melting point, pyrolysis gas amount) is strongly influenced by the content of acetate in the EVA.
(Berger et al., 2010)	Vacuum blasting	Easy removal of semiconductor and recovery of clean glass without using chemicals.
(Radziemska et al., 2010)	Chemical/ thermal treatment	Comparison of chemical and thermal treatment for recycling PV module and refining of separated cells. Thermal treatment was shown to be sufficient in the first step, while the chemical was shown to be more advantageous in the second step.
(Klugmann-Radziemska & Ostrowski, 2010)	Thermal process followed by a series of etching treatments	Used for the removal of EVA from the module. The chemical processing is the most important stage of the recycling process. The chemical treatment conditions need to be adjusted to achieve a required purity level of the silicon.
(Marwede et al., 2013)	Leaching process	Entire removal of metals with high usage of chemicals.
(Wang et al., 2012)	Two step heating/ Acid and alkaline chemical processes	85% of copper and 62% of the silicon can be separated by this process. Glass can be recovered, and semiconductor layer is removed without any use of chemicals.
(Kang et al., 2012)	Dissolution of EVA by organic solvents and treatment of the PV cell by chemical etching	Process allowed to recover up to 86% of the silicon with very high purity.

(Zhang & Ciftja, 2008)	Filtration	Very small inclusion particles can be filtered and removed easily before reuse. The process is very efficient.
(Pagnanelli et al., 2017)	Two blade rotors crushing followed by thermal treatment	The two blade rotors crushing followed by hammer crushing was the preferred option to recover 80–85% of the glass.
(Tammaro et al., 2015)	Lab scale technology	After removing the aluminium frame and the junction box, the panel is cut by a circular saw and then heated in a furnace. Successively, residues are separated by manual and mechanical treatments. The study concluded comparatively low efficiency in the recovery of some material fractions (especially precious metals).
(Frisson et al., 2020)	Pyrolysis	This process separates 100% of glass sheets and 80% of wafers.
(Lin & Tai, 2010)	Phase transfer separation	The process does not use toxic heavy liquid but recovers high-purity silicon
(Zhang & Xu, 2016)	Nitrogen pyrolysis process	Decompose plastic.
(Doi et al., 2001)	Organic solvent dissolution	The silicon cell was separated without any damage from a single cell module by dissolution in trichloroethylene at 80°C for 10 days. Glass can be easily recovered.
(Lee et al., 2018; Park et al., 2016)	Thermal process	High silicon recovery.
(Bombach et al., 2006)	Deutsche Solar's process including chemical and thermal treatment	This process yields about 76% of recovered cells which can be reused.
(Shin et al., 2017)	Delamination	EVA and metal layers can be removed.
(J. Tao & Yu, 2015)	Materials purification	Hydrometallurgical and pyrometallurgical processes involved.
(Choi & Fthenakis, 2014)	Pyrolysis	Effective for removing EVA encapsulants from the module laminates, therefore separating solar cells and module glass. Heating the module at 150–200°C melts and softens the PET layer of the backsheet, allowing the backsheet to be peeled from the module sandwich.
(P. Dias et al., 2021)		Process includes the following steps: manual separation of frame and junction box; toluene immersion to swell EVA; peeling the glass substrate and backsheet; returning the EVA, cell, tabbing mixture to a thermal decomposition treatment at 500°C to remove the EVA; and sorting solar cell fractions for leaching treatment.
(Eshraghi et al., 2020)		Different acids, such as nitric (HNO_3), hydrochloric (HCl), and sulfuric (H_2SO_4) acid, have been tested to dissolve silver from the cell at varying concentrations and temperatures. Concentrated HNO_3 (> 35%) is the most effective, dissolving 100% of silver and copper within 1–4 h at room temperature.

(Zante et al., 2022)	Metals extraction from crystalline silicon cells	Current hydrometallurgical technologies generally include the use of strong mineral acids to solubilize silver and/or aluminium. Concentrated sodium hydroxide for hydrolysis and solubilization of aluminium and silicon.
(Wang et al., 2008)	Centrifugation	High purity of silicon recovered but unable to remove submicron silicon carbide particles
(Tsai, 2009; Tsai & Huang, 2009)	Electrokinetic separations	Removal of iron fragments from slurry waste without using additive chemicals
(Li et al., 2014)	Sedimentation and leaching	Separation of silicon and silicon carbide using physical processes

Table D.2 State of the art for the recycling of wind turbines.

References	**Recycling method**	**Details**
(Palmer et al., 2009)	Mechanical	Through pulverizing and reincorporation, the study investigated closed-loop recycling of thermoset composites and utilized recycled GFRP in lieu of virgin reinforced materials in new thermoset composites.
(Cousins et al., 2019)		The study examines the difference in decomposition energy between a commercially available epoxy and Elium, analyzes the tensile qualities of recycled thermoplastic, shows the process of thermoforming on a spar cap, and assesses the economic feasibility of using dissolution for recycling thermoplastic components.
(Beauson et al., 2014)		The research analyzed wind turbine blade waste recycled GFRPCs as shredded composites and GFs. Recyclates were employed to create new composites with varying wt. % or VGF replacement.
(Mamanpush et al., 2018)		This study examines a set of advanced composites produced by using recycled wind turbine material and a polyurethane glue and the impact of the refined particle size, moisture content, and resin content on the characteristics of recycled composites was evaluated.
(Tahir et al., 2021)		This study examines how recycled fiber categories affect the tensile qualities of fused filament fabrication 3D-printed reinforced polylactic acid (PLA) specimens. Virgin, ground, and pyrolyzed fibers are compared experimentally and analytically using micro-mechanical models. Ground and pyrolyzed recycled fibers are more resilient and stiffer than virgin

		fibers. Pyrolyzed fibers have better stiffness but lower ultimate tensile strength than ground recycled fibers.
(Yazdanbakhsh et al., 2018)		The research examined mechanically processed GFRPC wind turbine blade shells. Needles, thin recycled materials, were added/replaced (5% and 10% by volume) in concrete. Results showed no detrimental influence on fresh concrete's stability, workability, tensile, compressive, and flexural strength. 10% needle replacement increased concrete energy absorption from 1.2 J to 33.3 J.
(Pickering et al., 2000)	Thermal	Research on recovering GFs from thermoset waste composite materials using a low-temperature combustion method found that, due to fiber quality loss, combustion may not be an appropriate recycling approach.
(Chen et al., 2023)		The characteristics, kinetics, and product distribution of the pyrolysis of end-of-life WTBs were investigated in this study. Additionally, it was discovered that the pyrolysis of WTBs can be carried out with reduced energy consumption. The pyrolysis products exhibited a carbon chain distribution primarily composed of C9–C16 compounds. This group comprised phenolic compounds, alcohols, ketones, and carboxylic acids.
(Pender and Yang, 2020)		This study uses an in-house fluidized bed technique to test various treatments to restore the strength and surface functioning of glass fibers reclaimed from retired wind turbine blades. Tensile characteristics of recovered GFs enhanced after NaOH treatment (approx. 130%).
(Tian et al., 2022)	Chemical	The research provided a concise overview of the chemical recycling techniques, such as oxidation, solvolysis, and alcoholysis, used for carbon fiber reinforced composites (CFRCs). Chemical recycling is capable of selectively breaking down certain resin bonds in order to accomplish controlled deterioration. The epoxy resin matrix undergoes degradation, resulting in the formation of monomers or oligomers, whereas the carbon fibers may be reused.
(Ma et al., 2021)		Closed loop recycling of CFRP resin and CFs produces high-performance composites. Recovered CFs had 330 MPa maximum tensile strength and 34 GPa modulus.
(Yang et al., 2012)		In under 50 minutes at 180°C and atmospheric pressure, the research demonstrated that a polyethylene glycol (PEG)/NaOH catalytic system effectively solvolyzed the epoxy matrix,

		therefore dissolving the epoxy resin. According to the studied process, ester hydrolysis and transetherification are the two main steps in the solvolysis process.
(Sommer et al., 2022)	Mechanical/ thermal/ chemical	The environmental effect of different end-of-life treatment routes using Lifecycle effect Assessments are evaluated. It also created a mathematical optimization-based decision support tool to examine how political laws affect treatment infrastructure design.

Table D.3 State of art for the recycling methods of BESS.

Reference	**Technology/ Process/ Technique used**	**Details**
(Diaz et al., 2020)	Electrochemically assisted technique	Electrons were used as an environmentally friendly reagent in a hydrometallurgical leaching process within the realm of technology, serving as a substitute for chemicals. Compared to the peroxide-based leaching procedure, the chemical consumption was lower. In addition, operating the process at room temperature resulted in an 80% reduction in both chemical and energy expenses.
(Peng et al., 2018)	Material recovery	The investigation revealed that scraps obtained from industrial mechanical processing exhibit superior leaching efficiency for Co and Li compared to pure LiCoO. Conversely, the leaching efficiency of copper falls when reducing agents are included, which contrasts with the behavior observed for Co and Li.
Chan et al. (2021)	Recovery method	This study aims to recover lithium, cobalt, nickel, and manganese from spent lithium-ion batteries from electric vehicles. Using experimental and theoretical approaches, the optimal operating conditions and leaching conditions are determined. The recovered metals are coprecipitated as $Ni0.15Mn0.15Co0.70(OH)_2$ and lithium carbonate. This process generates a new cathode material, enabling high electrochemical performance and conserving natural resources while contributing to the circular economy.
(Ali et al., 2021)	Direct physical recycling process	Direct physical recycling was compared to advanced hydrometallurgical recycling. Due to its low cost, ability to recover a variety of materials (e.g., cobalt, nickel, aluminum, manganese, copper, and lithium), and process combination opportunity, recycling is becoming more popular.
(Chen et al., 2015)	Hydrometallurgy	The study recovers precious metals from sulfuric acid leaching liquid of wasted LIB cathodes. Nickel ions were selectively precipitated and recovered with dimethylglyoxime following purification. Second, solvent-extracted Co-loaded D2EHPA separated Mn and Co. Finally, sodium carbonate and ammonium oxalate precipitated Li_2CO_3 and

		$CoC_2O_4.2H_2O$ to recover Li and Co. Optimal recycling efficiency was 81% for Li, 98% for Co, 99% for Ni, and 97% for Mn.
(Freitas et al., 2010)	Electrochemistry	Electrochemistry is used to recover and isolate metals from a solution obtained by leaching. However, the use of technology often leads to excessive power consumption, which negatively impacts economic efficiency.
(Zheng et al., 2022)		The research examined a new approach to recover lithium from spent LIBs using imidazolium ionic liquid.
(Tokoro et al., 2021)	Mechanical pre-treatment	This paper investigated the use of high voltage treatment for more effective separation. Using high-voltage treatment, 94% of the cathode particles were successfully separated from the aluminum foil using a screening process. Additionally, 99% of the particles retained the same chemical structure as the original NMC.
(Fu et al., 2021)	Mechanical pre-treatment using supercritical CO_2	The use of supercritical CO_2 resulted in the extraction of cathode material from the current collector, with over 99 wt. % of polyvinylidene fluoride (PVDF) being dissolved in a supercritical CO_2-dimethyl sulfoxide system at a temperature of 70°C and a pressure of 80 bar during a duration of 13 minutes.
(Golmohammadzadeh et al.,2018)		The research examined the recycling process that used organic acids to reclaim discarded LIBs.