Decommissioning Trends, Circular Economy Policy Incentives, and Secondary Markets for Solar Photovoltaics

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Executive Summary

As solar PV deployment increases in the U.S., so will the volume of decommissioned PV modules and balance of system equipment, and large amounts of annual waste are anticipated by the early 2030s. Currently, there are over 65 GW of solar PV installed in the U.S., which is the equivalent of over 5 million tons of PV modules. In order to get ahead of this looming, as well as present challenge, our team has worked with the National Renewable Energy Laboratory (NREL) to conduct an in-depth study of material flow pathways from PV system decommissioning to secondary use applications and recycling in order to inform an evidence-based assessment of decommissioning trends and regulatory policy in the United States. Our study focused on four main themes: (1) an analysis of U.S. decommissioning policies and regulations, (2) an analysis of U.S. decommissioning costs, plans, and trends, (3) a comparative analysis of international decommissioning policies and regulations, and (4) a market analysis of the potential for a U.S. PV system circular economy.

Decommissioning costs are still poorly understood but are expected to be a not trivial part of the total lifetime cost of solar PV systems. Our analysis of 24 decommissioning plans from 9 different states showed considerable variation in estimation methods and outcomes. The costs reported ranged from -$226,000/MW (for a project for which the value of salvage materials was expected to exceed costs) to $105,000/MW with an average of $9,525/MW. We concluded that it was not possible to do any further analysis or comparison across the entire set of plans, given the vastly different methodologies utilized. To support additional insights, we thoroughly reviewed each plan and separated the methods into three categories: Per unit; single number lump sum, and itemized lump sum. We then drew on our extensive knowledge of the plans to develop a set of confidence criteria that can be used to score a given decommissioning plan's methodology. Transparency of methods and assumptions, strength of the estimator's credentials, and inclusion of comprehensive set of components were the most important factors influencing our confidence in each plan. We ultimately found that our confidence was on average highest for plans using a per unit method, followed by plans using an itemized lump sum method. We had the least confidence in plans using a single number lump sum method. While we were able to develop qualitative metrics for confidence, it should be noted that it was impossible for us to judge the empirical accuracy of any particular method. This is because no reliable data on actual decommissioning cost currently exists. We concluded that filling this data gap as well as establishing a more standardized approach for estimating decommissioning costs would benefit both local planners and solar developers.

Secondary markets and services for new, used, and end-of-life PV modules are becoming increasingly important to managing material flows and establishing a circular economy for PV modules. In the context of PV modules, secondary markets are the markets that facilitate transactions between buyers and sellers for goods that have already been sold into the primary market by a manufacturer, distributor, retailer, etc. Secondary markets are particularly useful for keeping PV modules in use that would otherwise be landfilled or recycled and for providing backup supply when primary markets face increased demand. As PV material flows out of secondary markets increase, it is imperative that those materials are managed responsibly under a circular economy system. Creating a U.S. PV system circular economy is in part dependent on the availability and affordability of solar PV module recycling services and economic value that module owners can recoup from selling PV modules to recycler or selling recycled module materials into recycled and commodity materials markets. Secondary market outlets and PV module recycling services and materials markets are showing promising growth and traction, but will continue to face headwinds from improvements in PV technology performance, declining PV prices, government incentives for new systems, and consumer and regulatory skepticism towards used systems.

In the absence of solar PV-specific waste laws in the U.S., and regulations mandating the collection and recycling of solar PVs at the end their useful lives, U.S. states and their local jurisdictions are beginning to develop their own processes of regulating the responsible management of solar PVs.[1] As solar PV deployment increases in the U.S., so will the volume of decommissioning solar PVs within communities. Solar ordinances and decommissioning policies are becoming increasingly important considerations within U.S. State and local jurisdiction's planning practices. Currently, there is little information about what purpose the policies are intended to serve from the local perspective. However, because such policies may have implications on the development of solar projects across the U.S., it is important to understand why U.S. states and localities passed solar decommissioning policies in the first place, what stakeholders are or should be involved in the development of such ordinances, and what impacts solar policies are having on the solar industry. By reviewing U.S. state and local regulatory frameworks and ordinances, the project team sought out to better understand how local communities are responding to increased renewable energy project developments and identify potential impacts state and local decommissioning policies may have on various stakeholders including developers, state and local authorities, landowners, and community members.

Many international jurisdictions are wrestling with how to responsibly manage material flows of decommissioned and waste PV modules and energy storage technologies. Certain member countries of the European Union have robust materials management frameworks in place, and continue to refine regulations that govern these waste types. Other countries, such as Australia, China, and Japan, are taking steps to develop their own regulatory frameworks. While government officials are responsible for enacting and enforcing regulations governing solar and storage wastes, in virtually every jurisdiction we studied solar industry stakeholders played an important role in shaping solar and storage waste management policies. The importance of industry input on how waste management policies are crafted and contribution to developing the technologies, business models, and operational capabilities needed to manage secondary markets and waste material flows cannot be overstated.

The research and analysis performed in this project is essential to the understanding and formation of a sustainable circular economy for solar photovoltaic energy generation. Our greatest desire is that this work informs and inspires many others in this impactful and promising field.

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Chapter 1: Project Background

1.1 Problem Statement

Solar energy is an increasingly important and growing source of renewable power in the United States. According to the Department of Energy, since 2008 photovoltaic (PV) solar installations have increased 35-fold, and as the price of solar continues to fall, the solar industry will continue to see exponential growth of solar PV[2]. The rapid growth of solar energy in recent years has largely been due to two main driving forces: the increasingly competitive economics of harnessing solar energy and a global push to greener forms of renewable energy that can help mitigate climate change and reduce our dependence on more traditional and extractive sources of energy.

As solar PV deployment increases in the U.S., so will the volume of decommissioned PV modules and balance of system equipment (BOS) (together, "PV systems"), and large amounts of annual waste are anticipated by the early 2030s[3]. Currently, there are over 65 GW of solar PV installed in the U.S., which is the equivalent of over 5 million tons of PV modules[4]. While PVs are revolutionizing U.S. energy systems and serve as a critical component of efforts to solve the climate crisis, growing PV system waste presents new environmental challenges that will require practical and effective avenues to recycle PV systems. In addition to environmental challenges, failure to adequately address the end of life (EOL) problem of PV systems may also result in new economic, legal, and reputational challenges for the solar PV industry. Despite this apparent growing issue and that PV modules are federally governed as hazardous waste, neither the U.S. government nor virtually any State or PV module processing companies have policies or regulations to facilitate appropriate disposal practices of PV systems.

In order to get ahead of this looming, as well as present challenge, The National Renewable Energy Laboratory (NREL) would like to enable an in-depth study of material flow pathways from PV system decommissioning to secondary use applications and recycling in order to inform an evidence-based assessment of decommissioning trends and regulatory policy in the United States. Our study will focus on four main themes: (1) an analysis of U.S. decommissioning policies and regulations, (2) an analysis of U.S. decommissioning costs, plans, and trends, (3) a comparative analysis of international decommissioning policies and regulations, and (4) a market analysis of the potential for a U.S. PV system circular economy. The findings of this study will inform staff at NREL and the U.S. Department of Energy's (DOE) Solar Energies Technologies Office. This study will also inform solar PV industry professionals and stakeholders within the solar energy markets, as well as other relevant decision makers such government officials and elected leaders on the Local, State and Federal levels.

1.2 NREL Background

The National Renewable Energy Laboratory (NREL) is a federally funded research and development center sponsored by the U.S. Department of Energy. NREL's mission is to advance the science and engineering of energy efficiency, sustainable transportation, and renewable power technologies and to provide the knowledge to integrate and optimize energy systems. NREL employs 2,974 and operated with an annual budget of approximately $600 million in 2021 that enabled them to publish 2,160 technical materials and reports last year. The organization has over 1,000 partnerships with industry, universities, foundations, and governments and has received 645 patents to date[5].

1.3 Project Objectives & Scope

The project seeks to understand barriers to and opportunities for more sustainable materials management practices in the solar industry. NREL is interested in gaining a better understanding of the following issues:

U.S. Decommissioning Policy and Regulatory Analysis

- Solar PV end of life management trends, including frequency of decommissioning, repowering, disposal, and second life use cases between different US states
- Current policy and regulatory regimes in different US states that influence EOL trends and outcomes, and opportunities to improve the policy and regulatory environment to promote circularity;

Decommissioning Costs, Plans, and Trend Analysis

- Cost trends for different end of life management options, including common methods for estimating costs prior to installation and cost breakdown by sectoral contribution
- Current trends seen in the industry and factors that lead to decommissioning, repowering, disposal (i.e., landfilling vs. recycling), or second life applications of solar PV modules;

International Policy Comparative Analysis

- Solar PV end of life management trends, including frequency of decommissioning, repowering, disposal, and second life use cases in international jurisdictions (e.g., China and EU);
- Current policy and regulatory frameworks in international jurisdictions that influence EOL trends and outcomes- such as waste classifications, waste handling and transportation requirements, economic incentives or requirements that fund EOL management, minimum reuse and recycle thresholds for discarded PV arrays, etc.- and opportunities to apply successful international policy and regulatory regimes to the US context;
- Ongoing challenges related to solar EOL management in international jurisdictions;

U.S. PV Circular Economy Market Analysis

- Identifying viable, economic opportunities to increase flows of PV systems towards second life applications and materials circularity via market and policy-driven incentives, and analyzing the current state of circularity economics;
- Identifying solar PV design factors that affect system lifetimes and options for disposal.

Chapter 2: Project Methodology

To begin to understand the facets of this complex topic, the team began by reviewing materials provided by NREL, and seeking out additional literature to contribute to our foundational knowledge. After familiarizing ourselves with the topic, we compared what we learned with the goals NREL expressed at the beginning of the project. This allowed us to outline a set of four priority sub-topics related to solar PV and circular economy. To improve team efficiency and coordination, we divided the work evenly among the 5 team members. The four tasks and the team members responsible are listed below in the order they appear in this report, along with a brief summary of each task's objectives and methods.

- Decommissioning Costs Analysis (Matt Boelens, Xindi Huang, and Christina Pastoria): The purpose of this task was to evaluate decommissioning cost estimates in plans submitted by developers to local and state government entities. The team worked to characterize the methodologies used by each developer so that an assessment could be made about the accuracy of the cost estimates that are being proposed and accepted by government agencies. To accomplish this task, the research team collected additional publicly available decommissioning plans to add to a set of plans that NREL staff had already collected. We then used an iterative and deliberative review process to categorize the decommissioning cost estimation method used in each plan. Using the same review process, we the developed a set of criteria for evaluating the reliability of a given method and applied it to each of the plans in our library. This section provides guidelines for understanding decommissioning cost estimates, a high-level framework for assessing estimation methods, and a database of decommissioning plans that have been evaluated and can provide a template for separating a good estimation method from a bad one.
- Secondary and Circular Economy Market Analysis (Matt Boelens, Xindi Huang, and Nolan Woodle): The objective of this task was to assess the state of current end of life options for solar PV, with a particular emphasis on the more circular alternatives like reuse, repowering, recycling, and remanufacturing. The research team sought to characterize the feasibility of existing opportunities to divert PV systems from landfills and to identify ways to promote these opportunities going forward.

  To accomplish this task, our team performed a preliminary analysis of secondary market circular economy market opportunities via desktop research. This initial research stage helped us understand which sectors and topics carry the most importance to establishing a circular economy, and which sectors and topics are least understood by the solar industry. We supplemented our desktop research by performing research interviews with two circular economy and secondary market experts to learn more about the challenges their respective businesses and the broader industry was facing.
- U.S. Local Policy Survey (Christian Koch and Christina Pastoria): This task's goal was to establish a preliminary library of local solar decommissioning policies and to help deepen NREL's understanding of the purposes and impacts of local regulations have on solar development. To achieve this goal, we first conducted a local policy survey to gather information about what is typically included in a local solar decommissioning policy. We then recruited and interviewed city and county planning staff in 7 jurisdictions to learn more about the motivations behind these policies. Finally, we used a thematic content analysis methodology to derive insights from the interviews. This section provides crucial information about local perspectives on solar development and solar decommissioning.
- International Policy (Christian Koch and Nolan Woodle): The purpose of this task was to summarize international end of life policies for solar PV and batteries (which have relatively similar end of life challenges to PV modules) to understand how other countries are tackling this issue. Our team relied on desktop research to accomplish this task. After consulting with NREL to understand which countries were absent from known solar PV and battery waste

studies, we compiled a policy database to help track and organize information relevant to our case studies.

The rest of this report describes each task's methodology in greater detail, along with an in-depth summary of each task's results.

Chapter 3: Decommissioning Costs Analysis

3.1 Introduction

When a solar installation reaches the end of its useful life (usually around 20-30 years), developers must choose how they will dispose of waste materials. Their options include repowering, reuse, recycling, and landfilling, which will be discussed in greater detail in section 4 of this report. No matter which of these options developers choose, there are likely to be some costs incurred to disconnect electrical equipment, remove structural elements, and transport materials a disposal facility. Some of these disposal options may also impose costs on developers, such as tipping fees or recycling charges. However, unless explicitly required to do otherwise, developers typically do not provide end of life plans at the outset of a project.
As the number and size of solar installations has increased over time, policymakers and planners at the local, state, and federal level have begun to express concern about the lack of planning. Federal and state governments fear that, without sufficient foresight, PV modules will be dumped in landfills en masse, potentially creating capacity challenges over time. This outcome would also result in low recycling rates and a greater demand for virgin materials and rare earth minerals. Local officials, on the other hand, worry that developers will simply leave equipment in place and leave local governments with the burden of restoring these sites. In response, governments have begun to include decommissioning requirements in their solar zoning ordinances. These requirements force developers to estimate the cost of removing and disposing of equipment and materials. In some cases, developers are also required to provide localities with some form of financial assurance or surety based on their decommissioning cost estimate.

As these kinds of decommissioning requirements and ordinance have grown more widespread, industry experts like NREL have begun to note inconsistencies and uncertainties in decommissioning cost estimation methods. There are currently no standards or consistent guidelines for estimating decommissioning costs. This has produced a great deal of variation in what costs developers choose to include in their decommissioning plans and how they calculate these costs. As a result, it is difficult to compare across estimates or to develop any rules of thumb for evaluating plans, such as an average decommissioning cost per megawatt of capacity. Additionally, very few large-scale solar installations have actually been decommissioned to date. With no reference point to compare new estimates to and no explicit list of costs that have actually been incurred, developers struggle to accurately forecast their costs. Units of government, which have less experience with solar development, face even greater challenges when they attempt to critically evaluate the accuracy of developers' estimates.

Some jurisdictions have attempted to provide cost estimation instructions or templates, but these instructions typically vary across jurisdictions, so comparison remains challenging. These templates also cannot address the underlying uncertainty about actual decommissioning costs, so units of government still have few reference points from which to evaluate developers’ estimates. This creates considerable risk that developers underestimate their decommissioning costs, either intentionally, to reduce the size of the financial assurance they must provide, or unintentionally, out of ignorance. Unless more rigorous guidelines for estimating decommissioning costs can be established, it is unclear how useful decommissioning plans can be for protecting communities from the financial burdens of site abandonment. It is also unlikely that having a decommissioning plan will have any impact on developers’ disposal decisions at end of life if the plan’s cost estimate is unrealistic. This creates a risk that developers will simply choose the easiest disposal option, which is likely to be landfilling rather than a more circular option like recycling or repowering. In the absence of actual decommissioning costs, greater standardization of estimation methods will be needed if decommissioning plans are to be effective in preventing these two outcomes.

In this report, we will attempt to provide some clarity about the common methods of decommissioning cost estimation and the range of estimates they produce. We will start by locating a set of publicly available decommissioning plans for solar installations around the United States. We will then identify the cost elements included in each report, characterize the common estimation methodologies, and create a framework for tracking methodological similarities and differences across plans. We will also generate descriptive statistics of the cost estimates by estimation methods, to demonstrate the impact that methodology has on the final outcome of the estimate. We will then identify criteria for evaluating confidence in a given decommissioning plan’s cost estimate. Finally, we will apply these confidence criteria to the plans we initially collected and analyze the range and distribution of estimates by confidence level.

3.2 Data Collection and Summary

3.2.1 Data Collection

As the need for solar project decommissioning plans increases, the lack of available information regarding existing plans becomes a larger and larger problem. In an effort to address that problem, our research team set out to collect, analyze, and share solar project decommissioning plans from around the United States. Our work was shaped by several key driving research questions:

1. How are decommissioning costs estimated? What is included and what is excluded? Are there any mandates, guidelines, or best practices for estimating costs?
2. What may motivate solar installation owners to choose a particular method for estimating decommissioning costs over other methods?
3. What factors contribute to the decommissioning costs of solar PV systems? Which aspects incur the largest proportion of cost?
4. Which decommissioning methods are most common today? What is influencing that outcome? Are certain decommissioning methods increasing or decreasing in popularity? What is causing that shift?

Initially, we set out with a plan to collect decommissioning plans from several states: California, North Carolina, Hawaii, Maryland, Virginia, Texas, New Mexico, Indiana, Colorado, Minnesota, and New Jersey. These states were selected because they represented locations with a large number of solar projects, diverse political leadership, and diverse geographic locations. However, we soon realized that we were actually quite constrained based on the public availability of decommissioning plans. As a result, we were only able to collect 24 plans as described below in Table 3.1.

3.2.2 Data Summary

Table 3.1: Summary of Decommissioning Plans Collected

State	Counties Represented	Number of Plans	Average Size (MW)
California	Sacramento	1	3
Connecticut	Hartford, New London	3	43
Hawaii	Honolulu	1	144
Maryland	Frederick, Queen Anne’s, Somerset, Wicomico, Washington, Carroll	8	33
Massachusetts	Essex, Hampshire, Worcester	4	6
New York	Suffolk, Greene, Tompkins	3	42
North Carolina	Halifax	1	94
Rhode Island	Washington	1	9
Virginia	Dinwiddie, Spotsylvania	2	253

Basic data for each decommissioning plan is included in a spreadsheet accompanying this report titled “Initial Decommissioning Cost Estimate Data Summary”. Additionally, this file includes the decommissioning cost and salvage estimates for each component of the solar project that was specified within each plan. We have also included a reading guide to explain the meaning of each term described within the spreadsheet (see Appendix C).

3.2.3 Data Analysis

In response to the dramatic variation between plans regarding how cost and salvage values were estimated, what components of the project were explicitly included, and how thorough each plan was overall, our team conducted an objective analysis to identify which methodology each plan employed when calculating cost and salvage estimates for each solar project in question. This would allow us to accurately categorize each decommissioning plan so that we could make accurate comparisons between plans that used a common methodology.

First, we identified four broad cost categories: Disposal, Salvage, Labor, and Other. Each project component and cost line item within each plan would fall into one of these four buckets. “Disposal” includes any costs related to removing, transporting, or disposing of solar project components. “Salvage” includes any salvage values assigned to project components. “Labor” includes any specific labor costs assigned to any project component. Finally, “Other” includes any project components or cost line items not included in the other three categories (e.g. project management and site remediation).

Once the four categories had been identified, we combed through each decommissioning plan and assigned each project component and cost line item to a category. We recorded the project component, the cost estimated, and the method used to calculate the cost estimate (see the “Labor Methodology”, “Disposal Cost Methodology”, and “Other Costs & Methodology” tabs within the “Decommissioning Costs – For Analysis” spreadsheet). Once this had been completed for every project component of each plan, we looked at all of the cost estimate methodologies for each plan one category at a time. Typically, each plan used a very similar methodology throughout each category, so we identified the common methodology used for each category in each plan. We ended up with four cost estimate methodologies for each decommissioning plan, one for each broad category (see the “The Clumper” and “Clumper Coding Table” tabs within the “Decommissioning Costs – For Analysis” spreadsheet).

Finally, we looked at the four methodologies for each plan and boiled them down into one general methodology that accurately merged and described the category methodologies. Now that we had a single cost estimate methodology for each plan, we could more confidently compare the cost estimate quantities between decommissioning plans that used the same methodology (see the “Summary” and “Costs” tabs within the “Clumped Decommissioning Data” spreadsheet).

In the end, we were able to name three general cost estimate methodologies that described all 24 of the decommissioning plans we analyzed.

1. **Per Unit:** Any cost estimation calculated by multiplying a known per-unit value by a known quantity of that unit (e.g. labor cost ($/hour) x hours of labor expected)
2. **Single Number Lump Sum:** Only a single value given as a cost estimate with no breakdown, context, or calculations described
3. **Itemized Lump Sum:** A series of single number lump sum estimates broken out by category or component, no context or calculations described

3.3 Confidence Criteria Development and Estimate Evaluation

After thoroughly reviewing each of the plans we collected, the research team established a set of criteria to help evaluate the reliability of a given plan. These criteria were developed through a deliberative process in which the research team members compared plans and identified methodological properties that facilitated or inhibited third party assessment. The criteria were the same for decommissioning cost and salvage value estimates, but we evaluated these two calculations separately for each plan.

The methodological properties we identified fell into three main categories – methodological transparency, credentials of estimate provider, and inclusion of key components. We then split methodological transparency into three subcategories: statement of methods, granularity of assessment, and validity of assumptions. After a final review of the plans, we noted that some estimations attempted to account for the effects of inflation by applying a price escalator to their estimates, while others did not. We included the use of a price escalator as our sixth and final criterion.

3.3.1 Defining the Confidence Criteria

The six criteria are defined as:

1. **Statement of Methods** describes the degree to which it is possible for a third party evaluator to understand how the estimate was calculated and to identify the costs, price rates, and quantities that were used in the calculation. This criterion does not address the validity of the price rates or quantities—that is covered in another category. It only assesses whether the third party evaluator can determine what the prices and quantities are and how they were combined to produce the final estimate. For example, the cost estimate in Figure 3.1 below would receive a low score for this category because no additional information is provided to explain how the numbers in the estimated cost column were calculated. The cost estimate in Figure 3.2, meanwhile, would receive a high score because it is clear that the estimate is the product of the clearly defined quantities and unit prices.
2. **Granularity of Assessment** refers to the extent to which the cost estimate is broken out into its constituent components. For example, an estimate that provides only a single number for the entire project would relieve a low score in this category. An estimate that provides cost estimates for all relevant decommissioning activities (removal of equipment, site restoration, labor, transportation, etc.) would receive a high score. It is possible to receive a high score for statement of methods and a lower score for granularity of assessment if, for example, the estimate uses a per unit method but fails to provide separate categories for labor and transportation, as in Figure 3.3.

Figure 3.1: Estimate with a Low Statement of Methods Score

Tasks	Estimated Cost ($)
Remove Panels	$2,450
Remove Rack Wiring	$2,459
Dismantle Racks	$12,350
Remove and Load Electrical Equipment	$1,850
Break up Concrete Pads	$1,500
Remove Racks	$7,800
Remove Cable	$6,500
Remove Ground Screws and Power Poles	$13,850
Remove Fence	$4,950
Grading	$4,000
Seed Disturbed Areas	$250
Truck to Recycling Center	$2,250
Current Total	**$60,200**
Total After 20 Years (2.5% inflation rate)	**$98,300**

Figure 3.2: Estimate with a High Statement of Methods Score

ITEM	DESCRIPTION	QUANTITIES	UNITS	UNIT PRICE	COST
A.	**General Conditions**				
1	Bonds and Insurance	1.0	LS	$168,000.00	$168,000.00
2	Mobilization and Demobilization	1.0	LS	$335,900.00	$335,900.00
3	Erosion and Sediment Control	1.0	LS	$100,800.00	$100,800.00
B.	**Decommissioning**				
1	Facility Substation	1.0	EACH	$285,000.00	$285,000.00
2	PV Modules	184.0	MW-DC	$2,500.00	$460,000.00
3	Inverters	132.5	MVA	$630.00	$83,475.00
4	Racking	184.0	MW-DC	$8,300.00	$1,527,200.00
5	Collection Lines & Other Electrical Equipment	184.0	MW-DC	$3,000.00	$552,000.00
6	Fencing	99,500	LF	$3.00	$298,500.00
7	BESS	100	MWh	$7,817.40	$781,740.00
C.	**Waste Disposal**				
1	Inverters	345.0	TON	$200.00	$69,000.00
2	Step-up transformers	53.0	EA	$1,000.00	$53,000.00
3	Misc - Solid Waste Disposal	120.0	TON	$200.00	$24,000.00
4	BESS	100	MWh	$16,702.60	$1,670,260.00
5	PV Modules (Damaged modules that cannot be re-sold)	22,700	EACH	$34.44	$781,896.96

Figure 3.3: Estimate with a High Statement of Methods Score but Low Granularity of Assessment Score

OPINION OF PROBABLE COST - PV PLANT DECOMISSIONING - 9 MW				
DISASSEMBLY & DISPOSAL				
ITEM	DESCRIPTION	QUANTITY	UNIT PRICE	TOTAL
1.0	PV Modules (340 W)	33,282	$ 5.33	$ 177,393.06
2.0	Inverter(s) (1.8 MVA)	5	$ 1,085	$ 5,425.00
3.0	Transformer(s) (1.8 MVA)	5	$ 543	$ 2,715.00
4.0	Racking Frame (Fixed Tilt)	925	$ 26	$ 24,050.00
5.0	Racking Posts	4,642	$ 20	$ 92,840.00
6.0	Tracker Motors	-	-	-
7.0	LV Wiring	13,754 LF	$ 0.76	$ 10,453.04
8.0	MV Wiring	5,000 LF	$ 0.41	$ 2,050.00
9.0	Fiber Optic Cable	1,250 LF	$ 0.66	$ 825.00
10.0	Fence	2,769 LF	$ 2.41	$ 6,673.29
11.0	Concrete	45 CY	$ 71	$ 3,195.00
12.0	Gravel	1,037 CY	$ 61	$ 63,257.00
13.0	General Conditions	9 MW	$ 2,692	$ 24,228.00
			SUBTOTAL	$ 413,104.39
SITE RESTORATION				
ITEM	DESCRIPTION	QUANTITY	UNIT PRICE	TOTAL
13.0	Re-Seeding	11 ACRES	$ 3,924	$ 43,164.00
14.0	Re-Grading	0 CY	$ 11	$ -
			SUBTOTAL	$ 43,164.00
SALVAGE				
ITEM	DESCRIPTION	QUANTITY	UNIT PRICE	TOTAL
15.0	PV Modules (340 W)	31,618	$ 30	$ 948,540.00
16.0	Inverter(s) (1.8 MVA)	5	$ 1,676	$ 8,380.00
17.0	Transformer(s) (1.8 MVA)	5	$ 1,792	$ 8,960.00
18.0	Racking Frame (Fixed Tilt)	799,200 LBS	$ 0.09	$ 71,928.00
19.0	Racking Posts	765,930 LBS	$ 0.09	$ 68,933.70
20.0	Tracker Motors	-	-	-
21.0	LV Wiring	18,375 LBS	$ 1.47	$ 27,011.25
22.0	MV Wiring	12,650 LBS	$ 0.75	$ 9,487.50
23.0	Chain Link Fence	42,522 LBS	$ 0.09	$ 3,826.98
			SUBTOTAL	$ 1,147,067.43

3. **Validity of Assumptions** describes the strength of the justification the estimate gives for why particular assumptions were made. This category also assesses whether assumptions appear to be reasonable and realistic, based on the justification proved. Assumptions covered by this criterion might include the unit prices and quantities or the share of material that is recyclable. One plan, for example, clearly defined the kind of labor that would be required for each particular task and used wage rates appropriate for that kind of labor. This plan received a high score for validity of assumptions. Other plans, such as the one shown in Figure 3.4 below, provide unit prices for each line item, but the prices are clearly the result of some calculation that was not described in the plan. As a result, it is difficult to determine whether the assumptions are reasonable or not. This plan received a lower score for validity of assumptions.

Figure 3.4: Estimate with a Low Validity of Assumptions Score

Item #	Item	Quantity	Unit Cost	Per	Cost
1	Rack Wiring Removal	153	$30.00	Rack	$4,590.00
2	Panel Removal	8262	$4.00	Panel	$33,048.00
3	Rack Removal	153	$100.00	Rack	$15,300.00
4	Rack Support pile (12/rack)(12x153)	1836	$20.00		$36,720.00
5	Cabinet	4	$2000.00	Each	$8,000.00
6	Cable removal	1,300	$1.00	LF	$1,300.00
7	Electrical disconnect			Lump Sum	$500.00
8	Utility Pole removal	6	$1000	Pole	$6,000.00

4. **Credentials of Estimate Provider** assesses the level of solar decommissioning expertise the person or organization that created the estimate was expected to have. A technical consulting firm with strong solar credentials or explicit experience with decommissioning, for example, would receive the highest score in this category. We included this criterion in part to allow for the possibility that a less transparent estimate might still be valid if it was developed by a highly knowledgeable consultant or professional engineer.
5. **Inclusion of Key Components** evaluates whether the estimate accounts for all of the major components of a solar decommissioning project. We identified the material components that should be considered using NREL's definition of the main parts of PV system (Curtis, et al., 2021). We also incorporated input from the local policy research team, which found that some ordinances require developers to include site restoration and some form of overhead/mobilization and demobilization in their cost estimates. The full list of nine key components is:
    - PV modules
    - Racking equipment
    - Inverters
    - Other electrical equipment (such as wiring, cables, conductors, transformers, etc.)
    - Fencing
    - Utility poles
    - Labor
    - Site Restoration (such as grading, re-seeding, re-vegetation, access road removal, etc.)
    - Overhead / management
6. **Inclusion of Inflation Cost Estimator** is a simple existence / non-existence assessment that describes whether or not the cost estimate and salvage values are scaled for inflation over the 20–30-year life of the solar installation. An estimate would receive the highest score if inflation is included and the lowest score if inflation is not included.

3.3.2 Weighting the Criteria and Ranking Plans

Figure 3.5: Pairwise Comparison of Confidence Criteria

	Assignment of Weights																							
	A-B	A-C	A-D	A-E	A-F	A - Dummy	B-C	B-D	B-E	B-F	B - Dummy	C-D	C-E	C-F	C - Dummy	D-E	D-F	D - Dummy	E-F	E - Dummy	F - Dummy	Dummy	Sum	Weight
A	0	0	1	1	1	1																	4	0.182
B	1						1	1	1	1	1												6	0.273
C		1					1					1	1	1	1								6	0.273
D			0					0				0				1	1	1					3	0.136
E				0					0				0			0			1	1			2	0.091
F					0					0				0			0		0		1		1	0.045
Dummy						0					0				0			0		0	0	0	0	0

After defining the confidence criteria, the team then used a pairwise comparison method to assign weights to each criterion (Figure 3.5[1]). The pairwise process determined that Granularity of Estimate and Validity of Assumptions were the two most important criteria, followed by Statement of Methods, Credentials of Cost Estimate Preparer, Inclusion of Key Components, and Inclusion of Inflation Cost Escalator, in descending order of importance. This means that the total score each plan received in our ranking process was governed by the following equation:

$$(0.182 \times Statement) + (0.273 \times Granularity) + (0.273 \times Validity) + (0.136 \times Credentials) + (0.092 \times Key\ Components) + (0.045 \times Cost\ Escalator)$$

With the scoring criteria established, the research team then developed a rubric to guide the categorical ranking. The rubric, available in Appendix B, describes what a low, medium and high score would look like for each criterion. The team then assigned each plan a score from 1-5 for each category, keeping decommissioning cost separate from salvage valuation. We chose to keep these two components separate because many plans had strong decommissioning cost estimates, but weak salvage value estimates, or vice versa. The methodologies were distinct enough in the plans that it was possible to evaluate them separately. The final scores for each plan are available in the attached spreadsheet labeled "Confidence Rating". The range of scores for decommissioning cost estimates was 1.4 (for the Sweetleaf Solar project in Halifax County, North Carolina) to 4.6 (for the Taugwonk Spur Facility in New London, Connecticut). The range of scores for salvage value was 1.0 (for the North Stonington Solar Energy Facility in New London, Connecticut) to 4.8 (a three-way tie between the Union Bridge facility in Carroll County, Maryland, the Great Bay Solar Project in Somerset County, Maryland, and the Frontier Road Hopkinton PV Plant in Washington, Rhode Island).

3.4 Data Analysis and Comparison

Once we had finished rating and scoring the confidence level for each decommissioning plan, some clear patterns had emerged. First, we observed that plans with the highest overall confidence scores were scoring very highly in the following criteria: statement of methods, granularity of assessment, and validity of assumptions. Intuitively, this is quite obvious as these

[1] In the figure, the criteria were recoded as letters to save space. A: Statement of methods ; B: Granularity of estimate ; C: Validity of assumptions ; D: Credentials of cost estimate preparer ; E: Inclusion of key components ; F: Inclusion of inflation cost escalator

are the three most highly-weighted criteria. However, it is an important realization to acknowledge that the decommissioning plans that instilled the highest degree of confidence in the reader were those that clearly stated and described their methods employed, that transparently stated and defended their assumptions made, and that included a high degree of detail and granularity in their cost estimations.

Next, we observed a clear pattern that decommissioning plans that had applied the “Per Unit” estimation methodology were consistently scoring higher in both their decommissioning and salvage value confidence levels as shown in Table 3.2. These plans were able to achieve a higher confidence rating by applying a methodology that is far more detailed and transparent than the two “Lump Sum” approaches.

Table 3.2: Decommissioning Cost Estimate Confidence Score By Methodology

Methodology	Average Decommissioning Confidence Score	Average Salvage Confidence Score
Single Number Lump Sum	1.55	2.05
Itemized Lump Sum	2.25	2.00
Per Unit	3.51	3.33

We also sought to get an understanding of how the actual decommissioning and salvage estimate values corresponded to the estimation methodologies employed in each plan. In Table 3.3, it’s clear that the “Per Unit” methodology resulted in the highest average decommissioning cost and the largest ranges for both decommissioning and salvage costs relative to the size of the solar project they are describing. Plans that applied the “Itemized Lump Sum” approach generated the highest salvage values on average.

Table 3.3: Cost Estimate Averages and Ranges by Methodology

Methodology	Avg. Decommissioning Cost ($/MW)	Decommissioning Cost Range ($/MW)	Avg. Salvage Value ($/MW)	Salvage Value Range ($/MW)
Single Number Lump Sum	$46,200	$18,300 - $110,000	$40,800	$0 - $120,000
Itemized Lump Sum	$120,100	$30,100 - $205,000	$268,070	$0 - $125,000
Per Unit	$155,200	$21,700 - $1.1 million	$172,130	$0 - $1.1 million

Turning our attention to geographic relationships, we found that Connecticut and Rhode Island had the highest average decommissioning and salvage estimate confidence scores respectively as shown in Table 3.4. Once broken out by state and county, our sample sizes become extremely small, so these trends and findings are not extremely conclusive.

Table 3.4: Decommissioning Cost Estimate Confidence Score By Region

State	County	Average Decommissioning Confidence Score	Average Salvage Confidence Score
California		**2.50**	**2.41**
	Sacramento	2.50	2.41
Connecticut		**3.45**	**1.48**
	Hartford	4.27	2.36
	New London	3.05	1.05
Hawaii		**3.23**	**2.32**
	Honolulu	3.23	2.32
Maryland		**3.11**	**3.61**
	Carroll	3.59	4.82
	Frederick	3.64	4.41
	Queen Anne's	3.00	2.70
	Somerset	3.59	4.82
	Washington	2.23	2.41
	Wicomico	2.23	2.18
Massachusetts		**2.55**	**2.30**
	Essex	1.95	1.32
	Hampshire	3.09	2.82
	Worcester	2.57	2.52
New York		**2.64**	**2.42**
	Greene	3.32	3.59
	Suffolk	2.41	1.55
	Tompkins	2.18	2.14
North Carolina		**1.36**	**1.23**
	Halifax	1.36	1.23
Rhode Island		**1.27**	**4.82**
	Washington	1.27	4.82
Virginia		**2.61**	**2.52**
	Dinwiddie	2.14	2.50
	Spotsylvania	3.09	2.55

Additionally, Hawaii's decommissioning plans generated the largest decommissioning and salvage value estimates of all states included in this analysis, as shown in Table 3.5. Plans from Massachusetts had the largest range of decommissioning cost estimates while North Carolina had the largest range of estimated salvage values.

Table 3.5: Decommissioning Cost Estimate Confidence Score By Methodology

State	Avg. Decommissioning Cost ($/MW)	Decommissioning Cost Range ($/MW)	Avg. Salvage Value ($/MW)	Salvage Value Range ($/MW)
California	$198,333	NA	$125,000	NA
Connecticut	$59,076	$27,300 – $110,000	$40,000	$0 – $120,000
Hawaii	$1,129,012	NA	$1,111,557	NA
Maryland	$23,228	$21,600 - $43,500	$25,015	$0 – $50,000

Massachusetts	$124,114	$18,300 – $195,000	$94,485	$0 – $147,000
New York	$43,959	NA	$63,277	NA
North Carolina	$50,685	$30,100 – $73,200	$99,951	$0 – 300,000
Rhode Island	$58,730	NA	$21,622	NA
Virginia	$61,912	$50,400 – $73,400	$56,708	$51,400 – $61,900

We also found that when labor is included in a decommissioning cost estimate, it is on average 60.7% of the total cost. It's also important to note that these descriptive statistics are the result of a rather small data set of 24 decommissioning plans, which get even smaller when categorized by estimation methodology and geography. To generate more accurate and significant relationships, it would be valuable to greatly expand the sample size for this analysis.

3.5 Conclusion

Our collection and analysis of 24 solar project decommissioning plans from 20 counties within 9 states allowed us to make some very interesting comparisons and draw out some fascinating insights. The initial process of identifying the cost estimation methodology used in each plan (Per Unit, Single Number Lump Sum, or Itemized Lump Sum) gave us the information needed to assess our confidence level in the accuracy of each plan as well as to make comparisons between plans with the same methodology.

We used our extensive knowledge of the 24 plans in our library to identify a set of criteria to evaluate the strength of a particular decommissioning plan's cost estimation method. We relied on three measurements of transparency (statement of methods, granularity of estimate, and validity of assumptions), one measurement of qualifications (credentials of cost estimate preparer), and two measurements of the comprehensiveness of the estimate (inclusion of key components and inclusion of inflation cost escalator). In the absence of actual decommissioning cost data, our confidence criteria cannot provide much information about the accuracy of a particular estimate. However, they can be used to assess whether the estimate provider has acted in good faith to provide a fair estimate, despite the considerable uncertainty surrounding decommissioning.

We also used our criteria to evaluate each plan in our library. These plans can now be used to provide examples of strong and weak cost estimation methodologies. Overall, the 24 plans in our library had an average confidence score of 2.8 for decommissioning cost estimates and 2.7 for salvage cost estimates. Although these scores are numerically similar on average, we often found that plans with strong decommissioning cost methodologies did not have strong salvage cost methodologies, and vice versa. Given the relatively average performance of our library of plans, it is clear that guidance is needed to improve the consistency and quality of decommissioning cost estimates. Due to the fact that the "Per Unit" estimation methodology generated the highest confidence scores on average, it may be wise for any future regulations governing decommissioning plans to consider requiring a certain methodology over others as the results can vary dramatically. Theoretically, if all written decommissioning plans applied the same estimation methodology, then meaningful comparisons could be made across plans and across different regions, making plans more meaningful and useful to project owners.

Chapter 4: Secondary and Circular Economy Market Analysis

4.1 Market Overview

In 2021, the US installed 23.6 GWdc of solar PV capacity, and total capacity swelled to 121.4 GWdc.[6] As total installed capacity increases and existing systems reach the end of their useful life, solar industry stakeholders and US policymakers have begun to consider how to manage solar PV modules that are reaching the end of their useful life or coming offline. There are several pathways that end-of-life (EOL) solar PV modules can follow, each with its own set of issues and advantages. The broad EOL categories include landfilling, recycling, reusing, and repowering systems.

4.1.1 Common End-of-Life Outcomes

Landfilling is typically the least expensive option for disposing of EOL solar PV modules. It is estimated that landfilling a single PV module costs between $1 and $2, whereas recycling a single module can cost upwards of $20 to $30.[7] However, landfilling PV modules is not a desirable EOL outcome. In many cases, modules that are taken offline still have remaining useful life, and have the potential to be reused or resold. Where solar PV modules no longer have remaining useful life (e.g., they become inoperable due to damage), landfilling foregoes the opportunity to recover materials from modules via recycling.

Recycling offers the advantage of keeping solar PV modules and their constituent materials in use for extended periods of time, and solar PV module owners may be able to recoup some economic value by selling their modules to recyclers or selling recycled materials into commodity markets. However, recycling modules remains an expensive EoL pathway that often represents a net cost to solar PV owners. Solar PV recyclers are an important component of establishing a circular economy for the solar industry, but much work is needed to improve the availability and affordability of recycling services.

Reusing modules also offers several advantages from an EOL management perspective. Reuse allows solar PV modules with remaining useful life to remain in operation, avoids permanent loss of module materials to landfilling, can be cost competitive with landfilling, and offers module owners an opportunity to claw back some of their initial investment (assuming the reused modules are sold to a third party). Reuse is becoming an increasingly popular option for solar PV module owners and buyers as supplies of virgin modules tightens and overseas demand for cheaper reused systems increases.[8] However, reuse strategies carry risk when solar PV module owners neglect to verify that solar PV modules intended for reuse are performing correctly or are sent to third parties who have a legitimate interest in reuse. If managed irresponsibly, reuse strategies can in some cases contribute to increased landfilling of solar PV modules.

Finally, repowering involves replacing old solar PV modules and system components (e.g., inverters, transformers, etc.) with new solar PV modules and system components, or supplementing (i.e., adding to) existing modules and system components with new solar PV modules and system components. Repowering is often driven by two factors. First, solar PV owners may need to repower their systems when existing solar PV modules or system components stop operating at their rated performance. Second, owners may choose to repower their systems when repowering generates increased financial returns via more efficient systems (e.g., more efficient solar PV modules or system components may generate more electricity that a module owner can sell or use to offset the energy they pull from the grid) or project subsidies (e.g., project owners may be able to take advantage of lucrative investment tax credits by repowering their systems). Across all scenarios, repowering has important implications for circularity, as project owners must weigh where to source replacement parts or additions to their existing systems and how to dispose of solar PV modules and system components that have reached the end of their useful life.

4.1.2 Market Sizing

The size of the secondary market for solar PV modules is very dependent on the market for new module installations. Using this method of thinking, our team generated an expected annual capacity of used solar PV modules that will become available to enter the secondary market between 1990 and 2039. We started by collecting data from the U.S. Energy Information Administration regarding the total existing electricity generation nameplate capacity of all fuel sources within the U.S each year, specifically the "Existing Nameplate and Net Summer Capacity by Energy Source, Producer Type, and State (EIA-860)" dataset[9]. Then we pulled out and isolated the annual nameplate capacity for the fuel source "Solar Thermal and Photovoltaic". In order to isolate solar photovoltaic generation, we manually adjusted the data by subtracting out the capacity generated by the four largest solar thermal generation plants in the U.S: California SEGS Thermal Solar Plant (428MW), Ivanpah Thermal Solar Plant (377MW), Genesis Thermal Solar Plant (250MW), and Solana Thermal Solar Plant (280MW).[10] [11] [12] [13] We also made the assumption that all of the installed solar generation capacity as of 1990 was also solar thermal generation. To calculate the annual quantity of new solar PV installations each year, we simply subtracted the total nameplate capacity of the previous year. This yielded our annual installations data from 1990-2020.

For future projected data, we used the Solar Energy Industry Association's (SEIA) "Solar Market Insight Report 2021 Year in Review", which included values for the annual capacity of solar PV installations from 2021-2032[14]. The report included two different projection models: one assuming that the current U.S solar investment tax credit would not be extended, and the other assuming that it would.

To estimate the capacity of solar PV modules decommissioned annually, we assumed that 25% of all solar capacity installed each year would be repowered after 10 years, and that the remaining 75% of installed solar capacity would be decommissioned at the end of its useful life after 20 years. Repowering can occur at any point in a project's lifetime, but they are increasingly occurring earlier than module end-of-life due to the need to replace inverters sooner, and in many cases new inverters require new modules as well that are compatible. Additionally, if a project has high O&M costs or isn't performing as expected, repowering can reduce costs and improve generation and profitability[15]. Our final solar PV module secondary market projections are shown below in Table 4.1. As long as there is no physical damage done to the modules being repowered after 10 years, this is the annual capacity of used solar PV modules available to enter the secondary market. If purchased, they would be expected to have 10-15 years of useful life remaining. A few important routes by which used solar modules enter the secondary market that are missing from our projection are distressed assets, modules that are undesired following failed project deals, and modules removed following a commercial or residential property sale[16].

Table 4.1: Projected Annual Capacity of Used Solar PV Modules Available to Enter Secondary Market

	No ITC Extension (2021-2032)				ITC Extension (2021-2032)			
Year	Annual Installations (MW)	Active Generating Capacity (MW)	Repowered After 10 Years (MW)	Decommissioned After 20 Years (MW)	Annual Installations (MW)	Active Generating Capacity (MW)	Repowered After 10 Years (MW)	Decommissioned After 20 Years (MW)
1990	-	-			-	-		
1991	-	-			-	-		
1992	-	-			-	-		
1993	2.00	2.00			2.00	2.00		
1994	(13.60)	(11.60)			(13.60)	(11.60)		
1995	-	(11.60)			-	(11.60)		
1996	0.20	(11.40)			0.20	(11.40)		
1997	2.40	(9.00)			2.40	(9.00)		
1998	(0.08)	(9.08)			(0.08)	(9.08)		
1999	111.76	102.68			111.76	102.68		
2000	0.20	102.88	-		0.20	102.88	-	
2001	(2.00)	100.88	-		(2.00)	100.88	-	
2002	-	100.88	-		-	100.88	-	
2003	(20.00)	80.88	0.50		(20.00)	80.88	0.50	
2004	-	80.88	(3.40)		-	80.88	(3.40)	
2005	14.00	94.88	-		14.00	94.88	-	
2006	-	94.88	0.05		-	94.88	0.05	
2007	184.00	278.88	0.60		184.00	278.88	0.60	
2008	72.00	350.88	(0.02)		72.00	350.88	(0.02)	
2009	203.00	553.88	27.94		203.00	553.88	27.94	
2010	694.00	1,247.88	0.05	-	694.00	1,247.88	0.05	-
2011	1,153.80	2,401.68	(0.50)	-	1,153.80	2,401.68	(0.50)	-
2012	3,301.00	5,702.68	-	-	3,301.00	5,702.68	-	-
2013	6,540.60	12,243.28	(5.00)	1.50	6,540.60	12,243.28	(5.00)	1.50
2014	6,998.00	19,241.28	-	(10.20)	6,998.00	19,241.28	-	(10.20)
2015	6,641.20	25,882.48	3.50	-	6,641.20	25,882.48	3.50	-
2016	16,799.20	42,681.68	-	0.15	16,799.20	42,681.68	-	0.15
2017	10,174.00	52,855.68	46.00	1.80	10,174.00	52,855.68	46.00	1.80
2018	10,059.60	62,915.28	18.00	(0.06)	10,059.60	62,915.28	18.00	(0.06)
2019	11,098.60	74,013.88	50.75	83.82	11,098.60	74,013.88	50.75	83.82
2020	21,101.00	95,114.88	173.50	0.15	21,101.00	95,114.88	173.50	0.15
2021	24,000.00	119,114.88	288.45	(1.50)	23,000.00	118,114.88	288.45	(1.50)
2022	22,000.00	141,114.88	825.25	-	22,000.00	140,114.88	825.25	-
2023	30,000.00	171,114.88	1,635.15	(15.00)	30,000.00	170,114.88	1,635.15	(15.00)
2024	25,000.00	196,114.88	1,749.50	-	33,000.00	203,114.88	1,749.50	-
2025	28,000.00	224,114.88	1,660.30	10.50	40,000.00	243,114.88	1,660.30	10.50
2026	29,000.00	253,114.88	4,199.80	-	42,000.00	285,114.88	4,199.80	-
2027	30,000.00	283,114.88	2,543.50	138.00	49,000.00	334,114.88	2,543.50	138.00
2028	31,000.00	314,114.88	2,514.90	54.00	56,000.00	390,114.88	2,514.90	54.00
2029	33,000.00	347,114.88	2,774.65	152.25	64,000.00	454,114.88	2,774.65	152.25
2030	35,000.00	382,114.88	5,275.25	520.50	71,000.00	525,114.88	5,275.25	520.50
2031	37,000.00	419,114.88	6,000.00	865.35	74,000.00	599,114.88	5,750.00	865.35
2032	39,000.00	458,114.88	5,500.00	2,475.75	75,000.00	674,114.88	5,500.00	2,475.75
2033			7,500.00	4,905.45			7,500.00	4,905.45
2034			6,250.00	5,248.50			8,250.00	5,248.50
2035			7,000.00	4,980.90			10,000.00	4,980.90
2036			7,250.00	12,599.40			10,500.00	12,599.40
2037			7,500.00	7,630.50			12,250.00	7,630.50
2038			7,750.00	7,544.70			14,000.00	7,544.70
2039			8,250.00	8,323.95			16,000.00	8,323.95
2040			8,750.00	15,825.75			17,750.00	15,825.75

4.2 Solar PV Module Secondary Market Analysis

One of the primary research questions we set out to answer within this aspect of the project was: how viable and competitive are secondary markets for solar PV modules today and in the near future? Our approach to answering that question consisted of determining the level of demand for used modules by comparing the market prices of new and used modules with varying characteristics as well as understanding current market dynamics and trends.

4.2.1 Used Module Pricing

Pricing data for used modules is available across several online marketplaces, such as Second Sol, Great Solar Panels, Kinect Solar, Solar Wholesale LLC, EnergyBin, Alibaba, and Jay's Energy. Where possible, we identified each module's type, chemistry, manufacturer, model number, quantity available, nameplate capacity, price per module, price per Watt, age, and country of origin. The used PV module listings we located were split relatively evenly between monocrystalline and polycrystalline silicon cell types, making it difficult to assess whether secondary marketplace operators prefer to sell a certain cell type, if customers have higher demand for a certain cell type, or if a certain cell type is more likely to be resold through secondary marketplaces. We also sourced a portion of our data from Julien Walzberg and his Agent-Based Model research team that was also studying the market prices of solar PV modules. Of the 209 modules we collected data for, 138 had a "used" module price associated with them and 119 were provided by Julien and his team.

Despite the growing list of retailers selling used modules, the overall marketplace for used modules is still in its infancy. Secondary markets often lack transparency regarding product conditions and performance and how used PV modules are priced. When asked whether he knew of sources or sites that track average pricing and performance characteristics for used modules, Commercial Solar Guy, an East Coast-based solar project developer commented that he was not aware of any. In general, secondary markets would benefit from tracking used PV module data to help potential buyers understand the risks or upside associated with sourcing used modules. One marketplace operator, EnergyBin, has begun publishing a first-of-its-kind report on the secondary solar marketplace, their PV Module Price Index. The 2021 Index tracked over 2.1 million c-Si modules that were posted for sale on the EnergyBin trading platform over the past two years, and represents an important step in making the secondary solar market more accessible to potential buyers.

4.2.2 New Module Pricing

In a nearly identical manner to used solar PV modules, we collected data on the pricing of new modules by sifting through several different online marketplaces including Second Sol, Great Solar Panels, Kinect Solar, Solar Wholesale LLC, EnergyBin, Alibaba, and Jay's Energy. Where possible, we identified each module's type, chemistry, manufacturer, model number, quantity available, nameplate capacity, price per module, price per Watt, age, and country of origin. The vast majority of modules found were either monocrystalline or polycrystalline silicon, but we also found 4 postings for thin film A-Si and CdTe modules. Nearly all of the new modules that we collected data for were being sold through sites that also sell used PV modules, and it seemed like many of them were brand new modules for sale following a failed project deal. As a result, many of the prices seemed to be discounted slightly. We also sourced a significant portion of our data from Julien Walzberg and his Agent-Based Model research team that was also studying the market prices of solar PV modules. Of the 209 modules we collected data for, 193 had a "new" module price associated with them.

4.2.3 Pricing Analysis

Once we had collected all of the PV module pricing data, we sought to identify and understand any patterns or relationships that may exist in order to firmly grasp the market dynamics between new and used modules. First, we pulled out the average costs for each module type as shown in Table 4.2.

Table 4.2: Average Market Prices by Module Type

			Used Modules				
Module Type	**Average Used Price ($/w)**	**Average New Price ($/w)**	**Average Year Manufactured**	**Average Age Upon Re-Sale (years)**	**Average Annual Watts Peak Degradation (%)**	**Total Watts Peak Degradation (%)**	**Adjusted Used Price ($/W)**
Monocrystalline Silicon	$ 0.20	$ 0.55	2015	7	1.1%	7.7%	$ 0.22
Polycrystalline Silicon	$ 0.18	$ 1.07	2012	10	1.1%	11.0%	$ 0.20
Thin-Film a-Si		$ 0.94					
Thin-Film CdTe		$ 2.18					

It is clear to note that the price of used modules is indeed significantly lower than that of new modules on average for both monocrystalline and polycrystalline silicon. To adjust for the fact that the used PV modules' price per Watt value is calculated from their original peak power output rather than the current slightly degraded output, we used the average age of the used modules and the average annual efficiency degradation rate (1.1%) to estimate the average peak power degradation[17][18]. We then used those values to recalculate the price per Watt, which was only a very small change from the original values. Additionally, we analyzed new and used module prices according to the peak power of each module as shown in Table 4.3.

Table 4.3: Average Market Prices by Power Output

Module Type	Nameplate Capacity (W)	Average Used Price ($/w)	Average New Price ($/w)
Monocrystalline Silicon	100	$ 0.81	$ 0.90
	175	$ 0.25	$ 1.02
	200	$ 0.13	$ 0.89
	205		$ 0.78
	215	$ 0.13	$ 0.85
	230	$ 0.12	$ 0.94
	250	$ 0.13	$ 0.67
	255	$ 0.15	$ 0.77
	260	$ 0.14	$ 0.68
	265	$ 0.14	$ 0.70
	270	$ 0.14	$ 0.67
	285	$ 0.12	$ 0.63
	290	$ 0.18	$ 0.50
	295	$ 0.27	$ 0.56
	300	$ 0.19	$ 0.50
	305	$ 0.19	$ 0.51
	310	$ 0.19	$ 0.52
	315	$ 0.21	$ 0.55
	320	$ 0.20	$ 0.61
	325	$ 0.10	$ 0.50
	330	$ 0.10	$ 0.61
	335		$ 1.31
	345	$ 0.51	
	350	$ 0.23	$ 0.61
	360	$ 0.21	$ 0.47
	365		$ 0.38
	370		$ 0.48
	375		$ 0.38
	380		$ 0.38
	390		$ 0.44
	400		$ 0.36
	405		$ 0.38
	410		$ 0.37
	415		$ 0.35
	470		$ 0.39
	500		$ 0.33
	525		$ 0.34
Polycrystalline Silicon	95		$ 2.91
	125		$ 2.10
	140		$ 2.32
	160		$ 1.50
	165	$ 0.16	$ 1.10
	175	$ 0.16	$ 0.89
	180		$ 1.54
	184		$ 1.33
	185		$ 2.10
	190	$ 0.27	$ 1.08
	200	$ 0.33	
	210	$ 0.10	$ 0.85
	220		$ 1.05
	225	$ 0.21	$ 1.26
	230	$ 0.13	$ 1.53
	235	$ 0.30	$ 0.43
	240	$ 0.14	$ 0.94
	245	$ 0.13	$ 1.25
	250	$ 0.18	$ 0.83
	255	$ 0.12	$ 1.13
	260	$ 0.14	$ 0.71
	265	$ 0.14	$ 0.92
	275	$ 0.14	$ 0.66
	280	$ 0.19	$ 0.50
	290	$ 0.18	$ 0.50
	315	$ 0.19	$ 0.50
	320	$ 0.29	$ 0.96
	330	$ 0.14	$ 0.50
Thin-Film a-Si	50		$ 0.56
	85		$ 1.33
Thin-Film CdTe	77		$ 2.87
	77.5		$ 1.49

There are no obvious trends in this comparison, except for new PV modules getting slightly less expensive per Watt as the peak power rating increases. This provides a more granular comparison of the prices for new and used modules between technologies. We also generated Table 4.4 to illustrate the effect that a module's age has on its price.

Table 4.4: Average Market Prices by Age

Module Type	Year Manufactured	Average Used Price ($/w)	Average New Price ($/w)
Monocrystalline Silicon	2006	$ 0.16	$ 1.02
	2008	$ 0.12	$ 0.94
	2009	$ 0.13	$ 0.89
	2010	$ 0.13	$ 0.85
	2012	$ 0.15	$ 0.80
	2013	$ 0.14	$ 0.67
	2014	$ 0.14	$ 0.73
	2015	$ 0.17	$ 0.75
	2016	$ 0.19	$ 0.61
	2017	$ 0.20	$ 0.50
	2018	$ 0.15	$ 0.50
Polycrystalline Silicon	2000	$ 0.13	$ 1.26
	2004	$ 0.16	$ 1.10
	2008	$ 0.13	$ 0.94
	2009	$ 0.16	$ 0.89
	2010	$ 0.10	$ 0.85
	2011	$ 0.14	$ 0.81
	2012	$ 0.13	$ 0.80
	2013	$ 0.13	$ 0.67
	2014	$ 0.13	$ 0.73
	2015	$ 0.19	$ 0.75
	2016	$ 0.14	$ 0.61
	2017	$ 0.17	$ 0.50
	2018	$ 0.17	$ 0.50

Clearly both monocrystalline and polycrystalline silicon modules have gotten less expensive per Watt each year. Photovoltaic technologies are advancing, and costs are coming down each year. Overall, used PV modules are consistently less expensive than new modules and could certainly seem like a great purchase for customers that don't mind the reduced remaining usable lifetime and power generating efficiency that come with used modules.

Pricing data from secondary marketplace retailers such as EnergyBin and Jay's Energy align with the data our team found. EnergyBin's recently released PV Module Price Index for Secondary Solar Markets notes that in many cases used solar PV modules sell for 50-75% below the cost of new solar PV modules.[19] The index tracks and compares trade prices for all black, bifacial, high efficiency, mainstream, low cost, and used crystalline-silicon modules.

Average PPW by Module Class

	All Black	Bifacial	High Efficiency	Mainstream	Low Cost	Used
Dec-20	$0.440	$0.490	$0.316	$0.302	$0.294	$0.138
Jan-21	$0.440	$0.395	$0.306	$0.297	$0.300	$0.110
Feb-21	$0.440	$0.380	$0.320	$0.297	$0.300	$0.149
Mar-21	$0.440	$0.340	$0.340	$0.310	$0.300	$0.185
Apr-21	$0.400	$0.345	$0.354	$0.320	$0.300	$0.149
May-21	$0.464	$0.350	$0.354	$0.336	$0.300	$0.149
Jun-21	$0.464	$0.360	$0.376	$0.300	$0.300	$0.149
Jul-21	$0.521	$0.390	$0.357	$0.308	$0.300	$0.149
Aug-21	$0.448	$0.390	$0.385	$0.320	$0.300	$0.148
Sep-21	$0.603	$0.398	$0.410	$0.320	$0.300	$0.161
Oct-21	$0.614	$0.429	$0.410	$0.343	$0.300	$0.173
Nov-21	$0.624	$0.460	$0.405	$0.350	$0.300	$0.140
Dec-21	$0.624	$0.481	$0.356	$0.369	$0.300	$0.106

ENERGYBIN © 2022

Figure 4.1: EnergyBin Average Price-per-Watt by Module Class Data

Jay Granat, owner of the wholesale solar technology brokerage firm Jay's Energy in California, notes that he sees PV modules with power ratings below 300 watts sell for $50-$70 per PV module ($0.17 - $0.23 per watt), while prices for bulk-ordered used modules can get as low as $0.10 per watt.[20]

4.2.4 Secondary Market Analysis

Global demand for used solar PV modules is increasing, and is expected to continue doing so through 2030[21]. As mentioned previously, used modules enter the market from either project repowering, failed project deals, or property sale, and project repowering is expected to become increasingly common in the next 5-10 years. The primary reason for repowering is to replace inverters that typically have a 10-year lifetime. Additionally, project owners can choose to repower and upgrade to newer module technologies to reduce O&M costs, increase generation, improve profitability, and extend the project's lifetime[16]. A used solar module broker, Jay Granat, told us that he only used to source deals for unwanted modules following failed project deals, but due to the increasing frequency of repowering and the growing demand for lightly used modules, he has begun to purchase used modules for resale as well[21].

The greatest demand for used modules is coming from the Middle East, Africa, Latin America, and the Caribbean. Afghanistan is currently the largest market followed by Pakistan, Djibouti, Somalia, and Ethiopia. These are locations where the solar resource is so large that projects are willing and eager to install PV modules with slightly degraded efficiencies for a lower cost. The increase in demand in these areas is driven primarily by three factors. First, customers are concerned about grid reliability in areas where natural disasters are frequent and local grid services are unreliable. Second, international scares such as the COVID-19 pandemic have spiked interest in off-grid energy generation. And third, these customers are looking for less expensive PV modules. Due to the lower efficiency and shorter lifetime of used modules, they are not very cost effective for grid-scale utility generation, but customers have found other uses. The application of used modules is primarily focused on micro-grids and on powering homes, water pumps, internet, solar irrigation, and battery charging[16]. Generally, international customers like purchasing used modules from the U.S. because they consider it a more trustworthy source. Additionally, Jay Granat has recently observed a sharp increase in U.S. demand for used modules coming primarily from individuals with concerns over global emergencies who want affordable off-grid backup power[21].

When making the decision to purchase used solar PV modules, there are several things that customers must consider. The age of the module is important because that determines the estimated remaining lifetime of the module as well as its degree of efficiency degradation. As shown previously, the average annual rate of efficiency degradation is 1.1%, so the older a module is the less energy generation you will receive for the same surface area. Also, non-transferrable warranties would result in the buyer taking on more financial risk should the used modules fail prematurely. However, the reduced cost of used modules is worth the risk to many customers. There is also a risk that the used modules could already be damaged or broken, so purchasing from a trusted source and performing amp and voltage tests is recommended[16]. Many brokers and buyers of used modules are also hesitant to purchase used thin-film modules due to the presence of hazardous materials that present higher disposal costs upon end of life. This, coupled with the fact that the vast majority of solar PV modules installed are either monocrystalline or polycrystalline silicon, these two module technologies dominate global secondary markets today[21].

Currently, the secondary market for solar PV modules is quite small and is dominated in the U.S. by a small number of companies solely focused on this segment. However, given the shift in recent years towards both increased project repowering rates on the supply side and increased interest in reliable behind-the-meter energy generation both domestically and internationally on the demand side, the industry is poised for a period of rapid growth over the next decade.

4.3 Secondary Market Landscape - Recyclers

Another important research question that we were interested in understanding was the availability of solar PV module recycling services in the US. This question was a logical extension of our research on emerging trends in secondary markets and recycled material and commodity markets because solar PV recycling services are the bridge that enables material flows between secondary markets for used solar PV modules and markets for recycled materials and commodities markets.

While conducting desktop research and thinking about the how to make our findings useful and accessible to the broader solar industry, our team was introduced to Kate Collardson and Amanda Bybee of SolarRecycle.org, a volunteer-run organization focused on promoting sustainable disposal practices for end-of-life solar equipment and aggregating disposal information for the solar industry. SolarRecycle.org had already begun developing a database to track solar equipment recycling services and welcomed our help increasing the scope of their database.

Before our additions, SolarRecycle.org's database contained contact information for 8 recycling vendors across 18 states.

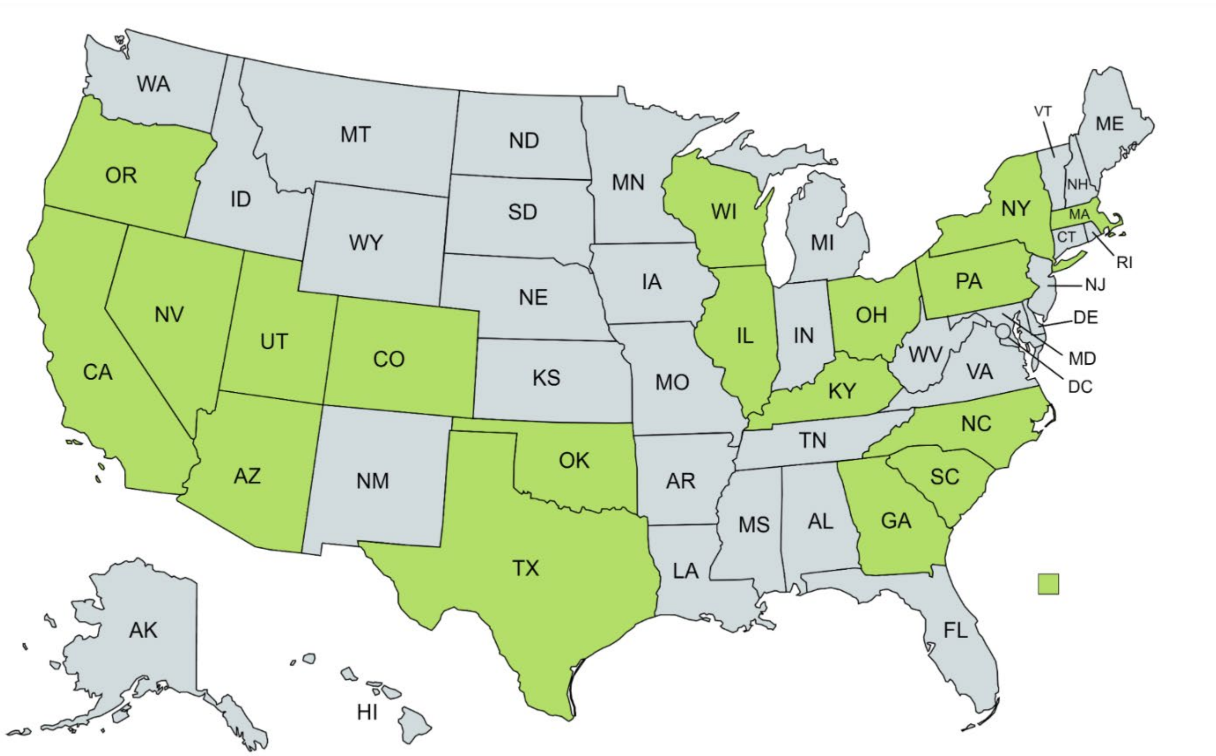


Figure 4.2: SolarRecycle.org Starting Database Coverage
Green highlights denote states with recycling services

Following our research, we were able to add 13 new recycling vendors, 31 new recycling facilities, and 6 new states to SolarRecycle.org's database. A full list of the new vendors we located is shown in Appendix E.

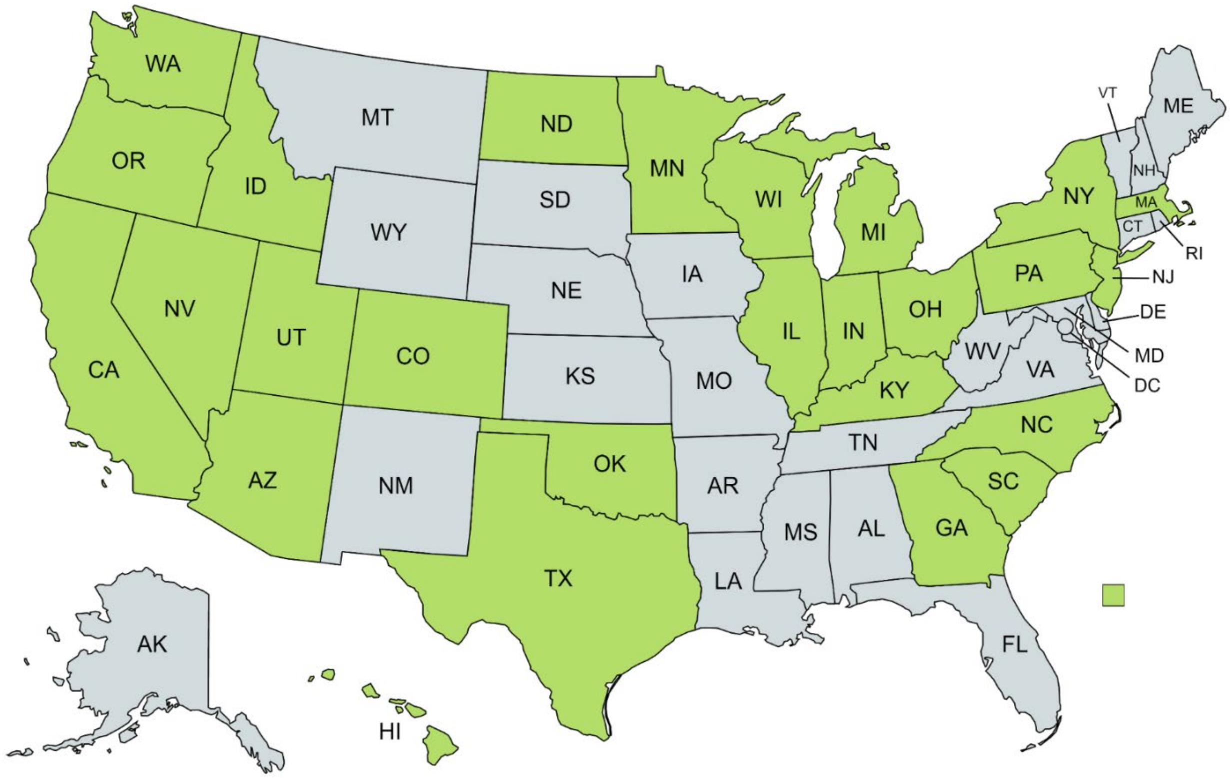


Figure 4.3: SolarRecycle.org Ending Database Coverage
Green highlights denote states with recycling services

The availability of solar recycling services is increasing, but there are still large swaths of the US that do not have access to local or in-state recycling services. We were unable to locate recycling services in 24 states, and in 12 states (Hawaii, Idaho, Indiana, Michigan, Nevada, North Dakota, New Jersey, New York, Oklahoma, Pennsylvania, Utah, and Wisconsin) we were only able to locate a single recycling provider. Even more troubling, four of the top ten states with the highest cumulative installed solar capacity either have no in-state recycling provider (Florida, who has the third highest amount of installed capacity, and Virginia, who has the ninth highest amount of installed capacity) or only one recycling provider (Nevada, who has the sixth highest amount of installed capacity, and New Jersey, who has the eighth highest amount of installed solar capacity).[22]

4.4 Case Studies

4.4.1 NuLife Power Services

NuLife Power Services is a solar PV construction firm that offers system restoration, repowering, and decommissioning services for end-of-life solar PV systems. NuLife was founded by Cesar Barbosa in 2015 after Cesar's experience decommissioning solar installations for big box stores showed him that the solar industry and solar customers were not adequately prepared to carry out solar PV decommissioning work. Prior to founding NuLife, Cesar held numerous construction-related positions in the construction and solar industries as a PV

Technician, an installer for commercial and residential solar PV systems, and a solar PV system operations and maintenance specialist.

Today, Cesar finds that many solar PV system owners do not yet understand the difference between "repurposing" solar PV modules and "recycling" solar PV modules. Whereas recycling end-of-life solar PV modules can be a time intensive and expensive process (costing approximately $0.32/lb), repurposing modules is sometimes as simple as ripping the serial number off a PV module and shipping it overseas (costing approximately $0.04/lb), whether it is working correctly or not. Mr. Barbosa mentions that there is currently a large market for repurposed modules overseas, such as Latin America and China. NuLife's customers consist mostly of independent power producers and individual system owners who control their PPAs and are easily able to install reused modules, and NuLife relies on a limited set of partners that it knows and trusts (e.g., WeRecycleSolar and Eco Minerals) to assist with recycling modules that cannot be repurposed. It is estimated that NuLife repurposes about 20,000 used modules each year. Repurposing modules could receive even more attention as supply chain and mining of materials to manufacture new modules become a constraint.

Though primarily a construction company, NuLife has been involved frequently in creating and reviewing decommissioning cost estimates, and sometimes also helped draft decommissioning plans for new projects as a consultant. They usually categorize costs into three functions: labor, recoverable assets--in particular solar modules--and other recoverable materials. Some municipalities do not allow including any salvage values from modules in the cost estimates due to lack of experience and other uncertainties, but it is often unclear whether the estimate needs to include a cost to cover recycling. Today, two-thirds of the cost to recycling is from the transportation of modules to recycling facilities, and therefore a national network of recyclers would greatly reduce costs by allowing project owners to locate the closest recycler. Mr. Barbosa also recommends that instead of creating a single estimate for the cost at end-of-life, costs should be broken down by life intervals of every 5-10 years, due to failure of modules and potential repowering. NuLife has been benchmarking cost data for years and is planning to create a calculator tool where project owners can input a few key metrics and get a rough estimate of decommissioning costs, while more detailed estimates need to be evaluated case-by-case. Looking at the industry as a whole, solar projects are frequently repowered 10 years after installation and decommissioned after 15-25 years. The quantity of demand for solar PV repowering and decommissioning is therefore driven by the quantity of solar projects that were installed both 10 and 15-25 years prior to the year in question. Given that 10 years ago the quantity of new solar PV installations in the U.S. was approximately 4 GWdc and in 2020 the new installed capacity was 19.2 GWdc, it is safe to say that the need for domestic solar project repowering and decommissioning is going to grow dramatically over the next decade[23]. With annual new solar installations in the U.S. expected to grow to over 50 GWdc by 2030, solar end-of-life processing firms such as NuLife will become increasingly important and will serve a rapidly growing market for years to come[24].

4.4.2 Jay's Energy

Jay's Energy is a wholesale solar technology brokerage firm headquartered in northern California. The firm is a one-man operation led by Jay Granat, who had a career as a solar installer prior to founding Jay's Energy in 2009 when former colleagues began asking him if he was capable of selling large quantities of lightly used solar PV modules. After the success of his first few deals, Jay officially established his new firm and began buying dozens of URLs to expand his network and reach more potential module buyers and sellers. Jay's primary approach is to locate extra solar PV modules belonging to contractors or developers that were never installed due to project cancellations. Once located, Jay connects the owner of the extra modules to a buyer, typically another contractor or a small-scale DIY installer, and the buyer purchases the modules from the supplier directly while Jay receives a cut of the sale. Jay has brokered numerous sales in this manner including a single sale of 25MW of Trina 240/250 modules to an importer in Pakistan. In this case, the modules were packed into shipping containers without pallets in order to maximize module availability.

This business model has worked well for Jay as his firm has been able to benefit from growth of the overall solar module resale market over the past decade. Interestingly, Jay has seen strong growth in the demand for lightly used modules each year beginning in 2018. This led Jay to expand his firm into this growing market segment and to now locate used modules for resale in addition to new leftover modules. Jay typically finds and purchases used PV modules through other online brokers such as EnergyBin, through referrals from his contacts, or by direct contact from sellers through his websites. With demand for used solar modules so high, purchases can often turn into bidding wars. He looks for modules at a good price that are less than 10 years old and only slightly degraded as this makes them much easier to sell. Once purchased, Jay spot tests the used modules with a multimeter, checking each panel's current capacity against its nameplate capacity to assess the degree of degradation. There is no formal certification process for rating used modules. Once tested, Jay must store his modules in warehouses until they can be sold. Shipping and storage are the largest costs that Jay faces, and as a result he focuses on sourcing used modules locally. Jay does not typically pay for the removal of his used modules from their original site, but he will if the modules are in exceedingly good condition and available at a great price.

When Jay first began reselling unwanted new solar PV modules and used modules, the majority of his customers were large international importers. However, as Jay noticed overall demand for used modules growing since 2018, the demand for used modules within the U.S. grew as well. Today, he sees a much larger volume of internal solar module movement domestically. Jay attributes this growth to increasing frequencies of project repowering, a national shortage of polysilicon, as well as booming demand from individual homeowners since the emergence of COVID-19. Many individuals are seeking smaller scale behind the meter solar generation in the case of widespread infrastructure failure due to the pandemic, extreme weather events, or other potential global catastrophes.

Looking forward, Jay believes that in order to keep solar PV modules out of landfills, solar projects should be repowered every 10 years or sooner. This helps ensure that there will be secondary market demand for the used modules upon repowering. Jay also has concerns about the cost to recycle a module because currently the broken-down raw materials within each module aren't worth the $25 it costs to recycle the module. Additionally, used thin-film modules present end-of-life challenges due to the presence of hazardous chemicals. Brokers don't want disposal issues or liability for disposal, and there are no buyers for these modules because they also want to avoid liability[21].

4.5 Conclusion

By collecting data from several different solar PV module retail websites, we were able to determine the average costs of new solar PV modules to be approximately $0.55/W for monocrystalline modules, $1.07/W for polycrystalline modules, $0.94/W for thin-film A-Si modules, and $2.18/W for thin-film Cd-Te modules.

As expected, used solar PV modules are significantly less expensive than new solar PV modules. Multiple secondary market retailers report that used solar PV modules frequently sell for less than $0.20 per watt, with prices varying based on module type and power rating. There are several secondary marketplace retailers that reliably carry used solar PV modules, but further work is needed to increase their visibility, accessibility, and geographic reach.

Our research and analyses indicate that the secondary market for used solar PV modules is poised to continue growing dramatically in the coming decade. This trend will be driven by an increase in the frequency of project repowering, growing international demand for functional and inexpensive PV modules, and increasing demand domestically for behind-the-meter emergency generation.

Furthermore, building a robust secondary marketplace is essential to improving the circularity of the solar industry, and recycling services will continue to be a key component of the secondary markets ecosystem. Recycling services are beginning to emerge and scale throughout the US. However, the supply of these services is still lacking or non-existent in many parts of the country. Where recycling services are not available or cannot support circular material flows, secondary markets are needed to keep solar PV modules with remaining useful life in operation.

Markets for used solar PV modules face many challenges. Improvements in solar PV module technology performance, declines in cost, and the availability and economic benefits of tax credits for new projects all incentivize consumers to purchase new solar PV modules or repower existing installations with new solar PV modules (as opposed to keeping existing systems until the end of their useful life or supplementing existing systems with additional used solar PV modules). In addition, markets for used solar PV modules must face down consumer and regulatory concerns regarding used module performance and safety.

The most promising market and application for used solar PV modules in the next 10 years is small scale behind the meter generation for residential customers or microgrids. As stated previously, there is large demand in the Middle East, Africa, and Latin America for inexpensive PV modules to power microgrids that support family and community resources such as water pumps, lighting, charging, and internet access. The quantity of communities in these regions that could benefit from solar power is immense, and if used module retailers can connect with this demand, the secondary market for PV modules will expand dramatically.

Chapter 5: U.S. Local Policy Survey

5.1 Background

Between 2010 and 2020, installed capacity for utility scale solar PV grew from 393 MW to 46,306 MW, an increase of more than 11,000%[25]. As capacity has grown, siting of new solar generating facilities has emerged as a key challenge for the future of the industry. In part, this is because the prevalence and complexity of solar regulations and zoning restrictions has grown in tandem with the growth in capacity. One expression of this trend is the recent increase in solar decommissioning requirements. equipment, including wiring, inverters, and structural elements, after the useful life of the installation has come to an end. Decommissioning also includes restoring the land on which the installation stood. The decommissioning regulations collected by NREL typically require solar developers "comply with specific decommissioning performance activities, submit decommissioning plans, estimate costs of decommissioning, and/or provide proof of financial assurance to state and/or local jurisdiction" (p. vi).

In 2021, NREL published a comprehensive survey of state level decommissioning policies, which found that 15 states[2] had implemented some form of statewide decommissioning requirement. The remaining 35 either explicitly or implicitly left regulation up to local units of government (LUGs). The study also mapped the similarities and differences between different state policies, focusing particularly on whether they required developers to provide some form of financial assurance for future decommissioning[26]. The report also identified one policy at the federal level, developed by the Bureau of Land Management, the pertains to solar installations on federal land. However, little is known about the form and purpose of solar decommissioning ordinances enacted at the local level solar decommissioning ordinances.

This study examines city and county level decommissioning policies to evaluate a) why local decommissioning requirements are implemented, b) who advocates for and against them within a given community, c) how they are developed, and d) what their effect on solar development has been.

5.2 Literature Review – Renewable Energy Siting

Although public support for renewable energy development in general remains high[27], local opposition to the siting of particular projects has increased in recent years[28]. In some cases, community members mobilize to stop installations at the time the developer applies for its land use permit. In other cases, community leaders proactively implement zoning ordinances that are restrictive enough to make solar development effectively impossible.

A body of literature about opposition to renewable energy siting already exists, but the root causes of local resistance to solar development are still unknown. Explanations from media and activist sources tend to characterize resistance as NIMBYism[29] [30] [31], but recent research proposes a range of more complex motivations. Bailey & Darkal (2018)[32] and Schumacher & Yang (2018)[33] found that residents expressed concerns about changing place identity and the ecological risks of large installations. Because solar energy is often best sited in open spaces, communities may fear that permitting solar installations will require development of virgin land or agricultural spaces. These spaces may be important to residents' perceptions of community character and sense of place. Walker & Swift (2015)[34] observed residents' worries about property value reduction caused by proximity to solar developments. Finally, Schelley, et al.

[2] California, Hawaii, Illinois, Louisiana, Minnesota, Montana, Nebraska, New Hampshire, New Jersey, North Dakota, Oklahoma, Vermont, Virginia, Washington, and Wyoming

(2020)[35] noted that some residents were concerned about the distribution of benefits – they were more willing to support solar developments if they benefitted the community in some way.

This research applies these and other themes to an analysis of interviewees with local planning staff.

5.3 Methodology and Site Selection

We began by expanding the scope of NREL's existing decommissioning policy research to include local ordinances and regulations. We collected 11 county level ordinances from 5 states (see Table 5.1, below) and compared their requirements to the requirements that were usually observed in state level policies. The purpose of this exercise was to help us understand the concerns that local policies addressed in their ordinances and to assess whether these concerns were similar or different from those addressed by state policies. We found that most of the counties we researched regulate solar installations via conditional or special use permits, though 4 of the 13 allow solar by right in specified districts. The most common district that counties permit solar in was agricultural (10 counties); followed by light and heavy industrial / manufacturing (9 counties). A few counties also allow solar in residential, commercial, natural resource, airport, and rural conservation districts. Finally, we found that all but 3 of the counties we researched require solar project developers to submit some form of financial assurance to cover decommissioning costs. We developed short case studies describing our findings for each county, which are available in the attached Chapter 5 addendum.

Table 5.1: County Decommissioning Policies

County	State	Policy Number	Financial Assurance	Regulation Type
Butte	CA	Butte County Zoning Ordinance Section 24-157C.7; Butte County Solar Guidebook, Ch. 3	No	Conditional use permit grazing or "other" land in agricultural, commercial, natural resource, and some residential zones. Some structures are permitted by right in industrial zones while others require CUPs
Los Angeles	CA	Los Angeles County Code of Ordinances, Ch. 22.140.510	Performance / financial guarantee	Conditional use permit in some residential, agricultural, commercial, rural, and manufacturing districts
Napa	CA	Napa County Code of Ordinances, Ch. 18.117.040.	Bond; deposit; instrument of credit; letter of credit; or property lien	Use permit; allowed in most districts
San Bernadino	CA	County of San Bernardino Development Code, Ch. 84.29.070	No	Special use permit; allowed in most agricultural, rural,

				commercial, and industrial districts
Kaua'i	HI	Kaua'i County Code, Sec. 8-2.4	Proof of financial security	If >20 acres – variance permit required; allowed in agricultural district, with some conditions
Maui	HI	Maui County Code 19.30A.050	Proof of financial security	If >15 acres – special use permit required; allowed in agricultural district, with some conditions
Frederick	MD	Frederick County Code 1-19-8.401, 1-19-10.700	Monetary guarantee	Permitted by right in Limited Industrial and General Industrial; with supplemental conditions in Agricultural districts
Queen Anne's	MD	Queen Anne's County Ordinances, Ch. 18: 1-95, S-5	Bond or other financial assurance	Conditional use in agricultural and countryside districts
Catawba	NC	Catawba County Code of Ordinances, Sec. 44-633	Surety or performance bond, certified check held in escrow, or irrevocable letter of credit	Permitted by right in light and general industrial districts (supplemental use conditions apply); conditional use permit in rural conservation and residential districts
Cleveland	NC	Cleveland County Code of Ordinances, Sec 12-160	Surety bond	Permitted by right in Light and Heavy Industrial zones
Wayne	NC	Wayne County Code of Ordinances, Sec. 18-199	No	Special use permit; allowed in residential-agricultural, light industrial, airport, and heavy industrial districts
Mecklenburg	VA	Mecklenburg County Code, Article 20	Funds held in escrow, performance bond, letter of credit, or other security	Special use permit*
Suffolk	VA	Suffolk County zoning Ordinance, Sec 31-724(c)	Performance surety	Conditional use permit; allowed in agricultural and light and heavy manufacturing districts

*Mecklenburg's zoning ordinance was updated to include solar arrays in 2020, and the ordinance is not yet available online.

We chose counties listed above using a two-step process. First, we checked NREL's statewide policy report and identified states that either used a hybrid regulatory approach (some functions left to LUGs and some reserved for the state) or left decommissioning regulations entirely to LUGs. We omitted any state that had an entirely state government led approach. We then used the Solar Energy Industry Association (SEIA)'s database of large scale planned and implemented solar projects to identify ‘hot spots’, I.e., areas with a large concentration of solar projects[36]. We emphasized these locations because we reasoned that jurisdictions with large amounts of solar would be more likely to have decommissioning ordinances. As we researched counties, we returned to this map to identify additional potential locations until we had found a sufficient number of policies.

5.4 Interview Methods

The project team conducted seven interviews to gain a better understanding and explore interviewees’ experiences regarding the creation and existence of local solar ordinance and their respective decommissioning policies. The semi-structured interviews allowed for the project team to ask questions that were relevant and specific to the research project, while also inviting more open-ended conversation and follow-up questions. The project team conducted interviews with planning officials from the following states:

- Maryland
- Massachusetts
- Minnesota
- Virginia

The research project involved semi-structured interviews over both virtual conferencing and phone call mediums.

5.4.1 Participants and Recruitment

The project team recruited interviewees to participate in the project through email initiations which outlined our research aims, why the project team was interested in interviewing potential interviewees, and the interview process. In addition to follow-up emails, the project team also conducted follow-up phone calls to contact potential interviewees. While during recruitment efforts, the project team explained the purpose and scope of the interviews, the interviewees did not receive the project team’s semi-structured questions in advance before the interviews.

5.4.2 Interview Design

To help formulate our interview process and expectations, the project team met with Dr. Sarah Mills, Senior Project Manager and Professor at the University of Michigan. Dr. Mills’ research includes conducting interviews with stakeholders concerning the development of renewable energy siting and planning ordinances, especially with local government officials and their planning departments. Therefore, the project team turned to Dr. Mills to learn from her experiences in order to better conduct their interview methods, including interview script development and questions.

To gain a better understanding for each local government’s solar ordinances and decommissioning policies, the project team structured interview questions based on seven main theme-based sections:

1. Introductory questions, especially concerning local government’s histories with solar zoning ordinances and stakeholder involvement in the development of solar zoning ordinances;

2. Community involvement in the development of solar ordinances;
3. Identifying planning regulations that may impact solar decommissioning processes;
4. Past solar decommissioning processes before such ordinances were developed;
5. Identifying cases in which solar projects had to comply with solar ordinances and decommissioning policies;
6. Understanding the process in which local governments created financial assurance requirements for solar projects;
7. Understanding the value that solar ordinances and decommissioning policies have had for local governments and their communities.

The project team disclosed to interviewees that that all participants would retain their autonomy and interviewees had the right to refuse answering questions, as well as freedom to stop the interview process at any time. At the beginning of each interview and before the project team began conducting questioning, interviewees were asked if they had any questions for the project team and the goal of the research project. Interviewees were asked permission and notified that the interviews would be recorded and later transcribed by the project team, in order to accurately understand and present interviews within the research project.

During the interview, one consistent project team member led the interview, while another project team member took notes. During the interview, each project team member was welcome to ask follow-up and clarification questions both during and at the end of interviews. Each interview lasted approximately 30-60 minutes.

5.4.3 Site Selection

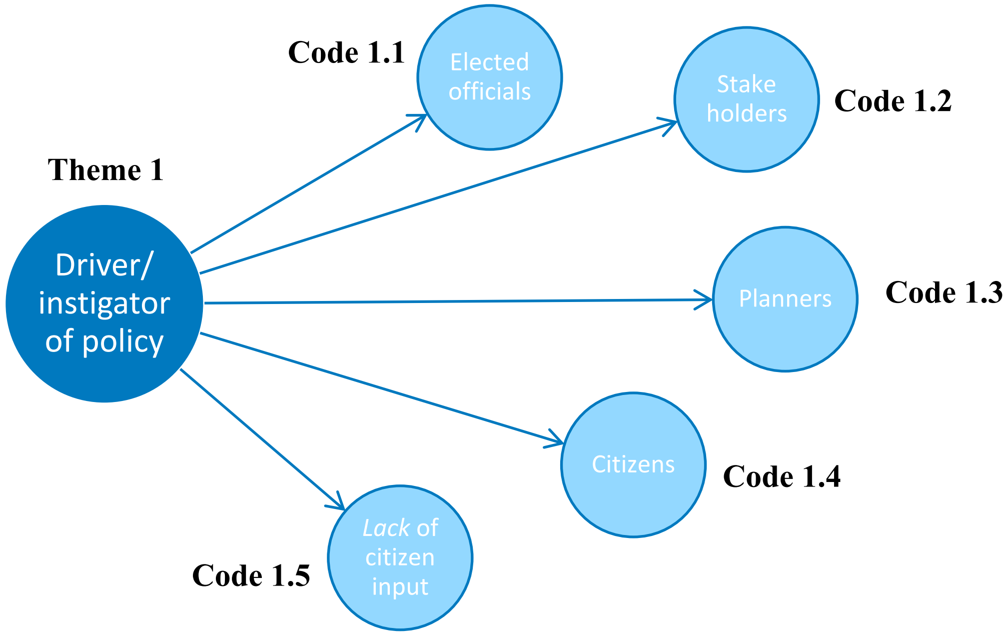
Sites were originally selected fromife team contacted planning staff in 16 counties or independent cities, 6 of whom consented to be interviewed.

To boost the sample size, the team then expanded the inclusion criteria to include any county or independent city that had a decommissioning policy or had required a decommissioning plan as part of a conditional use permit. There are over 3,000 counties in the United States as a whole. To narrow this search, counties were selected for consideration based on the size and concentration of solar installations in their jurisdiction, as reported by the Solar Energy Industries Association (SEIA, 2022). Using this method, the research team contacted planning staff in an additional 7 counties, one of whom consented to be interviewed. The total interview sample size was 7, with representation from Virginia, Maryland, Massachusetts, and Minnesota.

5.5 Analysis

Interviews were analyzed using thematic content analysis. Thematic content analysis relies on frequency and interaction analysis of codes and themes. In this study, a *theme* refers to the general *concept* or *research question* that the study seeks to evaluate. A *code* refers to the *specific expressions* of the concepts that are exhibited by individual interviewees. Codes and themes are related to one another as described by Figure 5.1.

Figure 5.1: Relationship between codes and themes



The research team used a hybrid inductive and deductive approach to developing themes and codes. Inductive development is a method by which themes and codes are derived by reading the transcripts and identifying patterns or particularly impactful perspectives. In deductive development, meanwhile, codes and themes are developed prior to transcript analysis, based on the research question for the project, literature review, and expert opinion[37].

The following seven themes were identified for use in this analysis:

1. Driver/Instigator of Policy/Ordinance (I.e., which stakeholders were most responsible for the creation and implementation of the policy)
2. Motivation for Administrative Policies/Ordinances (I.e., why did stakeholders choose to create the policy?)
3. Perception of Solar
4. Emotional Response
5. Method for Policy/Ordinance Development
6. Process for Reviewing Decommissioning Plans
7. Effect of Policy/Ordinance

Corresponding codes were identified for each code based on established literature and expectations based on NREL's prior experience with the topic. Additional codes were added as they arose during interview transcription and analysis. These codes are provided in Table 1 in Appendix A. The team used Descript to transcribe interviews. To remove any potential for bias, both team members coded interviews simultaneously, and then met to harmonize findings into a single combined coding record. Additionally, the audio recording for one of the interviews failed to save, so coding for that interview relied on the interviewers' detailed notes.

5.6 Results

The interviews produced a wealth of information about local experiences with utility scale solar projects. Through this analysis, we deepened our understanding of 1) who advocates for solar decommissioning policies, 2) what purpose decommissioning policies are intended to serve; 3) motivations behind decommissioning policies; 4) how decommissioning policies are developed; and 5) what effect decommissioning policies have on local governments, communities, and solar development.

5.6.1 Advocates for Decommissioning Policies

This section describes interviewees' responses when we asked who first proposed adding decommissioning to a given jurisdiction's solar zoning ordinance.

Six out of seven participants (86%) reported that the solar zoning ordinance itself was developed at the request of elected officials, usually a planning board/commission or city council. Four of these six participants (57% overall) indicated that the elected officials specifically asked that decommissioning be included and emphasized in the ordinance. The remaining two indicated that elected officials had left the content of the ordinance to county or city planners who had then researched the topic and identified decommissioning as a common element of solar regulations in other jurisdictions. We viewed such cases as "administrator-led", meaning that the decision to include decommissioning was largely made by planning staff. In total, three participants indicated that decommissioning was administrator led (two of these overlapping with those who had first been directed by elected officials).

Citizen involvement in policy development was slightly more complicated. Five of the seven interviewees explicitly noted that citizens were not heavily involved in developing or passing their solar ordinance. Several of these participants indicated that their jurisdictions had solicited feedback or comments on their ordinances, but still received little to no response. However, of these five participants, four also reported that citizens had become engaged during the review process, after the city or county had received a solar development application. Two of these reported that citizens had become *highly* involved in the review process:

> **Participant 2:** "The zoning ordinance amendment and policy... garnered less interest, but it was when there was a specific solar farm proposed for a certain piece of property and it was working its way through the public hearing process, that's when we did get a lot of citizen input and a lot of that revolved around...the impacts to adjacent property owners."
> **Participant 5:** "It look[s] like we actually didn't have very many people speak at the planning commission on the ordinance itself, but we had hundreds of people involved in the case as it went through the [permitting] process."

Overall, five out of the seven participants reported some level of citizen involvement (with four of these five overlapping with those who said that citizens only became involved during the individual application review process, not the ordinance development process). Of these five, three reported that citizens had specifically mentioned decommissioning or end of life in their concerns. For the rest, citizen concerns covered a range of topics, including aesthetics, glare, noise, and ecological and ecotoxicity concerns.

Finally, two of the seven participants mentioned involvement by specific stakeholders in the ordinance development process. These same two participants also indicated that citizen as a whole were not heavily involved in ordinance development, indicating that they viewed 'stakeholders' as a separate category from the general public. These two participants also both mentioned property owners when talking about stakeholders. One discussed only supporting property owners, i.e., those who wanted solar development on their land. The other discussed both supporting and opposed property owners, i.e., property owners who did not want to see solar development on land adjacent to their land.

5.6.2 Purpose of Decommissioning Policies

To try to elicit information about why localities had included decommissioning in their ordinances, we first asked participants to describe the history of their decommissioning regulations. From this, we gleaned valuable insight into the mindsets of planning staff and learned about their perceptions of community attitudes toward solar development. This also helped us deepen our understanding of the motivations behind decommissioning policies, which will be discussed in the next section.

If participants did not immediately provide information about the purpose of their policy, we asked probing questions about what prompted the development of the ordinance, the nature of local concerns surrounding solar development, and the difference between solar developments and other, similar structures that are already regulated in their community. Code development for this section required the research team to identify common themes in explanations given by participants who often relied on different language or terminology. As such, the codes described below describe the general sentiment expressed by participants, rather than reflecting their words verbatim. Notably, although we asked about decommissioning specifically, many participants answered as if we had asked about solar regulations in general. Table 2, below, indicates whether each code describes motivations for decommissioning policies, motivations for solar regulation in general, or both.

The most common motivation for including decommissioning in a locality's solar ordinance was protecting the community from the future burden of decommissioning, if the site were to be abandoned. All seven of the participants spoke about this concern in some capacity, such as:

> **Participant 1:** "...and we require a bond from the solar developer so that if they leave it and don't decommission it...[if] they go out of business or whatever, we have the money to do it ourselves."
> **Participant 2:** "I think that end of life stuff was mostly a concern of city council members, knowing that, you know, was the city going to be on the hook for this. How are we going to deal with this? If it goes bankrupt?"
> **Participant 4:** "...it had to do with, you know, [we] didn't want the county holding the bag if the project should, uh, you know, not be successful..."
> **Participant 7:** "...what do we do if a solar company just ups and leaves this area? Where's that security gonna come from? So just like a lot of other small towns in the state, we don't really have ready funds to decommission these projects. So that was the initial thinking, going into it."

This sentiment was repeated multiple times in each interview--we recorded a total of 18 mentions in 7 interviews.

However, we also recorded multiple motivations for solar regulations in each interview. Each of the codes identified in Theme 2, *Motivation for Administrative Policies* was noted at least once:

Table 5.2: Prevalence of Codes for Theme 2

Motivation for Regulatory Policies	Mentioned in ____ interviews	In reference to
Protecting local character	3	Both
Avoiding future burden	7	Decommissioning
Response to sudden trend	4	Solar in general
Avoiding use phase harm (glare, noise, etc.)	5	Solar in general
Ecological impact concerns	2	Both
Pre-empting public concern	2	Both
Overall resistance to solar development	4	Solar in general
Experience with other permitted structures	2	Decommissioning
Maintain local autonomy	1	Solar in general

The second most common motivator of solar regulations was a desire to protect the community from potential use phase harms, such as glare, noise, or disruption of view. Use phase harm was a concern most commonly raised by citizens – in each of the five cases that use phase harm was mentioned, citizens were mentioned as one of the originators of the concern. Two of the five participants also indicated that another party raised concerns about use phase harms (administrators in one case and elected officials in another). Additionally, the two participants who reported "ecological impact concerns" both indicated that citizens raised these concerns in conjunction with their other use phase concerns. In one case citizens were concerned about the potential for fires, adverse soil impacts, clear cutting, and reversion back to agricultural land. In the other case, citizens discussed the implications of large-scale landfilling of PV modules. In both cases, heavy metals and potential human or ecological toxicity concerns were raised.

Following "avoiding use phase harm", the third most common response was a tie between "response to sudden trend" and "overall resistance to solar development". Both explain jurisdictions' decisions to regulate solar in general, more than they specifically explain decommissioning. In the case of "response to sudden trend", several participants indicated that planners had begun thinking about including solar installations in their ordinances after the zoning office received one or more applications for development:

> **Participant 3:** "It was kind of a knee-jerk reaction to some activity from some solar developers in the county. We didn't have an ordinance that direct directly dealt with solar."

> **Participant 5:** “We received an application or were going to receive an application for a solar facility in 2018. And we didn't have, at that point in time, a specific solar provision in our ordinance. So we worked to develop both our comprehensive plan…and also develop a solar ordinance.”

For these four participants, the decision to craft a solar ordinance was sparked by external activity that made planners and/or elected officials realize they were unprepared for an influx of solar applications. Each participant also reported that they developed their ordinance by researching solar regulation and mimicking what they found in other jurisdictions. In these cases, decommissioning requirements, including financial assurance, were included in the solar ordinance largely because they had already been included in other jurisdictions’ ordinances and had the appearance of a best practice.

Four participants also expressed motivations consistent with a general desire to restrict solar development in their jurisdiction. Three of these four participants indicated that this sentiment was prompted by citizen feedback, for example:

> **Participant 5:** “There were people that were opposed to the project that kind of divided up and each had their specialty to research. So, uh, we had a lot of citizens that became very educated and decommissioning was one of the topics that they were very concerned about.”
> **Participant 7:** [The community] liked [solar development] at first, but then they realized that people were selling their land left and right… Residents kind of got tired of it after a while, and we still allow for it, we're not going to discriminate against solar developments, but we're trying to limit them.”

Participant 5 was the only interviewee to mention decommissioning in conjunction with the desire to reject or limit solar development. In general, we found other mechanisms for restricting development, usually siting restrictions, to be more common. This was described by Participant 6, when asked why she had speculated that her jurisdiction received fewer large solar applications than others:

> **Participant 6:** “I don't think we've gotten ones as big but a lot of it might be locational cause they want to locate near the grid, and a lot of times maybe the best locations we have would not be something that we would recommend approval for. For instance, we have a rural conservation area [and] we do not recommend solar [in these areas]. When I tell [developers] that they often are like, oh, but that's the best place to put it, but I know you guys won't approve it.”

The fourth most common sentiment expressed by participants was the desire to “protect local character”. In each of the three cases, this was a reference to the agricultural aesthetic or rural culture of the area. In two of the three cases, participants mentioned using siting restrictions to ensure that solar development could not occur in areas that had been designated to be free of anything “that could be considered a [large-scale] agricultural [or] industrial type use”, as described by Participant 6. Notably, Participant 6 differentiated small-scale and large-scale agriculture when specifying the aesthetic her community wanted to preserve. The other interviewee, Participant 1, did not make this distinction. None of the participants mentioned decommissioning specifically when discussing their desire to protect local character—this sentiment focused more on the use phase.

The fifth most common motivation for solar policies was a three way tie between "ecological impact concerns (which has already been discussed, above) "pre-empting public concern", and "experience with other permitted structures". Two participants mentioned a desire to address likely public concerns before citizens raised these issues themselves:

> **Participant 1:** "If you look at what tends to be community opposition, you know, around the country, we tried to. address some of those things…to mitigate impacts for adjoining property owners and to try to address, to some extent ahead of time, what community concerns would be"
> **Participant 2:** "It really just started out as kind of a pure information gathering process. And then based on what we gathered and what we were hearing is kind of the major concerns, we put together, this kind of memo to city council that outlines a lot of the information that we had gathered and specifically addressed some of the concerns that were raised."

In both cases, the participants relied on experiences in other jurisdictions to attempt to predict what concerns their own citizens might have. Similar to the participants who spoke about responding to external influences in the "sudden trends" section above, in this case, decommissioning was included in these participants' ordinances largely because it had already been included in other jurisdictions' ordinances. There was one overlap between these sets of participants, bringing the number of participants who were driven by established practices in other jurisdictions to 5.

Two participants also mentioned that experiences with other structures had motivated the inclusion of decommissioning requirements in their ordinances. Participant 5 spoke compared solar installations to telecom towers, which her community had imposed decommissioning requirements on until federal regulations superseded state and local authority. Participant 7, meanwhile, spoke about his community's experiences with abandoned buildings when asked why decommissioning was included the solar ordinance:

> **Participant 7:** "The issue is, we have a bunch of vacant buildings in certain parts of our town, especially in the downtown area. So they kind of transfer that mindset onto solar fields".

Notably, only Participant 7 spoke about an actual experience with structure abandonment. Participant 5 only spoke about concerns her community had about *potential* abandonment of telecom towers in the future.

Finally, only one participant spoke about using solar ordinances to maintain local autonomy:

> **Participant 1**: "[the state] has the authority to approve solar projects pretty much anywhere regardless of the local zoning, but they don't necessarily want to do that if the local jurisdiction…can demonstrate that they are making ample opportunities for solar development in the county. That was one of the reasons we

> did the most recent amendment…not wanting to be forced to do something, being able to choose it ourselves."

Though one other participant did mention the state as a driver for solar development in his jurisdiction, no other interviewee described their ordinance as a mechanism for maintaining local control over permit decisions.

Overall, the most common motivator of decommissioning policies specifically (as opposed to solar ordinances more generally) was the desire to protect the local government from the burden of future costs. The second most common driver was mimicking of other jurisdictions that had already included decommissioning requirements in their ordinances. The third was experiences with other structures. Finally, only one participant mentioned decommissioning in conjunction with a general desire to reject or limit solar development.

5.6.3 Motivations Behind Decommissioning Policies

When asked to describe the history of their decommissioning regulations, participant also provided valuable insight into how they and their communities perceived solar development in general. Although understanding these attitudes was not our main objective in asking about regulations, characterizing them allowed us to contextualize our findings.

First, we characterized the language participants used to try to deepen our understanding of communities' perceptions of solar development. Of the code we identified for this theme, we ultimately separated half into "statements about administrators' perceptions" and "statements about citizens' perceptions". The two we did not separate—industrial and harmful—were only mentioned by one participant each, so separating them would have resulted in two empty codes.

Table 5.3: Prevalence of Codes for Theme 3

Perception of solar	Mentioned in ____ interviews
Opportunity (administrator)	3
Opportunity (citizen)	3
Industrial	1
Obligation/burden (administrator)	2
Obligation/burden (citizen)	1
Harmful	1

The most common code we identified was the "opportunity" code, characterized by a belief that either the local government (in the case of the administrator code) or property owners (in the case of the citizen code) might be able to benefit from solar development. This sentiment was expressed by four out of seven participants, with two of the participants indicating that both administrators and citizens viewed solar as a potential economic opportunity. Participant 1 indicated that the view of solar as an opportunity came primarily from individual property owners who wanted the opportunity to allow installations on their land. Participant 2 observed the same phenomenon, while also noting:

> **Participant 2:** "I think there's maybe a little bit more reluctance to kind of accept [solar]. Now, the state has done more to give localities more local benefit from [developments]…through greater taxing provisions or…siting agreements…So

> there's more to gain for a specific locality now than there was even two or three years ago from a financial standpoint, from a kind of community benefit standpoint."

Participant 3 noted that lawmakers in his jurisdiction were attempting to develop similar policies, to allow localities to capture a greater share of the value of solar development. Participant 7, meanwhile, noted a sense of hope about solar in his community:

> **Participant 7:** "At first, I believe the community was optimistic, because we're a former mill town. We used to have industry here, but of course, manufacturing left, so the jobs [left], so a lot of people wanted to see industry and sort of a tax base come back to town."

However, Participant 7 also noted that community members eventually became overwhelmed by the rapid development, and this dampened the community's enthusiasm for solar. Participant 2's comments suggest that there are measures state policymakers may be able to implement to create greater willingness to accept solar in local communities. However, Participant 7's remarks suggest that allowing too much solar development too quickly could inspire some degree of backlash.

The next most common sentiment was a perception of solar as an obligation or burden, which was expressed by two different participants. One described this feeling only on the part of administrators, while the other indicated that the perception was shared by administrators and citizens. Both participants indicated that the perception was driven by state renewable energy laws that threaten to overrule localities that refuse open their zoning laws to renewable energy.

> **Participant 2:** "Honestly I think [the state law] probably has been more of a detriment to kind of the political willingness and acceptance of solar. A lot of times these solar farms are being proposed in more rural…parts of the state, which don't necessarily love the idea of the state saying we need this much, so we're going to build it."

This sentiment was shared by Participant 1, as demonstrated by the quote in the "maintain local autonomy" section of Theme 2. Notably, both of these participants *also* spoke about a perception of solar as an opportunity in their communities. This demonstrates a number of critical insights. First, that local communities are not monolithic—many conflicting interests can exist simultaneously. Second, it again suggests that policymakers should take care in crafting renewable energy laws. As this section demonstrates, some policy measures may tip public opinion toward opportunity while others may incline it toward obligation.

Finally, Participants 5 and 6 spoke of solar development as harmful and industrial, respectively. Participant 5 indicated that citizens organized around the idea that solar was likely to bring more harm than benefit to their community. Participant 6 mainly discussed administrators' perceptions of solar as industrial, particularly when talking about the need to protect local agricultural character.

Table 5.4: Prevalence of Codes for Theme 4

Emotional/Value-based response	Mentioned in ___ interviews	In reference to
Nervous or anxious about the uncertainties of solar	5	Both

Cautious/suspicious about being taken advantage of	3	Both
Overwhelmed	2	Solar in general
Excitement	0	N/A
Anger	2	Solar in general
Fear	1	Both

Emotional and value-based responses also play a significant role in a local government's solar ordinances. The most prominent emotions and value-based responses that had implications for solar ordinance development stemmed from emotions of anxiety, such as attempting to address future uncertainties regarding the existence of solar projects within communities – especially potentially undesirable implications associated with uncertainty. The results from interviews showed that emotional and value-based responses associated with anxieties toward solar development were mentioned 5 times. Often, these anxieties included undesirable consequences that a solar project may have on a community or a local government, such as a local government receiving the brunt end of a solar project developed irresponsibly, or a solar project requiring decommissioning and a local government is forced to take responsibility in handling the project. Many of these anxieties had to do with financial responsibilities and potential obligations that would fall upon local governments.

Similarly, the second most prominent response associated with Theme 4 included caution or a suspicion that a community or local government may be taken advantage of by a developer of a solar project. Participant 2 expressed this sense of caution when expressing the following:

> **Participant 2:** "Localities want to know what's in it for me"…"…If you're going to build this, it's in my backyard, what do I have to gain from it."

Like developers, local governments – as well as their communities – want to reap in the benefits of a solar project.

With the rapid increase of solar projects in recent years, today's local governments are working on the front end an energy transition that is requiring local governments to think about and address how they plan to accommodate solar projects in their communities. The rapid expansion of solar projects across the country, therefore, does have implications on the emotional responses local governments have toward solar projects. Interview results indicated that some local governments are becoming overwhelmed with navigating what is in some cases, new territory for local governments to consider in their zoning ordinances and long-term planning. Participant 7, for example, captured the narrative that rapid solar expansion created an overwhelming feeling for local governments, as well as their communities.

> **Participant 7:** "At first, I believe the community was optimistic…because we're a former mill town. We used to have industry here, but of course, manufacturing left…so a lot of people wanted to see industry and sort of a tax base come back to town. So, they liked it at first, but then they realized that people were selling their land left and right...residents kind of got tired of it after a while."

While the project team's interview coding methods included assessing the interviews for statements of excitement over the opportunity for solar developments, participant comments did not reflect feelings of excitement over the idea of solar projects coming to their communities.

Instead, participants expressed emotional responses such as anger and fear over solar projects, both of which were also included as codes that the project team was seeking. Mentions of anger, such as a local government being told what to do and include in solar ordinances from outside institutions such as state governments, were mentioned 2 times. An example of this is explained by participant 2:

> **Participant 2:** "This general sense of the state [saying], 'well, we are going to do this, so you're going to have to allow it in your locality just kind of rubs people a little bit the wrong way."

Mentions of fear, such as feelings that a solar project would result in the loss of space or place to a community, were mentioned 1 times.

5.6.4 Decommissioning Policy Development Process

The development processes for policies, such as solar decommissioning, will naturally have implications for solar projects and their eventual solar decommissioning's. Therefore, the project team was intentional in gathering information regarding the process in which solar ordinances were created. This is especially important because many local governments are only now, or have recently, began considering solar projects within their planning ordinances. Therefore, local government naturally will turn external factors, such as other jurisdictions, mimicking other technologies, or rely on consultants to help guide their respective solar ordinances.

Table 5.5: Prevalence of Codes for Theme 5

Method for Ordinance Development	Mentioned in ___ interviews	In reference to
Mimicking other jurisdictions	7	Both
Mimicking other technologies/structures	1	Both
Noted lack of mimicking	4	Both
Engaged research (e.g. discussions with external experts, site visits, etc.)	2	Solar in general
Reliance on internal expertise	0	N/A
Broad ordinance and specific guidance	3	Both
Assistance from consultants	3	Solar in general
Developmental administrative burden	3	Solar in general
Other structures requiring financial assurances	5	Decommissioning

Of the methods in which jurisdictions developed their decommissioning policies, the majority turned to mimicking other jurisdictions as examples for which to base their own solar ordinances. Mentions of mimicking of other jurisdictions' decommissioning policies were prevalent in all 7 interviews conducted by the research team.

Additionally, since mimicking other jurisdiction's solar ordinances is so common within the methods in which decommissioning policies are developed, there is precedent that because jurisdictions tend to follow by example in respect to developing solar and decommissioning ordinances, that certain jurisdictions are setting the stage for many other jurisdictions. From the findings of the project team's interviews, the existence or absence of financial assurances within a decommissioning policy was often influenced by whether a jurisdiction was mimicking another jurisdiction that included such assurances.

In addition to mimicking other jurisdictions solar ordinances and decommissioning policies the finds of the project's team did show that while it was only mentioned once in our findings, jurisdictions also mimic other technologies and siting structures when developing their decommissioning policies. Participant 4, for example, mentioned that decommissioning policies inclusion of financial assurances were mimicked based on their decommissioning policies for other technologies, such as windmills. However, of the 7 interviews conducted, 4 participants explicitly mentioned that decommissioning policies for solar PV modules were not structured by methods of mimicking because jurisdictions perceived solar projects as different from other forms of developments. For example, participant 3 mentioned the following:

> **Participant 4:** "We have a bond during the operation to ensure reclamation is occurring during construction of the gravel or sand or concrete aggregate mines…but we haven't seen a big problem because the value of that land is great enough that somebody is willing to buy it afterwards…and that's not going to be the case with solar, I don't think."

Jurisdictions often turn to external factors when developing both solar ordinances and decommissioning policies, including engaging in research, and assistance from consultants. According to the results of project team's interviews, 2 participants mentioned engaging in independent research, such as consulting with academics, industry professionals, property owners, or conducting site visits to better understand the operations of solar projects. 3 participants mentioned utilizing services from outside consulting firms to help develop their solar ordinances and decommissioning policies. Pulling knowledge from external experiences, stakeholders, and consultants therefore plays another significant role in how solar and decommissioning policies are developed. Worth noting, however, none of the participants in which the project team spoke with solely relied on internal experiences when developing their solar ordinances and decommissioning policies.

Lastly, regarding a solar projects financial assurance requirement, 5 participants mentioned that the existence of this requirement was influenced by whether or not other similarly perceived structural developments also required financial assurances. For example, participant 3 mentioned that solar projects within their jurisdiction required financial assurances because they mimicked that requirement based on the fact that local metallic mines, gravel pits, and aggregate mines required such assurances, while participant 5 mimicked their requirement based on the fact telecommunication towners within their jurisdiction required such assurances.

5.6.5 Process for Reviewing Decommissioning Plans

The process in which jurisdictions review decommissioning plans for solar projects is also an important consideration in understanding how jurisdictions concern themselves solar decommissioning. According to the project team's findings, out of 7 different codes concerning the process for reviewing decommissioning plans, only three codes were identified during interviews with participants. Of the 7 interviews that were conducted, 4 participants mentioned relying on the confidence of external engineers' review processes for solar decommissioning plans, while 3 participants mentioned relying on internal review processes by non-technical staff, such as from jurisdiction planning and zoning departments. Additionally, there were 2 mentions of relying on review processes from a jurisdiction's internal engineers. Therefore, both external and internal review processes of decommissioning plans were prevalent in the project team's interviews.

In addition to the actual review process for decommissioning plans, the project team also learned that one of the reasons jurisdictions felt it was necessary to undergo a review process for decommissioning plans was because of underlying concerns that the cost of decommissioning may be underestimated by project developers. Concerns about decommissioning cost estimation was mentioned by 3 interview participants. 1 participant mentioned that reviewing decommissioning plans were done because of pre-established review processes.

Lastly, 2 interview participants expressed that the review process for decommissioning plans was a burdensome process.

Table 5.6: Prevalence of Codes for Theme 6

Process for reviewing decommissioning plans	Mentioned in interviews
Internal review by professional engineers	1
Internal review by non-technical staff	3
Trust in external professional engineers	4
Concern about underestimation	3
Review administrative burden	2
Establish review guidelines	1
No plans since ordinance passage	0

5.6.6 Effect of Decommissioning Policies

A jurisdiction's decommissioning policies may have implications for solar projects. Therefore, the project team wanted to better understand the effect that solar ordinances and decommissioning policies have – or may have – on the development of solar projects. From the project team's interviews, all 7 interview participants claimed that solar development companies complied with the requirements outlined by their jurisdiction's solar ordinances and decommissioning requirements and the jurisdictions did not receive any major pushback from solar developers. However, 2 participants did still note some degree of pushback from developers regarding decommissioning regulations, in which case a developer expressed that the jurisdiction's financial surety level was too high. One participant noted receiving pushback on other components of the jurisdiction's solar ordinance in general.

According to interview participants, while solar developers generally tended to comply to jurisdiction's solar ordinances and decommissioning policies, four participants did mention that their solar ordinances did create delays and development limitations on prospective solar projects. Worth noting, however, these delays reflected the jurisdiction's solar ordinance in general, such as regarding siting restrictions – not their decommissioning policy. An example of a delay or limitation that a solar ordinance had on a potential solar project was explained by participant 6:

> **Participant 6:** "A lot of times, maybe the best locations we have would not be something we would recommend approval for. For instance, we have a rural conservation area under our from our 2035 [master plan]. In those areas, we do not recommend solar because these areas are suppose to be a buffer between our growth areas, so we don't typically approve that. So what I tell [solar developers] that, they are often like, 'oh, but that's the best place to put it, but I know you guys won't approve it.'"

However, in one case, the existence of solar and decommissioning policies helped facilitate a pathway for the development of a solar project, as noted by participant 5:

> **Participant 5:** "Our board of supervisors kind of heard that argument and they said…we don't think [solar developers] should actually post the surety early in the project. And so there are some provisions [within our ordinance' that allow the surety to be delayed."

Also worth noting, no participants noted a complete rejection of solar proposals as a result of their solar ordinances nor decommissioning policies.

Table 5.7: Prevalence of Codes for Theme 7

Effect of Policy	Mentioned in interviews	In reference to
Limitation/reduction of solar developments	0	N/A
Company compliance (no major resistance)	7	Both
Company pushback on solar decommissioning regulations	2	Decommissioning
Company pushback on other components of solar ordinance	1	Solar in general
No applications since ordinance passage	1	Solar in general
Development of decommissioning policies for other structures	2	Both
Delays/development limitation caused by other structures	4	Solar in general
Rejection of solar proposals	0	N/A
Created a pathway for solar development	1	Solar in general

5.7 Conclusions

The interview process produced a wealth of rich insights into the methods and motivations for regulating solar installations at the local level. By examining the transcripts from multiple angles, we were able to distill a number of key insights. However, it should be noted that our sample size was too small to allow us to generalize these findings to the broader population of U.S. local governments. As such, the following insights apply only to our study population:

1. **Most decommissioning policies were proposed by elected officials or planning staff, rather than citizens.**

   Though citizens often became involved in the regulatory process eventually, in most cases, they did not express strong opinions until after regulatory ordinances had been passed and at least one solar permitting application had been received. Local stakeholders, like property owners who want to allow solar development on their lands, sometimes supported solar ordinance development, but were not the primary instigators of the regulatory process.

2. **The most common motivation for implementing decommissioning regulations is the desire to protect the local jurisdiction from the burden of these costs in the future.**

   It can be challenging to separate the motivations for *decommissioning regulations* from the motivations for solar regulations *in general.* Our interviewees often did not explicitly make distinction. However, when pressed, every respondent expressed concern about the 20-30 year lifetime of solar PV and referred to decommissioning regulations as something like an insurance policy. Furthermore, a majority of interviewees indicated that they added decommissioning requirements to their ordinances because they saw that other jurisdictions or best practice guides had done so.

3. **Solar development policies can impact local attitudes toward solar both negatively and positively.**
   We found evidence that policy can be used to build support for solar if it is used to ensure that some of the benefits of development accrue to local entities. However, we also found evidence that top-down policies that force solar upon localities can trigger resentment that may manifest as restrictive siting regulations.

4. **Emotional and value-based responses play a role in local jurisdiction's solar ordinances and decommissioning policies**
   Policies are often influenced by emotional and value-based responses, and solar ordinances and decommissioning policies are no exception. Local jurisdictions express anxieties over the future and anxieties regarding uncertainties that solar projects may bring to local governments and their communities. Additionally, participants expressed caution and degrees of skepticism over solar developments. Like solar developers, jurisdictions and their communities do not want to be taken advantage of by solar developers. Instead, like solar developers, they too want to realize the benefits from solar projects.

5. **Local jurisdictions often follow by example and turn to external actors for guidance**
   From mimicking other jurisdictions solar ordinances and decommissioning policies, to mirroring the regulatory frameworks of other structural developments and technologies, to turning to other external factors for guidance, local jurisdictions' solar ordinances and decommissioning policies are often influenced by outside stakeholders. Considering the relatively new and rapidly growing status of solar projects across the country, local jurisdictions are working hard to navigate what is in many cases unchartered territory of

planning. Additionally, because local jurisdictions turn to other jurisdictions for examples and best practices, it is important that local jurisdictions implement reasonable solar policies, considering that one jurisdiction may be setting the stage for many others.

6. **Decommissioning review processes rely on both external and internal expertise**
   Local jurisdictions put trust in external actors, such as professional engineers, as well as internal technical and non-technical experts to review decommissioning plans. Regardless, the need to conduct review processes for decommissioning plans is creating some degrees of administrative burdens on local jurisdictions. We believe that administrative burdens regarding solar projects is a notable narrative because jurisdiction staff are taking on, and will continue to take on, new responsibilities such as reviewing decommissioning plans with the rapidly growing expansion of the solar industry.

7. **Solar developers generally comply with local jurisdiction's solar policies and decommissioning requirements**
   When we began our research and interview processes, we wanted to better understand potential implications that local jurisdiction's solar ordinances may have on solar projects. Based on our interview results, all 7 participants claimed their jurisdictions did not receive major resistance from solar developers regarding jurisdiction's respective solar ordinances. However, our research findings did also indicate that there were cases in which local jurisdictions solar ordinances and decommissioning policies did receive some degrees of pushback from solar developers. Nevertheless, interview all participants claimed that their solar ordinances and decommissioning did not result in the rejection of any solar proposals to date. Additionally, one participant claimed that their jurisdiction's solar ordinance created a pathway for solar development.

8. **Outcome of solar ordinances and decommissioning are still largely to be determined**
   Considering the relatively new and rapid expansion of solar projects across the country, we believe it is still too early to tell the true outcome that local jurisdictions solar ordinances and decommissioning policies will have on local governments, the solar industry, as well as communities in which solar projects reside. In addition to the continued growth of the solar industry within communities across the country, it is also premature to claim to fully understand the implications that solar decommissioning will have on local governments, the solar industry, and communities. Regardless, because solar decommissioning will become increasingly prevalent over the coming decades, we believe it is important that local jurisdictions address such issues in a manner that is fair to all stakeholders involved in the development of a solar project, including local governments, the solar industry, and potentially impacted communities.

Chapter 6: International Policy

6.1 Overview

In addition to analyzing U.S. state and local policies covering solar PV module waste, NREL tasked our team with researching how solar PV module and battery wastes are regulated in international jurisdictions. Our team considered several approaches to picking international jurisdictions for this task.

For example, we considered looking at international jurisdictions with the highest amounts of installed solar and battery capacity (which would encompass both stationary energy storage and electric vehicles batteries). This approach would have pushed us to look at countries like China, Japan, Germany, India, and Italy for solar,[38] and China, South Korea, and Japan for storage.[39] This approach has the advantage of focusing our attention on the most mature markets for solar PV and batteries and researching whether established markets are positioned to manage solar PV and battery wastes. Similarly, we could have considered the jurisdictions that are projected to see the largest growth in installed solar capacity over the next 3-5 years. This approach has the advantage of focusing our attention on markets that will likely need comprehensive solar PV and battery waste management policies and regulations in the short to medium term and analyzing the current strengths and weaknesses of the regulatory regimes in those jurisdictions.
Across the approaches we considered, our team wanted to ensure that any sample of surveyed jurisdictions was geographically diverse. Our list of jurisdictions was finalized when our team and NREL were approached by the International Renewable Energy Agency (IRENA) with an opportunity to contribute to an updated version of their End-of-Life Management of Solar Photovoltaic Panels report, which was last updated in 2016.[40] Our international policy research focused on Germany, France, China, Japan, Australia, Saudi Arabia, Russia, and Turkey. After conducting preliminary research on each of these countries, our team settled on writing case studies for Germany (solar and storage), Japan (solar), Australia (solar), the European WEEE Directive (solar), and China (solar and storage).

6.2 Policy Database

An important component of conducting our international jurisdiction research involved creating a policy database for NREL and IRENA that could be used to track and code policies and regulations for each jurisdiction surveyed. With the help of NREL, our team recorded and coded policies governing solar PV and storage wastes according to the following criteria:

- Country covered
- Locality covered
- Technology covered (e.g., solar or storage)
- Parties covered (e.g., asset owners, government, industry organizations, etc.)
- The policy's defined pathway (e.g., does the policy target recycling, reusing, or reducing waste)
- The policy's effective date
- The policy's framework (e.g., government-led, industry-led, or public-private partnership)
- The policy type (e.g., government initiative, regulation, voluntary system)
- The policy subtype (e.g., waste labeling, waste management funding, extended producer responsibilities, etc.)
- How the policy is funded

A copy of the database, including coding criteria, can be found in Appendix D.

6.3 Case Study: Australia - Solar

6.3.1 Federal, State, and Local Policies

Australia has no national regulation or statute specific to the reuse, recycling, or disposal of PV modules. The Australian solid waste and recycling statutes—the 2018 National Waste Policy and the Recycling and Waste Reduction Act 2020—apply to PV modules like any other wastes. However, both the Australian Government and solar industry stakeholders have shown an interest in creating a regulatory framework.

Australian state governments are also taking action on PV waste, and some have already banned solar modules and inverters from being disposed of in landfills. The state of Victoria passed the Sustainability Victoria Act of 2005 to establish Sustainability Victoria, a statutory authority and board appointed by Australia's Minister for Energy, Energy and Climate Change. The body has already begun investigating solutions to manage PV waste, including modules and associated inverter equipment. In addition to banning solar modules and inverters from landfills, Sustainability Victoria has helped coordinate assessments of potential state, territory, and national PV stewardship programs. In New South Wales, the Environment Protection Authority established the Circular Solar trials grants program which created a $10 million fund to reduce landfilling of PV waste, improve the circularity of PV wastes, create new waste collection models, and develop recycling infrastructure.[41] In 2021, the Legislative Assembly for the Australian Capital Territory (ACT) issued Notice Paper No. 18 calling attention to the growing amount of waste solar PV modules, inverters, and batteries that are not being recycled. The Notice Paper emphasized the need to develop recycling schemes for renewable energy technologies in partnership with communities and industry stakeholders and pledged the support of the ACT government to helping develop recycling programs and coordinating with the federal government on their national product stewardship scheme.[42]

In 2011, the Australian Government passed the Product Stewardship Act to manage the impacts of different products and materials, promote product stewardship programs, and increase recycling and recovery of valuable materials.[43] The Act, which is maintained by the Department of Agriculture, Water, and the Environment, was originally drafted to manage the impact of e-waste on landfills, such as computers and televisions. In June 2016, photovoltaic systems (which include photovoltaic cells and inverter equipment and system accessories) were added to the list of products being considered for regulation.[44] In April 2018, the Australian government agreed to commence work on developing a new product stewardship scheme focused on managing end-of-life photovoltaic systems, but as of 2022 no progress has been made.[45]

6.3.2 Non-Regulatory and Voluntary Programs

In December 2020, the Australian government invited industry stakeholders to help develop a product stewardship scheme for end-of-life PV systems. The initiative offered grant funding up to $2 million total to one to two partners who would help establish a national end-of-life PV waste management scheme in tandem with the government by 2023. The program's scope included increasing resource recovery and recycling of wastes, promoting research and development of managing end-of-life PV systems, and creating a self-funded management scheme (Australian Government Department of Agriculture, Water and the Environment, 2021).[46]

However, following the closure of the partnership proposal period in January 2021, the Australian Government chose not to pursue a partnership with any applicants.[47]
In June 2021, the Minister for Environment announced a June 2022 deadline for the solar industry to develop a product stewardship scheme, and until June 2023 to implement the scheme. At the time of the announcement the Minister noted that government efforts to establish a product stewardship program for photovoltaic systems have stalled for more than six years, and help from industry is badly needed.[48]

6.4 Case Study: China – Solar

6.4.1 Federal, State, and Local Policies

China has no national regulation or statute specific to the reuse, recycling, or disposal of PV modules. The Chinese solid waste statute- the Solid Waste Environmental Pollution Control Law- applies to PV modules like any other wastes (e.g., solid, industrial, household, building, agricultural, and hazardous waste). China does have laws and regulations that govern the disposal of waste electrical and electronic equipment (WEEE), promote circular economy systems, and establish Extended Producer Responsibility (EPR) systems. While PV modules are omitted from those laws, they may aid the development of PV module waste-specific laws and regulations.[49]

In 2009 China passed the Circular Economy Promotion Law, which focused on the development of a circular economy, improving resource utilization efficiency, protecting the environment, and promoting sustainable development. The law acknowledges the importance of developing policies and technologies that promote upcycling products, waste management, and materials recycling, and offers financing, tax incentives, and process implementation and management support from the government for initiatives that boost circularity. The law simultaneously instructed enterprises to help recover, recycle, and reuse the products they produce, and acknowledged the responsibility consumers have for delivering covered products to enterprises for proper reuse or disposal. The 2009 law did not identify specific products that would fall under the circular program. Instead, the law stated that a catalogue of products subject to regulation would be regularly published by the administrative department of circular economy development under the State Council. Although not explicitly named in the legislation, the 2009 law set the framework for a formal Extended Producer Responsibility (EPR) in China.[50]
In 2020, China amended its Solid Waste Environmental Pollution Control Law to establish an official EPR system for electrical and electronic products, lead storage batteries, and automotive power batteries. The EPR system requires producers of covered products to fund the collection and recycling of covered products and raise public awareness of available recycling systems.[51]
The amendment also requires waste generators to establish an industrial solid waste management ledger to record waste types, quantities, storage, utilization, and disposal methods to aid waste traceability.[52]

6.4.2 Non-Regulatory and Voluntary Programs

Voluntary recycling programs have found some traction with Chinese solar manufacturers. Jinko Solar, the world's largest solar PV module manufacturer,[53] has been a member of PV CYCLE since 2011,[54] an EU-based non-profit that offers global waste management and compliance solutions for electrical and electronic equipment including PV modules. JA Solar, the world's second largest manufacturer of solar modules, is also a part of the PV Cycle organization.[55] LONGi, another world-leading PV module manufacturer, is actively tracking retirement and recycling rates of their modules, and plans to establish a recycling and materials management department in each of its factories to research module waste and recycling.[56] Trina Solar, who was the fourth largest manufacturer of solar modules in 2020 based on 2019 sales,[57] achieved an 80% scrapped recycling rate and a 75% reuse rate in August 2018.[58]

6.4.3 Supporting Policies

Although China has no direct policies on PV module reuse and recycling, the government has signaled support for technology and policy R&D for managing PV module waste. For example, the Chinese Environmental Science Research Institute received funding from the National Science Foundation of China to perform an environmental management study on the effects of recycled solar equipment on the environment and potential options for establishing PV module recycling systems.[59]

6.5 Case Study: China – Storage

6.5.1 Federal, State, and Local Policies

China has passed several federal regulations specific to the management of end-of-life lead-acid batteries and lithium-ion electric vehicle batteries (also referred to as "lithium-ion traction batteries" in some pieces of legislation).

In 1995, China passed the Law of the People's Republic of China on the Prevention and Control of Solid Waste Pollution, which mandated that battery wastes be recycled separately from other waste types. In 2003, the State Environmental Protection Agency of China issued the Policy on Pollution Prevention Techniques from Waste Batteries which made battery manufacturers responsible for collecting and labeling battery wastes.[60] A more robust extended producer responsibility (EPR) system was established for lead-acid batteries in 2016 with the passing of the Implementation Plan for the Extended Producer Responsibility (EPR) System. The EPR system requires lead-acid battery manufacturers to consider and manage the environmental impacts of battery waste throughout a battery's lifecycle, as opposed to only the manufacturing phase.[61] In 2018, China passed the Interim Measures for the Management of Recycling and Utilization of New Energy Power Vehicle Batteries, making automakers responsible for recycling the batteries in their vehicles. The Interim Measures also instruct battery manufacturers to help automakers achieve best practices around storing, dismantling (via standardized product designs), and tracking relevant information around battery reuse and recycling, and encourages battery production enterprises to reuse end of life batteries whenever possible.[62] In April 2020, China's Solid Waste Law was amended to establish EPR systems for additional battery types, including lead storage batteries and automotive power batteries.[63]

In 2021, China's Ministry of Ecology and Environment issued the Technical Specifications of Pollution Control for Treatment of Waste Power Lithium-Ion Battery. The specifications set rules for controlling pollution during the treatment process of waste lithium-ion traction batteries, with covered treatment stages including transportation of wastes to factories, and the dismantling, heating, shredding, and sorting of wastes. In addition, the specifications regulate where battery recycling factories can be sited and how they are operated. Finally, the specifications also act as technical standards that can be applied to managing other kinds of lithium-ion battery (LIB) waste, such as stationary energy storage batteries.[64]

6.5.2 Supporting Policies

In addition to policies which mandate recycling and recycling responsibility, China has passed several policies aimed at managing how the battery recycling industry operates and scales. In 2018, China's Ministry of Industry and Information Technology (MIIT) passed the Interim Provisions on the Management of Traceability of Recycling and Utilization of New Energy Vehicles Power Batteries to establish a management platform capable of tracking information related to producing, selling, using, scrapping, recycling, and re-using end-of-life vehicle batteries.[65] Also in 2018, the MIIT launched the Pilot Work on Recycling and Utilization of Power Batteries for Electric Vehicles initiative with the goal of launching electric vehicle battery recycling pilot projects in 17 cities and regions and establishing a regional recycling system for electric vehicle batteries. In 2021, the MIIT issued the Management Measures for the Gradual Utilization of New Energy Vehicle Power Batteries, which sought to increase collaboration between national and regional governmental departments and industry stakeholders to improve the traceability of second life applications of energy vehicle batteries. Second life applications typically include reuse of energy vehicle batteries for power backup and energy storage.[66]

6.6 Case Study: European WEEE Directive – Solar

In most countries and governmental jurisdictions, PV waste is considered general waste, while throughout Europe it is uniquely considered electronic waste.[67] The European Union (EU) and its 27 Member States (as well as the United Kingdom) are currently the only countries that have adopted PV-specific national regulations that mandate the reuse, recycling, and recovery of decommissioned PV modules. The EU's Waste Electrical and Electronic Equipment (WEEE) Directive – initially promulgated in 2002 and expanded in 2012 to include solar modules – aims to facilitate the sustainable production and consumption of electronic waste, repurpose valuable secondary raw materials, and protect the environment through **extended-producer-responsibilities** (see Figure 6.1).[68, 69]

With the notion of extended-producer-responsibilities at its core, the WEEE Directive requires producers of PV modules to ensure the take-back and recycling of their products, including related administration, reporting, costs of collection, treatment, and monitoring for all PV modules sold on the European market, for which they are liable.[70,71] While all EU Member States have incorporated the WEEE Directive into national law, implementation varies on how each country has implemented their respective WEEE Directives.[72]

"The purpose of this Directive is to contribute to sustainable production and consumption by, as a first priority, the prevention of WEEE and, in addition, by the re-use, recycling and other forms of recovery of such wastes so as to reduce the disposal of waste and to contribute to the efficient use of resources and the retrieval of valuable secondary raw materials. It also seeks to improve the environmental performance of all operators involved in the life cycle of EEE, e.g. producers, distributors and consumers and, in particular, those operators directly involved in the collection and treatment of WEEE. In particular, different national applications of the 'producer responsibility' principle may lead to substantial disparities in the financial burden on economic operators. Having different national policies on the management of WEEE hampers the effectiveness of recycling policies. For that reason, the essential criteria should be laid down at the level of the Union and minimum standards for the treatment of WEEE should be developed.

Figure 6.1: Description of the purpose for the WEEE Directive, Directive 2012/19/EU[73]

6.6.1 WEEE Directive Background and National Responsibilities

The original WEEE Directive (Directive 2002/96/EC), came into force in 2003 and mandated the treatment, recovery, and recycling of 100 electric and electronic equipment (EEE) products into 10 categories (see Figure 6.2).[74] According to Article 3 Section 1 of the WEEE Directive, electrical and electronic equipment (EEE)[1] is defined as "equipment which is dependent on electric currents or electromagnetic fields in order to work properly and equipment for the generation, transfer and measurement of such currents and fields and designed for use with a voltage rating not exceeding 1,000 volts for alternating current and 1,500 volts for direct current."[75]

Category 1: Large household appliances (i.e., microwaves, refrigerators, washing machines, etc.)

Category 2: Small household appliances (i.e., toasters, fryers, irons, etc.)

Category 3: IT and telecommunications equipment (i.e., mainframes, printers, telephones, etc.)

Category 4: Consumer equipment (i.e., radio sets, video cameras, television sets, etc.)

Category 5: Lighting equipment (i.e., various lamps, various lightbulbs)

Category 6: Electrical & electronic tools (except large-scale stationary industrial tools) (i.e., drills, sewing machines, gardening tools, etc.)

Category 7: Toys, leisure, and sport equipment (i.e., video consoles, video games, sports equipment with electronic components, etc.)

Category 8: Medical devices (except implanted and infected products) (i.e., radiotherapy equipment, laboratory equipment, analyzers, etc.)

Category 9: Monitoring and control instruments (i.e., smoke detectors, thermostats, heating regulators, etc.)

Figure 6.2: Categories of EEE covered by WEEE[76]

Under the WEEE Directive, EU Member States are required to meet EEE collection and recycling minimums.[77] As explained in IRENA's 2016 analysis of the WEEE Directive,

"Collection targets rise from 45% (by mass) of equipment 'put on the market' in 2016 to 65% of equipment 'put on the market' or 85% of waste generated as from 2018 [and beyond]. Recovery targets rise from 75% recovery/65% recycling to 85% recovery/80% recycling in the same time frame. Recovery is to be understood as the physical operation leading to the reclamation of a specific material stream or fraction from the general stream. Recycling, on the other hand, should be understood in the context of preparing that reclaimed stream for treatment and reuse."[78]
According to the WEEE Directive, Member States shall compile information on EEE collection rates on an annual basis and shall report collection to the European Parliament and Council by measuring the average collected and recycled weight of EEE categories (refer to box 2).[79]
Annual average collected EEE is measured by comparing the weight of EEE placed on a national market in the three proceeding years of that annual collection.[80] WEEE collection targets for EU Member States and quotas are not measured per individual EEE item, but rather as an aggregate of EEE categories (refer to Figure 6.2).
The guidelines for WEEE implementation are subject to the order of the European Commission's Implementing Decision, which exists to "deal with very specific issues and often address highly technical details of [European Parliament] legislation."[81] The Implementing Decisions of the European Commission supersedes a country's national legislation in the event of regulatory contradictions.[82] In the context of WEEE, the Commission's Implementing Decision is responsible for "laying down rules for the calculation, verification and reporting of data and establishing data formats for [the WEEE Directive]."[83]

6.6.2 Solar PVs in the WEEE Directive

Since its inception, the WEEE Directive has undergone several revisions to more adequately address the challenges associated with a quickly increasing and diverse waste stream.[84] In 2012, the WEEE Directive was revised to qualify solar PVs as EEE under the WEEE Directive.[85] This revision, which came into force February 2014, required EU Member States to include PVs in their annual EEE collection and recycling reports.[86]

The revised WEEE Directive classified solar PVs as both Category 1 (Large household appliances) and Category 2 (Small household appliances) EEE waste and subscribed solar PV waste codes for the purposes of proper waste management, classification, and treatment practices (see Table 6.1).[87]

Table 6.1 Examples of waste codes relevant to solar PV modules from the EU List of Wastes.[88]

Type	Waste code	Remark
All types	160214	Industrial waste from electrical and electronic equipment
	160213*	Discarded equipment containing hazardous components
	200136	Municipal waste, used electrical and electronic equipment
	200135*	Discarded electrical and electronic equipment containing hazardous components
In special cases also: *e.g.* amorphous-silicon (a-Si) panels	170202	Construction and demolition waste – glass

In December 2019 the European Commission revised its framework for WEEE implementation in order to provide more sufficient rules for EEE calculation, verification and reporting data.[xxiii]
Unlike former Implementing Decisions on WEEE, the revised 2019 version (Implementing

Decision 2019/2193) provided more specific guidance on quantifying WEEE targets as they pertain to solar PVs.[89] Specifically, the European Commission's 2019 revision to WEEE's Implementing Decision provides solar PVs their own sub-category under 'Large' EEE waste, known as category '4b: photovoltaic modules'.[90]

6.6.3 PV Solar Producer Responsibilities Under WEEE

While EU Member States are responsible for reporting to the EU Parliament on their EEE collection targets, as well as implementing and enforcing their national WEEE Directives, EEE Producers bear the responsibility for ensuring their put on market EEE is recovered, reused, or recycled.[91] With the principal of extended-producer-responsibilities at its core, the WEEE Directive outlines that, "Member States should encourage producers to take full responsibility for the WEEE collection, in particular by financing the collection of WEEE throughout the entire waste chain, including from private households..."[92] According to WEEE legislation, enforcing extended-producer-responsibilities avoids "sub-optimal treatment and illegal exports, to create a level playing field by harmonizing producer financing across the Union and to shift payment for the collection of this waste from general tax payers to the consumers of EEE, in line with the 'polluter pays' principle."[93]
Under the WEEE Directive, the definition of 'Producers' is a rather general term and applies beyond just the original manufacturers of solar PVs. The definition of Producers also includes solar PV distributors, importers, sellers and re-sellers.[94] Solar PV Producers are obligated to register in a respective country's national WEEE registration or are to appoint an authorized representative for each country in which they operate.[95]

Under the WEEE Directive, solar PV Producer responsibilities fall into three main categories:

1. **Solar PV Producer financial responsibilities:**
- Organizing and financing the take-back and waste management of solar PV modules[96]
- Ensuring a financial guarantee for the disposal operations when solar PV modules are considered household electronic waste [97]
- Financing public collection points and first-level treatment of solar PV modules (first-level treatment includes the removal of all liquids and gases, system dismantling, and, the segregation of hazardous and non-hazardous wastes)[98,99]
- Becoming a member of a collective compliance scheme or develop an individual scheme[100]

2. **Solar PV Producer reporting responsibilities:**
- Reporting monthly or annually to the respective national authority's WEEE register on modules sold, collected, and forwarded for treatment, and present results of waste treatment of products[101, 102]
- Voluntarily showing solar PV purchasers the costs of collecting, treating, and disposing of PV waste in an "environmentally sound way".[103]

3. **Solar PV Producer information responsibilities:**
- Displaying proper recycling labeling on solar PV modules with the official symbol indicating the collection of EEE (see Figure 6.3)[104]
- Informing treatment facilities of the solar PV product's composition, including potential hazardous materials[105]

- Informing end customers on how to properly dispose of solar PV modules and informing end customers that the disposal process is free.[106, 107]

Figure 6.3: Symbol for the making of EEE. The symbol indicating separate collection for EEE consists of the crossed-out wheeled bin. The symbol must be printed visibly, legibly, and indelibly on all EEE, including solar PV modules.[108]

In the event of solar PV Producer non-compliance with solar PV waste regulations, Article 22 of the WEEE Directive states that EU Member States, "shall lay down the rules on penalties applicable to infringements of the national provisions adopted pursuant to this Directive and shall take all measures necessary to ensure that they are implemented. The penalties provided for must be effective, proportionate and dissuasive."[109] WEEE Directive legislation also outlines that, "Member States should ensure that inspection and monitoring infrastructure enables the proper implementation of this Directive…"[110] Consequences for non-compliance typically include fines and possible jail sentences.[111]

6.6.4 WEEE Directive Financing Responsibilities and Modeling Schemes for Solar PV

Effective financing mechanisms are important features for successful EOL waste management. The WEEE Directive states that, "In order to give maximum effect to the concept of producer responsibility, each producer should be responsible for financing the management of the waste from his own products. The producer should be able to choose to fulfil this obligation either individually or by joining a collective scheme. Each producer should, when placing a product on the market, provide a financial guarantee to prevent costs for the management of WEEE from orphan products from falling on society or the remaining producers. The responsibility for the financing of the management of historical waste should be shared by all existing producers through collective financing schemes to which all producers that exist on the market when the costs occur contribute proportionately."[112]

The WEEE Directive provides frameworks for two financing approaches depending on the end-use of products, being either private households, or business-to-consumer (B2C transactions) or non-private households, or business-to-business (B2B transactions). Under B2C transactions, producers are required to collect and recycle EEE waste at the end of its life. For B2C transactions, the producer cannot enter into a contractual agreement with a customer on financing, though the producer must still fulfill mandatory collection and recycling requirements established by WEEE and the respective country. This model has proven to be more enforceable and efficient than forcing household customers to recycle EEE waste at the end of the product's life.[113] This framework for EEE collection and recycling, however, has not proven to be as efficient or cost-effective when it comes to dealing with high-volumes of EEE, often such as in the case of solar PVs.[114]

Therefore, the collecting and financing for high-volume waste management, such as for solar PV modules, typically falls under B2B transactions. Through B2B transactions, both customers and producers may collect and recycle EEE at the end of a product's life. For example, if utility scale solar PVs are needing disposal, often the project owner may be better fit to fulfill the recycling obligations under the WEEE Directive than the solar PV Producer. Under B2B transactions, contractual agreements between producers and customers – as well as third-party waste collectors – for financing EOL of products such as solar PVs are permitted, which may often be more cost effective.[115]

6.6.5 Discussion: Solar PV Success in WEEE

Starting in 2018, WEEE Directive collection targets have required 65% (by mass) of all equipment out on the market or 85% of waste generated be collected, with 85% of waste recovered and 80% prepared for reuse and recycling.[116] However, due to the long lifespans of solar PV modules (which according to a WEEE calculation tool estimates and average of 22 ½ years) and relatively recent large-scale market penetration, are not yet arising to significant quantities of waste, making current EEE collection and recycling targets for solar PV modules are currently un-achievable.[117] Available data on solar PV modules that are placed on the European market and collected are also scarce.

According to a publication from IRENA on EOL management for solar PV modules through the WEEE Directive, there was "no statistical data on solar PV collection and recycling" at the time of the publication's release in June 2016.[118] Since then, "available data on solar PV modules placed on the market and collected remain scarce," and "statistics show that Member States do not even remotely meet the (solar PV) collection targets," according to a June 2021 paper published by The WEEE Form (see Table 6.4).[119]

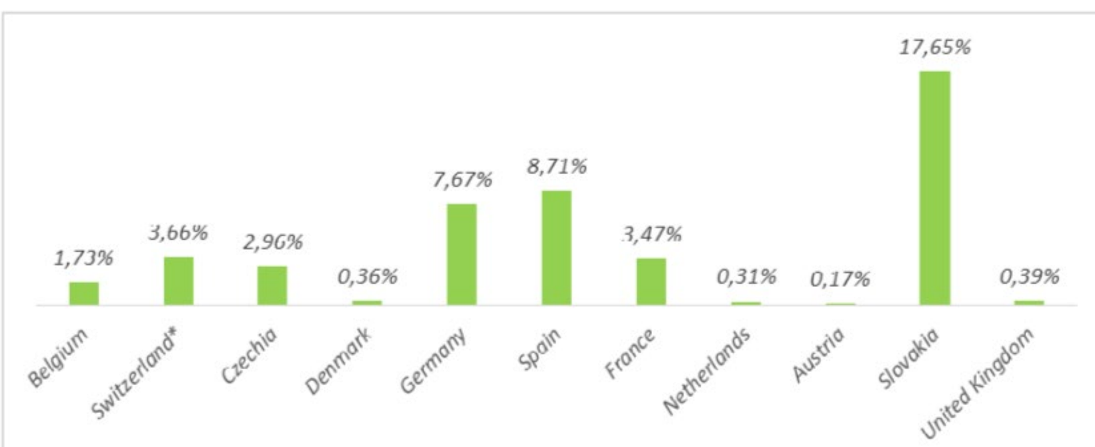


Figure 6.4: Percentage of the collection target achieved for PV modules using 2016-2018 and compared to 2018 collection.[120]

Considering the unique situation of solar PVs waste as they pertain to the quotas of the WEEE Directive, the European Commission is reportedly considering methodologies to establish individual collection and recycling targets for solar PV modules under the WEEE Directive, which may include the consideration of 'high-value-recycling' or other alternative collection targets for solar PV modules.[121, 122]

While the success of solar PV collection and recycling as a component of the WEEE Directive remains unclear, EU Member States remain the only countries that have adopted solar PV-specific national regulations that mandate the reuse, recycling, and recovery of decommissioned solar PV modules. Therefore, because of having a national mandate for solar PV recycling, several thousand tons of solar PV waste across Europe are being diverted from landfills and instead being collected for responsible EOL management, according to solar PV Cycle, a nonprofit dedicated to solar PV takeback and recycling.[123] Additionally, because solar PV manufacturers, distributors, importers, sellers, and resellers are legally responsible for the EOL management of their modules sold on the European market – even if the producer's manufacturing sites are located beyond the legal and geographic boundaries of EU Member States – the WEEE Directive is setting framework that can help promote responsible EOL practices and circulatory within the global solar PV market.[124] However, because the WEEE Directive allows EU Member States to define more stringent terms for solar PV waste, European countries have implemented slightly varying definitions of extended-producer-responsibilities, which may pose challenging to solar PV Producers operating in Europe.[125]

6.7 Case Study: Germany's Implementation of the European WEEE Directive

6.7.1 Country Background

Germany has a national total installed solar capacity of 54.6 GW, with 4.88 GW of those installations occurring in 2020.[126, 127] Germany is the leading country in Europe and fourth in the world for total solar deployment.[128] Considering the European Union's total 2020 solar capacity is 137.2 GW and Europe's second largest solar contributor is Italy at 21.3 GW, Germany holds the lion's share of Europe's total solar capacity and is expected to continue to holding Europe's largest share of solar additions in the coming years (see Figure 6.5).[129]

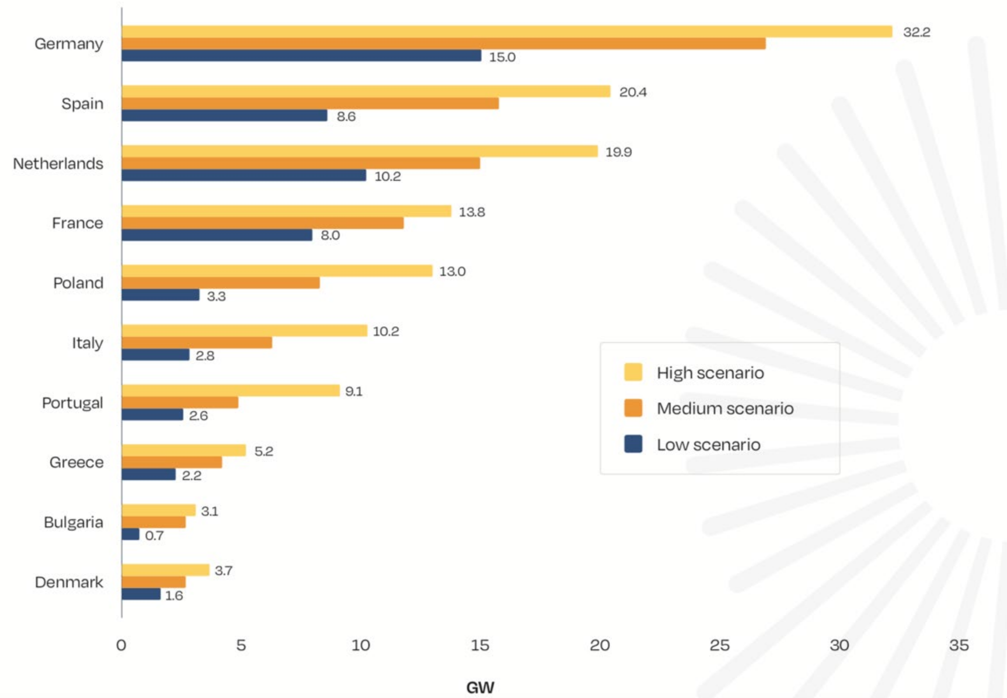


Figure 6.5: EU Top 10 Solar solar PV Market Additions 2021-2024 (SolarPower Europe 2020)[130]

Germany has a mature solar market and history of progressive clean energy policies. The German solar PV market started growing in the 1990s when the country developed national feasibility assessments on renewable energy grid-connectivity, especially in respect to decentralized rooftop solar PV installation.[131] Initiatives such as these facilitated the development of national programs such as the 1,000 Rooftop Programme and later the 10,000 Rooftop Programme, which were both policy initiatives introduced in the 1990s to promote rooftop solar.[132] Early initiatives such as these eventually facilitated Germany's Renewable Energy Sources Act (EEG) which established a first of its kind government-set feed-in tariff for 20 years. The German EEG came into force April 1, 2000 and further catalyzed German's solar PV installations.[133]

When the EEG came into force in 2000, Germany had less than 1 GW of solar but by 2008, Germany had 5.2 GW of solar capacity installed, making them the world's leader in solar deployment at the time.[134, 135] By 2015 solar PV solar generated almost 40 GW of energy and contributed 6% of Germany's total net electricity consumption.[136] For two consecutive decades Germany was the world's largest solar PV market, until 2015 when that title was eventually overtaken by China.[137]

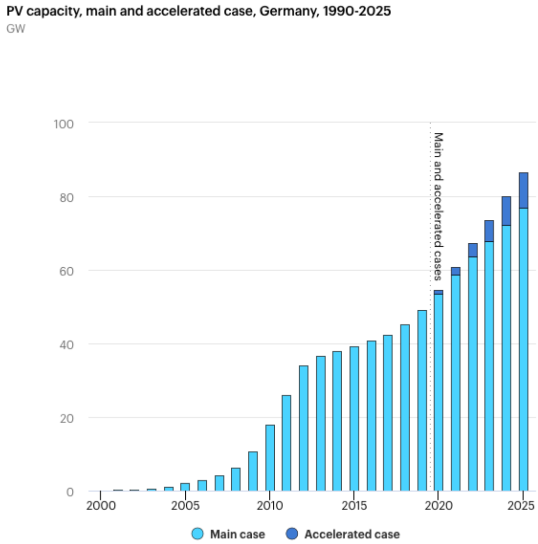


Figure 6.6: PV capacity, Germany, 1990-2025[138]

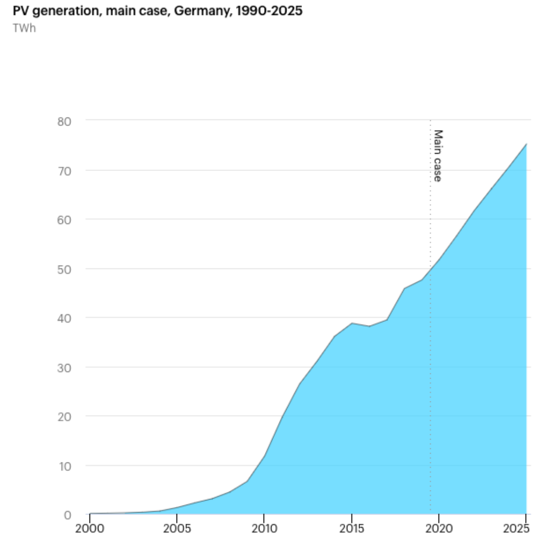


Figure 6.7: PV Generation, Germany, 1990-2025[139]

In 2021, the German government approved an EEG target for the installation of 100 GW of solar by 2030 and a recent proposal from the federal Climate Action Programme has proposed to increase this solar capacity to 150 GW of solar by 2030.[140]

Germany has a robust history when it comes to clean energy policy and solar PV deployment. Germany has seen constant growth for more than two decades, has been at the forefront of mass solar PV deployment, and has boasted the greatest nominal solar capacity in the world for more than 20 years.[141]

Considering Germany's mature solar market, solar history, and large outlook of solar PV installations, Germany will be one of the first and largest global markets to have to deal with managing large quantities of solar PV waste efficiently and sustainably, while ensuring that valuable resources are recovered.[142] While a powerhouse for solar PVs, Germany did not begin to address the EOL waste management and recycling for solar PVs on the national level until the European Parliament's passing of the WEEE Directive.

6.7.2 German WEEE Implementation

The revised EU WEEE Directive (2012/19/EU), which included the qualification of solar PV modules as EEE came into force February 14, 2014, though Germany did not implement the updated Directive until October 2015.[143] Because of this significant delay in transposing the revised WEEE Directive into national law, the European Commission referred Germany to the EU Court of Justice and asked the court to impose a financial penalty of €210,078 per day until Germany revised its domestic WEEE policy.[144]

The revised WEEE Directive was transposed by revising Germany's Electrical and Electronic Equipment Act (Elektroaltgerätegesetz or ElektroG) which served as the country's implementation of its original WEEE Directive. In accordance with the revised 2014 WEEE Directive, Germany required all EEE Producers to collect and recycle at least 85% of solar PVs.[145] Under the ElektroG, German EEE is regulated through the National Register for Waste Electrical Equipment (Stiftung Elektro-Altgeräte Register or Stiftung EAR) which administers the registration of EEE waste producers and coordinates the provision of containers and pick-ups of public waste across Germany. Other responsibilities of the Stiftung EAR include:

- Providing all EEE producers with a registration number (in which Producers must print on all their products and invoices)
- Collecting data on EEE amounts placed on the market
- Reporting the annual flow of materials to German's Federal Environment Agency
- Ensuring compliance with ElektroG mandates and reporting non-compliance issues to the Federal Environment Agency.[146]

Stiftung EAR is not responsible for operational tasks required by the WEEE Directive, such as collecting, sorting, dismantling, and recycling or disposing of EEE. Per the WEEE Directive's emphasis on extended-producer-responsibilities, those responsibilities remain imposed on EEE Producers.[147]

In implementing the ElektroG, Germany has approved specific provisions for solar PV module collection, recovery, and recycling which set financial guarantee calculations each solar PV producer must provide for each PV module sold (see Table 6.2). A simplified calculation formula for B2C financing schemes is as follows:

Cost responsibility =
basic amount for registration
(solar PV panel tonnage put on the market) x presumed return rate (%)
x presumed disposal costs (EUR/t).[148]

Table 6.2: Stiftung EAR factors for calculating guaranteed sum for solar PV modules[149]

Category	Type of equipment	Presumed return rate	Presumed medium-life expectancy	Average maximum-life expectancy	Presumed disposal costs/ group
Consumer equipment and PV panels	PV panels for use in private households	30%	20 years	40 years	EUR 200/t

Based on Stiftung EAR (2015)

Under B2C (business-to-consumer) transactions, the EletroG mandates that Producers selling EEE to private households fulfill all EOL obligations, to which the German government has established two compliance schemes for the operation and financing of EEE. Figure 6.8 illustrates a collective producer liability scheme that follows a joint-and-several liability format.

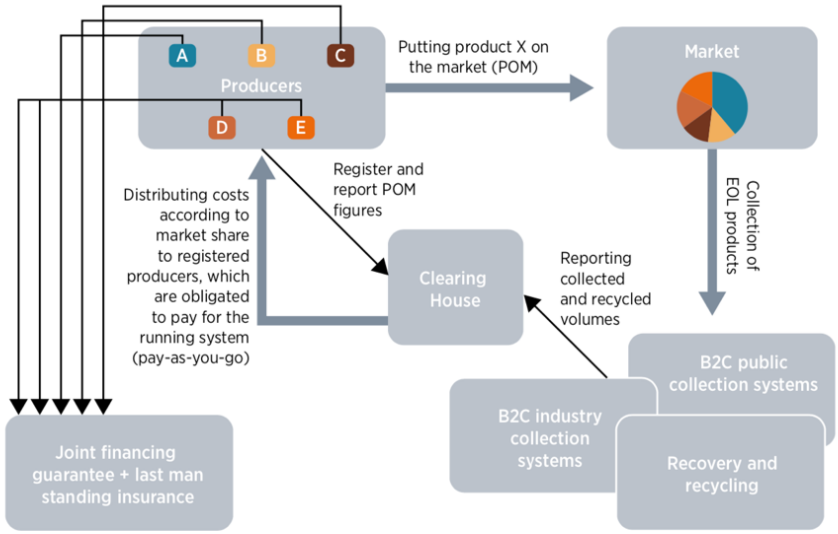


Figure 6.8: Collective producer responsibility system for EOL management of B2C solar PVs[150]

The collective producer compliance system establishes two levels of operation and financing. Level 1 includes the collection of costs related to system operations and recycling of EEE products, and Level 2 ensures that sufficient financing is available for the future collection and recycling of EEE products put on the European market.[151]

When it comes to B2B (business-to-business) transactions for solar PV modules, contractual agreements between Producers and businesses are allowed and Germany permits contractual partners to agree on EOL responsibilities that meet the standards of the ElektroG, either by contracting the Producer to collect and recycle solar PVs or seek competitive bids from outside EEE disposal contractors.[152] Large scale solar PV collections will likely fall under this financing model, especially because the B2B model tends to be more cost-effective at high quantities of collection. The B2B model better facilitates the possibility for more cash flow positive EOL practices for waste such as solar PVs.[153]

6.7.3 German Solar PV Waste and Collection

According to a June 2021 paper published by The WEEE Forum – a Brussels-based non-profit association representing 43 non-profit EEE 'producer responsibility organizations' (PROs) – "available data on solar PV modules that are placed on the European market and collected are also scarce" and "statistics show that Member States do not even remotely meet the (solar PV) collection targets" (refer to Table 1).[154] Additionally, according to a publication from IRENA on EOL management for solar PV modules through the WEEE Directive, there was "no statistical data on solar PV collection and recycling" at the time of the publication's release in June 2016.[155] In that publication, however, IRENA projected that between 2030 and 2050, Germany will see between 400,000 tons and 4.4 million tons of cumulative solar PV waste (see Figure 6.9).[156]

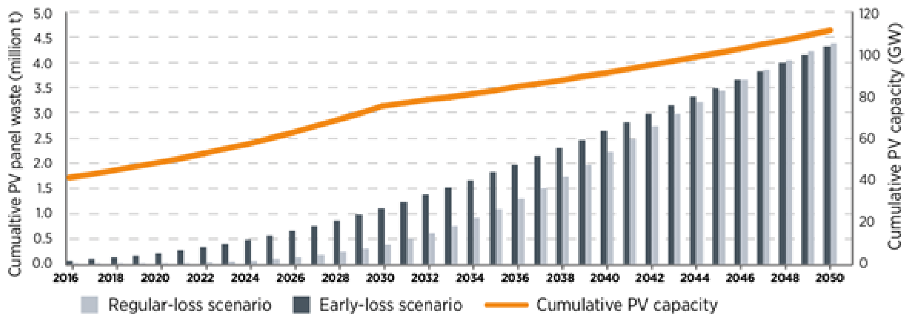


Figure 6.9: Cumulative end-of-life solar PV module waste volumes for Germany to 2050, based on 2016 data from IRENA.[157]

Due to Germany's implementation of its EEG in 2000, a significant amount of solar PV installations were installed between 2010 and 2012, meaning that Germany should expect to see PV decommissioning intensify in the second half of the 2030s.[158]

While national data on EU Member States' collection and recycling of solar PVs is scarce, estimates from the German Environment Agency (Umweltbundesamt, or 'UBA') predict that in 2018, just under 8,000 tons of solar PV waste were collected and processed in Germany, and that that figure could grow to 22,000 tons per year by 2025 and waste volume could total almost three million tonnes by 2035 and nearly 10 million tonnes by 2050.[159] More recently, a February 2021 article from Clean Energy Wire reported that, "According to Germany's largest waste management company Remondis, nearly all modules put into the waste collection system as of 2020 had been disposed of due to damage or malfunctioning and not due to reaching the end of their service life. In 2018, just under 8,000 tonnes of solar PV waste were collected and processed in Germany."[160]

While it remains statistically unclear the extent to which Germany's ElektroG program is collecting, recycling, and processing solar PV modules, the country's program appears to be gaining traction since the earliest available reports (such as IRENA's 2016 report was released) were published. Additionally, because of Germany's abundant solar market, IRENA predicts that Germany will be the first solar market that reaches profitability in recycling procedures, as rising amounts of solar installation and waste will allow economies of scale to set in and boost the country's learning curve.[161]

Overall, when considering Germany's mature solar market, solar history, and future outlook for large-scale solar PV installations, Germany will be one of the first and largest global markets to have to deal with managing large quantities of solar PV waste efficiently and sustainably, while ensuring that valuable resources are recovered.[162]

6.8 Case Study: Germany – Solar

6.8.1 Policy Drivers

Germany's solar PV market started growing in the 1990s when Germany developed national feasibility assessments on renewable energy grid-connectivity, which expanded distributed solar generation across Germany.[163, 164] In April 2001, Germany's Renewable Energy Sources Act (EEG) came into force and further catalyzed solar PV installations. Before EEG, Germany had less than 1 GW of installed solar capacity, but by 2008 Germany had achieved 5.2 GW of installed solar capacity, and by 2015, solar energy generated almost 40 GW of Germany's electricity.[165, 166, 167]As a result of early solar expansion programs, Germany is expected to see solar PV decommissioning intensify in the second half of the 2030s.[168]

Germany's solar PV market is also growing because of climate policies. In June 2021, Germany updated its Climate Action Programme to cut national carbon emissions at least 65% by 2030, and at least 88% by 2040, with the goal of achieving carbon neutrality by 2045.[169] To achieve carbon neutrality, Germany's 2021 EEG approved a target for the installation of 100 GWs of solar capacity by 2030.[170] In a draft of Germany's 2022 Climate Action Programme, Germany has set a target for 150 GW of solar by 2030.[171] The 2022 Climate Programme is expected to be approved by the German Cabinet in the first 100 days of Germany's new federal administration and take effect before the end of summer 2022.[172]

6.8.2 Current Specific to Reuse and End-of-Life Management Policy

Germany manages solar PV waste under a national EPR system promulgated under the WEEE Directive. Germany implemented the Recast WEEE Directive in October 2015 by revising its 2008 Electrical and Electronic Equipment Act (Elektroaltgerätegesetz or ElektroG) which served as the regulatory framework for Germany's original WEEE Directive.[173] Under ElektroG, German EEE is regulated through the National Register for Waste Electrical Equipment (Stiftung Elektro-Altgeräte Register or Stiftung EAR). Stiftung EAR administers the registration of EEE waste producers and coordinates the provision of containers and pick-ups of public waste across Germany and allocates pickup obligations to producers based on an algorithmic calculation method, coordinated by StiftungEAR.[174] Other responsibilities of the Stiftung EAR include:

- Providing all registered EEE producers with a registration number, in which producers must print on all relevant products and invoices,
- Collecting data on EEE amounts placed on the market,
- Reporting the annual flow of materials to German's Federal Environment Agency, in which business to consumer (B2C) waste streams are reported monthly and business to business (B2B) waste streams are reported annually,
- And, ensuring compliance with ElektroG mandates and reporting non-compliance issues to the Federal Environment Agency.[175, 176]

Stiftung EAR is not responsible for operational tasks required by ElektroG such as collecting, sorting, dismantling, and recycling or disposing of EEE – those responsibilities remain imposed on producers.[177] However, German municipalities are responsible for collecting EEE from private households and Stiftung EAR allocates EEE pick-up requests from municipalities to producers based on their current market share.[178] German municipalities are required to install municipal EEE collection points, where B2C end-users from can discard EEE for free.[179]

Germany follows producer-funded takeback and treatment for all EEE.[180] Unlike other European countries, Germany has no WEEE compliance schemes, meaning that obligations of collection and recycling remain the responsibility of each producer – including financial obligations.[181] Instead of monopolistic compliance schemes, Germany favors a competition-oriented compliance approach.[182]

As a result of Germany's implementation of the WEEE Directive, from 2016 to 2018, Germany has collected over 13 thousand tons of solar PV waste and recycled over 12 thousand tons of solar PV paste through WEEE waste management operations.[183, 184]

6.9 Case Study: Germany - Storage

6.9.1 Policy Drivers

As a result of its Renewable Energy Act (EEG), Germany saw an increase distributed renewable energy, resulting in an uptick in battery storage systems.[185] In addition to EEG, in 2010, Germany embraced *Energiewende* (or 'energy turnaround') which serves as a national policy concept focused on increasing renewables and phasing out nuclear energy by 2022 and coal by 2038.[186, 187] Batteries and energy storage are recognized as important components for the success of Germany's energy future and Energiewende.[188]

Germany is also using policy to boost EV deployment. As outlined in its 2030 Climate Action Programme passed in October 2019, the German government aims to have up to 10 million EVs and 1 million charging stations on German roads by 2030.[189]Additionally, Germany's £130 billion COVID-19 Economic Recovery Package, passed in June 2020, allocates significant investments into EV infrastructure, tax cuts, and subsidies.[190] The package also invests £2.5 in research and development for electric mobility and battery production.[191] This investment is in addition to Germany's 2020 decision to investment of over £1.5 billion in battery cell research and production.[192]

While German policies foster new deployment of energy and battery storage technologies, Germany has also introduced regulatory framework to promote the collection and recycling on such technologies.[193] In September 2006, the European Parliament adopted the European Battery Directive (2006/66/EC) which established rules or the collection, recycling, treatment, and disposal of batteries.[194] As outlined in the directive, collection rates for sold batteries of at least 25% and 45% were to be reached by EU Member States by September 26, 2012 and September 26, 2016, respectively.[195] Recycling targets are defined in terms of weight: 65% for lead-acid batteries, 75% for nickel-cadmium batteries, and 50% for others.[196] Collection rates are to be monitored annually by EU Member States and reported to the EU Commission annually.[197] Under the EU Battery Directive, Producers are required to label battery products with the WEEE collection symbol, finance collection and recycling programs, and public awareness campaigns for battery waste disposal.[198, 199] In 2009, Germany transposed the EU Battery Directive by implementing its national Battery Act ('Batteriegesetz' or 'BattG') which regulates the disposal of used and battery storage systems.[200]

6.9.2 Current Specific to Reuse and End-of-Life Management Policy

BattG is intended to extent the responsibility of battery producers to cover the financing, collecting, and disposal processing of battery storage systems at the end of product life cycles.[201] Under BattG, Producers of industrial, automotive, and appliance batteries are required to:

- Register with the German government's regulatory authority overseeing battery products;
- Register batteries before they go on market;
- Label batteries containing hazardous materials;

- Report the numbers of sold batteries to the German government's regulatory authority overseeing battery products at regular intervals;
- Offer facilities for returning batteries after they have been placed on the market;
- Finance the collection and recycling or reuse of batteries at the end of product life;
- And, ensure that batteries are disposed of in accordance with BattG regulation.[202, 203]

Beginning January 1, 2021 an amended German Batteries Act ('BattG2') came into force and introduced a number of notable changes to BattG. Amongst them, the most significant changes include:

- Increasing the collection rate for all batteries from 45% to 50%;
- StiftungEAR will now serve as the regulatory body and clearinghouse for Producer and battery registrations, for which Producers will report information regarding battery sales and collections (formerly the role of the Federal Environment Agency);
- Joint take-back systems for battery collection schemes will be abolished, in favor of private take-back systems to invite collection and recycling competition between Producers;
- An approval process of battery recyclers will be carried out by the German Federation (a duty formerly carried out by German states);
- A review and approval process carried out by StuftungEAR of information provided by Producers (for which were not formally reviewed and approved);
- And, expanding pickup sites for used batteries to include new establishments such as schools, universities, and private companies.[204, 205, 206]

Additionally, with the goal of increasing awareness of environmental practices in the battery industry and to encourage Producers to consider such practices in battery production, beginning in 2023, a Producer's financial obligation to support the collection and recycling of batteries will also address ecological considerations.[207]

Failure to comply with BattG2 includes penalties for Producers such as:

- Removing the Producer's product identifier code and links to their products on German markets;
- Seizing of goods by German custom authority;
- Confiscating Producer profits;
- And, a maximum fine of £100,000.[208]

BattG2 gives the German government more oversight of battery recycling practices and presents new stringency within Germany battery regulatory policy upon Producers.

6.10 Case Study: Japan – Solar

6.10.1 Federal, State, and Local Policies

Japan has no active national regulation or statute specific to the reuse, recycling, or disposal of solar PV modules. However, a regulatory framework is currently being developed.
In 2015, Japan's Environment Ministry convened a working group to study the issue of increasing decommissioned solar PV material flows. Alongside the Ministry of Trade, Economy,

and Industry (METI), the Environment Ministry pledged to create measures and a regulatory framework for removing, transporting, and processing solar power generation equipment. The working group formed in response to the country's rapid rise in installed solar capacity following the implementation of a feed-in-tariff (FIT) in 2012 which incentivized rapid solar development.[209]

In April 2019, the METI established the Working Group for Securing Funds for Decommissioning Solar Power Facilities. The Working Group was tasked with evaluating opportunities to establish a national regulatory regime that would enforce end-of-life solar PV material management requirements and secure financing for decommissioned projects. In their November 2019 draft report, the Working Group recommended creating a regulatory framework that would require owners of commercial projects, defined as systems larger than 10kW, to set aside reserves to fund decommissioning. The new reserve system would apply to both existing and planned systems, and take one of two forms- an external reserve, or an internal reserve.[210]

The external reserve scheme requires solar project owners to place a portion of their project's revenue in a third-party owned holding account until the date of decommissioning. Commercial solar projects in Japan have the benefit of receiving revenue from a FIT system, which was established in July 2012 by the METI and requires Japanese utilities to purchase renewable energy from project developers at fixed prices established by the Japanese government for certain periods of time.[211] The FIT system provides a stable source of revenue for project owners, and a portion of that revenue can be set aside to create the decommissioning fund. FIT payments are provided on a per-kilowatt hour basis, and the METI has published a set of proposed reserve rates based on the FIT payment a system receives. An example of how the reserve rate system may be structured is shown in Table 6.3.[212]

Table 6.3: METI Proposed FIT-Based Rates for Decommissioning Funds[213]

Approval Year		**FIT Price (procurement price)**	**Decommissioning Reserve Base Price (unit price of deposit)**
FY2012		JPY 40/kWh	JPY 1.62/kWh
FY2013		JPY 36/kWh	JPY 1.40/kWh
FY2014		JPY 32/kWh	JPY 1.28/kWh
FY2015		JPY 29/kWh JPY 27/kWh	JPY 1.25/kWh
FY2016		JPY 24/kWh	JPY 1.09/kWh
FY2017	Non-Auction	JPY 21/kWh	JPY 0.99/kWh
	Eligible to bid Round 1	varies for each successful bidder	JPY 0.81/kWh
FY2018	Non-Auction	JPY 18/kWh	JPY 0.80/kWh
	Eligible to bid Round 2	(no successful bidder)	-
	Eligible to bid Round 3	varies for each successful bidder	JPY 0.63/kWh
FY2019	Non-Auction	JPY 14/kWh	JPY 0.66/kWh

	Eligible to bid Round 4	varies for each successful bidder	JPY 0.54/kWh
	Eligible to bid Round 5	varies for each successful bidder	JPY 0.52/kWh
FY2020	10 kW or more and less than 50 kW	JPY 13/kWh	JPY 1.33/kWh
	50 kW or more and less than 250 kW	JPY 12/kWh	JPY 0.66/kWh
	250 kW or more	varies for each successful bidder	JPY 0.66/kWh
FY2021	10 kW or more and less than 50 kW	JPY 12/kWh	JPY 1.33/kWh
	50 kW or more and less than 250 kW	JPY 11/kWh	JPY 0.66/kWh
	250 kW or more	varies for each successful bidder	JPY 0.66/kWh

Projects that can sustain reliable, long-term energy generation and secure their own funding may be exempt from the external reserve requirement, and instead qualify for maintaining an internal reserve. While the external reserve system requires decommissioning fund contributions for every kilowatt hour of power that is sold and compensated by the FIT system, the internal reserve system requires contributions based on project size (i.e., on a per-kW basis). Official per-kW rates have not been released, but the METI has provided a theoretical rate to outline how the contribution system would be structured:

- For a project with a FIT price of JPY40/kWh, the internal reserve rate is JPY17,000/kW
- Project owners thus are required to create a plan for accumulating JPY17,000/kW times the project's capacity by the end of the FIT period
- E.g., if a project is 20MW, the project owner must create an internal reserve of JPY17,000/kW x 20,000kW = 340,000,000 JPY

The internal reserve system is only available to projects with project financing in place and financing agreements that require project owners to withhold at least the same amount of funds as are required under the METI's external reserve scheme. To qualify for the internal exemption, projects must meet at least one of the following requirements:

- A project must have financing agreements in place with a financial institution, and may not use the decommissioning reserve for anything other than covering project decommissioning costs; or
- A project must have secured financing reserves from its publicly listed parent or publicly listed subsidiary to cover decommissioning costs.

A project that qualifies for the internal reserve system must transition to an external reserve system once its project loans have been repaid and the project is no longer monitored by a financial institution.[214]

6.10.2 Non-Regulatory and Voluntary Programs

Prior to considering a binding decommissioning regulatory regime, the Japanese government and industry stakeholders tried to manage solar PV module wastes with a variety of voluntary solutions.

In 2017, the Japan Photovoltaic Energy Association (JPEA) published guidelines for proper disposal of end-of-life solar PV modules. The guidelines were released shortly after a survey conducted by Japan's Ministry of Public Management, Home Affairs, Posts, and Telecommunications found that government agencies and waste disposal businesses were interested in learning more about proper disposal methods for solar PV modules. However, the guidelines asked the Japanese solar industry for voluntary compliance and did not legally bind solar PV module manufacturers, importers, distributors, or waste disposers to recommended disposal methods.[215]

Following the release of the JPEA disposal guidelines, the Japanese government grew concerned that solar project owners might abandon their projects upon running out of FIT funding. In April 2018, METI urged project owners receiving FIT funding to begin creating their own decommissioning funds, and in July 2018 updated the Guidelines on Business Plans for Solar Power Facilities to require project owners to report their decommissioning plans and existing cost reserves.216 As of January 2019, less than 5% of solar project operators had set aside a reserve for decommissioning their systems.217 The external reserve scheme described above was developed in response to the lack of investment in decommissioning by project owners.

In 2021, solar PV manufacturer Next Energy, trading conglomerate Marubeni, and the Mitsubishi Research Institute announced a partnership with Japan's Ministry of the Environment focused on studying the potential of blockchain technologies to track and report information on the reuse and recycling of solar PV modules. In addition, Next Energy revealed it is assisting Japan's New Energy and Industrial Technology Development Organization with drafting guidelines covering the re-sale of solar PV modules and working with the Ministry of the Environment to pilot a solar cell recovery and recycling program.[218] Similarly, in June 2021 PV Cycle, the prominent EU-based PV waste management organization, announced the establishment of PV Cycle Japan. The organization's Japanese chapter is working with the Ministry of the Environment on a feasibility study regarding collecting discarded solar PV modules with the hope of increasing reuse and recycle rates.[219]

Chapter 7: Conclusion

Changing the nature of the solar PV economy from linear to circular before the first major wave of projects reaches end of life is complex task with legal, economic, and social dimensions. This study has attempted to clearly describe the current state of each of these dimensions, and to outline the major barriers and opportunities to creating a circular economy for solar PV. Our research has produced the following key takeaways and recommended next steps, organized according to the tasks we defined at the beginning of the report.

7.1 Decommissioning Costs Analysis

Key Takeaways

Decommissioning cost estimates are characterized by significant uncertainty and variation. It is challenging to compare estimates to one another because estimate providers often group data in different ways and include different cost components. Additionally, there is no general consensus about how these estimates should be calculated. This means that it is not always possible to determine whether the estimate provider is intentionally obfuscating information or simply does not know how an estimate should be calculated. With no reliable data on actual decommissioning costs, it is also not possible to hold estimate providers accountable for the accuracy of their estimates. At present, it is not clear what value these cost estimates can provide to anyone. As local governments increasingly rely on these estimates to avoid bearing the cost of decommissioning themselves, improving consistency and accuracy in these estimates will be critical.

Our research provides an initial framework for understanding a) what is commonly included in decommissioning cost estimates today and b) what characteristics make an estimate more or less trustworthy. However, more work will be needed to support the development of estimates that are reliable enough to support local government and developer planning efforts.

Future Research

One potential avenue for future research is to increase the number of plans in our plan library. Due to our small sample size of 24, the research team was unable to perform any statistical testing to determine whether, for instance certain estimation methods were more associated with high or lower outcomes. Increasing the sample size would allow future researchers to explore these avenues.

A priority for future research should be identifying a mechanism for evaluating actual decommissioning costs. This was particularly challenging for us because the relatively recent expansion of solar development means that large-scale decommissioning is still uncommon. Future researchers might have more luck reaching out to developers directly to see if they would be willing to share any data they might have. This research avenue could also include some modeling or the construction of a test case, if developers are unwilling or unable to provide data. If it is possible to find or create reliable data, we would recommend developing some kind of standard template or calculator that can be used to estimate decommissioning costs. This would considerably reduce the burden of evaluating plans for local government officials and could alleviate some of their concerns about the consequences of permitting solar development.

Finally, future researchers could reach out to developers directly, to better understand how they think about end of life costs and why they make the end of life decisions they make. This was a question of interest for our team, but we ultimately determined that it was not within the scope of our project. However, supporting a circular economy approach to solar PV would be easier if current barriers to recycling and repowering were better understood from the developer's perspective. We also suspect that improving guidance for estimating end of life costs would have value for developers' internal financial modeling.

7.2 Secondary and Circular Economy Market Analysis

Key Takeaways

The secondary market for solar PV modules in the U.S. is poised to continue growing dramatically in the coming decade. This growth will be driven by several key factors: the 66-84% cost advantage that used modules have over new modules, a steadily increasing rate of solar project repowering, rising international demand for inexpensive solar PV modules, and growing domestic demand for affordable behind-the-meter emergency generation. However, this growth will be challenged by continuous improvements in the performance of new solar PV modules, declines in the cost of new modules, the availability of tax credits for the installation of new projects, and concerns from consumers and regulators regarding used module safety and performance.

Furthermore, building a robust secondary marketplace is essential to improving the circularity of the solar industry, and recycling services will continue to be a key component of the secondary markets ecosystem. Recycling services are beginning to emerge and scale throughout the US. However, the supply of these services is still lacking or non-existent in many parts of the country. Where recycling services are not available or cannot support circular material flows, secondary markets are needed to keep solar PV modules with remaining useful life in operation.

Future Research
Looking forward, it would be valuable to estimate the current and future size of the U.S. secondary market for solar PV modules on a more detailed and granular level. Project scope and timeline limited us to a higher-level market sizing estimate based on assumptions made from market research and trends. Future research in this area could try to determine what percentage of repowered PV modules actually enter a secondary market as opposed to just being disposed of or recycled, and calculate a market size estimate for each module technology. It would also be interesting to more quantitatively understand the physical quantities of PV modules being sold and delivered to each customer segment via secondary markets.

Additionally, our analysis centered on the price competitiveness of used solar modules on a secondary market, but it would interesting to explore and compare the value generated for a solar project owner from recycling and selling lightly used modules. This could help drive a deeper study into the competitiveness, viability, and growth potential of the solar module recycling industry, and help determine how secondary markets and solar module recycling will compete with each other for used modules. Underlining all of this, it would be valuable to conduct more industry interviews and case studies as these provided our greatest insight into existing and emerging business models within the industry.

7.3 U.S. Local Policy Survey

Key Takeaways
In the absence of U.S. states, and especially their local jurisdictions, will continue to play an important role in regulating the responsible management of solar PV-specific waste laws in the absence of federal regulations mandating the collection and recycling of solar PVs at the end their useful lives. Recognizing this responsibility, most solar PV decommissioning policies have initially been proposed by elected officials or planning staff, rather than concerned citizens. Local jurisdictions' elected officials and planning staff express some anxieties over solar projects happening within their communities. As a result of these anxieties, the most common motivation for implementing decommissioning regulations is the desire to protect local jurisdictions from burdening future costs associated with solar projects. Emotional and value-based responses to solar developments are a factor in local jurisdiction's solar ordinances. That said, it should be

noted that solar development policies can both negatively and positively impact attitudes toward solar projects. While policies can be used to build support for solar projects, top-down policies that force solar upon localities can trigger resentment that may manifest as restrictive siting regulations. Nevertheless, when it comes to solar developers, our research shows that they are generally willing to comply with local jurisdiction's solar policies and decommissioning requirements. Ultimately, while solar developers will push for what they perceive as reasonable solar ordinance requirements, we believe that solar developers mainly want a clear understanding of a local jurisdiction's solar policies so that they can expedite their solar projects. Lastly, while we believe our research is important in helping to understand local government's experiences in managing solar developments in their communities – as well as the implications that their policies may have on solar projects – the outcome of solar ordinances and decommissioning policies is still largely to be determined. Navigating a solar planning and policies remains relatively new territory for many U.S. local governments. Therefore, it is premature to claim to fully understand the full context of how local governments can best grapple with a dynamic energy landscape, while also not creating negative implications on the U.S. solar industry.

Future Research

The intent of our local policy interviews was to gain a better understanding of how and why local jurisdictions solar ordinances came into existence, who was involved, and what the implications of solar ordinances and decommissioning policies are having on the solar industry. While we believe our research has resulted in notable findings and considerations, our research could be enhanced in the future in a number of ways. First, future research could expand upon our interview size. Though the project team contacted planning staff in 16 counties or independent cities, the team successfully conducted 7 interviews. With a larger sample size, future research could inform a deeper understanding and identify more trends concerning local jurisdictions experiences with solar ordinances and decommissioning policies. Secondly, future research could focus on a wider geographic range than the scope of our initial research. With the exception of Minnesota, our interviews were conducted with planning officials located on the east coast. With a wider geographic range, future research could help understand experiences going on in other parts of the country too, especially places with differing political makeups and energy landscapes. Future research would also benefit from a sample that includes interviews with planning officials from both urban and rural communities, as our research largely focused on rural communities. Lastly, as mentioned throughout this paper, governments and industries are on the early cusp of having to deal with solar decommissioning. Therefore, because solar decommissioning is sure to gain more attention in coming decades, future research would benefit from conducting interviews with local jurisdictions on solar ordinances and decommissioning trends years into the future. While local jurisdictions are now and in recent years beginning to think about this important topic, they do not have many examples or lessons learned yet from decommissioning solar modules. Until local jurisdictions have more experience operating in this space, our current understanding of this research is limited.

7.4 International Policy

Key Takeaways

The international community has begun to engage with the issue of how to manage material flows from decommissioned and waste solar PV modules and energy storage technologies. The European Union likely has the most mature and robust regulatory framework for managing solar and storage wastes, but other countries are gaining ground. Legislative willpower and capacity are important components of establishing waste management policies, but buy-in, input, and collaboration between governing bodies and industry stakeholders is of equal importance. On a global scale, the movement to establish solar and storage waste management policies is still in its infancy. Further research is needed to understand how policies are developing in regions we did not cover (e.g., Central and South America, Africa, and the Middle East) as well as policy differences between countries in regions we began to explore (Europe and Asia-Pacific).

Future Research

The research we've begun would benefit from a deeper analysis of how waste management policies are financed in different jurisdictions and their potential second and third order effects once enacted. For example, whether businesses must adjust their business models in response to the wider use of recycled or repurposed solar and storage technologies, or how industry and governmental supply chain strategies will respond to the increased availability of repurposed or recycled materials.

Appendix A: U.S. Local Policy Survey

Table A.1: Themes and Codes used for Interview Analysis

Theme	Code
1. Driver / Instigator of Policy	
	Elected officials
	Administrators / planning staff
	Citizens / community input
	Noted lack of community input
	Stakeholders (property owners, electric utilities, etc.)
2. Motivation for Regulatory Policies	
	Protecting local character
	Avoiding future burden
	Response to sudden trend
	Avoiding use phase harm (glare, noise, etc.)
	Ecological impact concerns
	Pre-empting public concern
	Overall resistance to solar development
	Experience with other permitted structures
	Maintain local autonomy
3. Perception of Solar	
	Opportunity (administrator)
	Opportunity (citizen)
	Industrial
	Obligation / burden (administrator)
	Obligation / burden (citizen)
	Harmful (citizen)
4. Emotional / Value-based Response	
	Anxious (about the future / uncertainty)
	Suspicious (being taken advantage of)
	Overwhelmed (too much too fast)
	Excited (opportunity)
	Anger (being told what to do)
	Fear (losing sense of place)
5. Method for Ordinance Development	
	Mimicking other jurisdictions

	Mimicking other technologies / structures
	Noted lack of mimicking
	Engaged research (discussion with experts, site visits, etc.)
	Reliance on internal experience
	Broad ordinance + specific guidance
	Assistance from consultants
	Developmental administrative burden
	Other structures require financial assurance
6. Process for Reviewing Decommissioning Plans	
	Internal review by professional engineers
	Internal review by non-technical staff
	Trust in external professional engineers
	Concern about underestimation
	Review administrative burden
	Established review guidelines
	No plans since ordinance passage
7. Effect of Policy	
	Limitation / reduction of development
	Company compliance – no major resistance
	Company pushback on other components of ordinance but not decommissioning
	No applications since ordinance passage
	Development of decommissioning policies for other structures
	Delays/development limitations caused by other solar regulations but not decommissioning
	Rejection of solar proposals
	Create a pathway for solar development

Appendix B: Decommissioning Costs Analysis

Table B.1: Decommissioning Plan Confidence Rating Rubric

Criterion	1	2	3	4	5
A: Statement of methods	No transparency on where cost estimate came from		Moderate transparency		Perfectly clear to see exactly how cost estimates were calculated
B: Granularity of estimate	Single lump sum with no additional details provided	Lump sum estimate with some additional details provided	Broken out by material component or cost component but not both	Broken out estimate missing some finer detail	Estimates are broken out by material (racking, modules, etc.) and cost component (labor, transportation, etc.)
C: Validity of assumptions (e.g., inclusion of reference for unit price)	No rate assumptions provided		Rate assumptions are provided but their validity / justification is unclear / rate assumptions are only provided for some components		Rate assumptions are sensible, and how they were developed is clearly defined
D: Credentials of cost estimate preparer	No contracting or building experience		Solar developer or engineering firm with minimal first-hand building experience / Engineering firm with minimal solar experience		PE-certified contractor with experience building / decommissioning solar projects
E: Inclusion of key components	Missing 9-10 components	Missing 6-8 components	Missing 3-5 components	Missing 2-3 components, or 1 component if that component is	Missing at most one component, unless that component is site reclamation or overhead

				site reclamation or overhead	
F: Inclusion of inflation cost escalator	No inflation adjustment		Inflation adjustment mentioned, but calculation not shown		Inflation adjustment

Appendix C: Initial Decommissioning Cost Estimate Data Summary Reading Guide

Table C.1 Decommissioning Cost Data Reading Guide

Column	Calculated or Reported?	Description	Notes
Project Name	Reported	Name of project	
Estimated Costs? (Y/N)			
Type of Cost Estimate	Created	Classification of estimation methodology (Per Unit, Single Number Lump Sum, Itemized Lump Sum)	
County/State	Reported	Location of project	
Facility Capacity	Reported	Nameplate production capacity of project	
No. Of PV Modules	Reported	Number of PV modules that are part of the project.	
Total Cost (present)	Reported	Sum of all costs incurred during decommissioning, not including salvage	Positive values are standard costs and would enter a profit calculation as negative numbers
Total Cost (future)	Reported	Sum of all costs incurred during decommissioning adjusted for inflation over a given timespan, not including salvage	Positive values are standard costs and would enter a profit calculation as negative numbers
Expected Net Cost (present)	Reported	Sum of all costs incurred during decommissioning, less the value of salvaged materials	Positive values denote estimates for which costs are greater than salvage values, I.e., standard costs that would enter a profit calculation as negative numbers. Negative values denote estimates for which salvage values are greater than costs, I.e., negative costs that would enter a profit calculation as positive numbers.

Expected Net Cost (future)	Reported	Sum of all costs incurred during decommissioning, less the value of salvaged materials, adjusted for inflation over a given timespan	Positive values denote estimates for which costs are greater than salvage values, I.e., standard costs that would enter a profit calculation as negative numbers. Negative values denote estimates for which salvage values are greater than costs, I.e., negative costs that would enter a profit calculation as positive numbers.
Net Cost per MW (present)	Calculated	Expected net cost / Facility Capacity	Positive values denote estimates for which costs are greater than salvage values, I.e., standard costs that would enter a profit calculation as negative numbers. Negative values denote estimates for which salvage values are greater than costs, I.e., negative costs that would enter a profit calculation as positive numbers.
Net Cost per MW (future)	Calculated	Expected net cost, adjusted for inflation over a given timespan / Facility Capacity	Positive values denote estimates for which costs are greater than salvage values, I.e., standard costs that would enter a profit calculation as negative numbers. Negative values denote estimates for which salvage values are greater than costs, I.e.,

			negative costs that would enter a profit calculation as positive numbers.
Total Net Salvage value/credit (present)	Reported	Total salvage as reported by the decommissioning plan (not necessarily equal to the sum of all salvage values reported)	In some cases, costs associated with salvaging materials were explicitly stated and subtracted from the total value. In other cases, costs were not stated and values were assumed to be net values.
Total Net Salvage value/credit (future)	Reported	Total salvage as reported by the decommissioning plan (not necessarily equal to the sum of all salvage values reported), adjusted for inflation over a given timespan	In some cases, costs associated with salvaging materials were explicitly stated and subtracted from the total value. In other cases, costs were not stated and values were assumed to be net values.
Sum of Salvage Reported	Calculated	Sum of all individual salvage values and costs reported	In some cases, regulations prevented developers from including the full salvage value in their estimate. In other cases, the estimates were just internally inconsistent.
Non-Labor Disposal/Recycling Costs	Calculated	Sum of removal costs not associated with labor hours or transportation, such as equipment and machinery costs, disposal fees, electrical disconnection costs, etc.	Positive values are standard costs and would enter a profit calculation as negative numbers
Total Labor Costs (present)	Both	Sum of all reported labor costs, including salvage and electrical disconnection labor costs	Positive values are standard costs and would enter a profit

			calculation as negative numbers
Total Labor Costs (future)	Both	Sum of all reported labor costs, including salvage and electrical disconnection labor costs, adjusted for inflation over a given timespan	Positive values are standard costs and would enter a profit calculation as negative numbers
Total Transportation Costs	Calculated	Sum of all reported transportation costs—generally, cost of transporting waste to landfill or to recycling facilities	Positive values are standard costs and would enter a profit calculation as negative numbers
Net PV Module Cost	Reported	Sum of labor and removal costs for PV modules, plus the cost of disposal and/or the expected recycling / repowering / salvage value	Positive values are standard costs and would enter a profit calculation as negative numbers Negative values denote estimates for which salvage values are greater than costs, I.e., negative costs that would enter a profit calculation as positive numbers.
Net Racking Cost	Both	Sum of labor, removal, and dismantling costs for all racking materials, plus the cost of disposal or the expected recycling / repowering / salvage value **a comprehensive definition of what is considered "racking material" is forthcoming.	Positive values are standard costs and would enter a profit calculation as negative numbers Negative values denote estimates for which salvage values are greater than costs, I.e., negative costs that would enter a profit calculation as positive numbers.
Net Inverter Cost	Reported	Sum of labor, removal, and disconnection costs for inverters, plus equipment costs, disposal costs, and/or	Positive values are standard costs and would enter a profit calculation as negative numbers

		the expected recycling / repowering / salvage value	Negative values denote estimates for which salvage values are greater than costs, I.e., negative costs that would enter a profit calculation as positive numbers.
Net other electrical component cost	Calculated	Sum of up-front material, labor, removal, and disconnection costs for all electrical components besides the inverter, plus the cost of disposal and/or the expected recycling / repowering / salvage value **a comprehensive definition of what is included in the category "electrical component" is forthcoming.	Positive values are standard costs and would enter a profit calculation as negative numbers Negative values denote estimates for which salvage values are greater than costs, I.e., negative costs that would enter a profit calculation as positive numbers.
Net Fencing Cost	Both	Sum of up-front material, labor, removal, and disconnection costs for all fencing, plus the cost of disposal and/or the expected recycling / repowering / salvage value.	Positive values are standard costs and would enter a profit calculation as negative numbers Negative values denote estimates for which salvage values are greater than costs, I.e., negative costs that would enter a profit calculation as positive numbers.
Net Utility Pole Removal Cost	Reported	Sum of labor and removal costs for utility poles, plus the cost of disposal and/or the expected recycling / repowering / salvage value.	Positive values are standard costs and would enter a profit calculation as negative numbers Negative values denote estimates for which salvage values are greater than costs, I.e.,

			negative costs that would enter a profit calculation as positive numbers.
Site Restoration Cost (present)	Calculated	Sum of labor, material, and equipment costs for all activities needed to return decommissioned sites to acceptable conditions. **a comprehensive definition of what is included in the category “site restoration” is forthcoming	Positive values are standard costs and would enter a profit calculation as negative numbers
Site Restoration Cost (future)	Calculated	Sum of labor, material, and equipment costs for all activities needed to return decommissioned sites to acceptable conditions, adjusted for inflation over a given timespan	Positive values are standard costs and would enter a profit calculation as negative numbers
Total Other Costs (present)	Calculated	Sum of other costs reported that don’t fit into other categories or are only reported in a few decommissioning plans **a comprehensive definition of what is included in the category “other costs” is forthcoming.	Positive values are standard costs and would enter a profit calculation as negative numbers
Total Other Costs (future)	Calculated	Sum of other costs reported that don’t fit into other categories or are only reported in a few decommissioning plans, adjusted for inflation over a given timespan	Positive values are standard costs and would enter a profit calculation as negative numbers

Glossary

- Per Unit: Any cost estimation calculated by multiplying a known per-unit value by a known quantity of that unit (e.g. labor cost ($/hour) x hours of labor expected)
- Single Number Lump Sum: Only a single value given as a cost estimate with no breakdown, context, or calculations described
- Itemized Lump Sum: A series of single number lump sum estimates broken out by category or component, no context or calculations described
- Racking Materials: includes aluminum, steel, and wooden beams
- Other Electrical Components: includes wiring and cabling (copper or aluminum), transformers, switchboards, AC/DC connectors, electrical disconnect, batteries, and other components
    - Some uncertainty as to whether “electrical disconnect” refers to an item or an action
- Site Restoration: includes concrete pad removal, gravel removal, erosion control, grading, reseeding, and other remediation activities.
- Other Costs: includes mobilization and de-mobilization, permitting costs, insurance, contingency, overhead costs, general conditions costs (?), site inspection costs, and other components.

Appendix D: International Policy

Table D.1 Policy Database

Country	Country (locality)	State/Locality/Company	Technology	CE Pathway	Policy Name	Year	Policy Framework	Policy Mechanism (for	Policy Type
Australia			Storage	Recycle	Battery Stewardship Scheme	2020	Hybrid	Initiative	EPR
Australia			Solar	Recycle	Solar Stewardship Scheme	2021	Government-led	Pending	EPR
Australia			Solar	Recycle	National Waste Policy Action Plan	2019	Government-led	Regulation/Statute-	EPR
Australia			Storage	Recycle	National Waste Policy Action Plan	2019	Government-led	Regulation/Statute-	EPR
Australia	Australia (New South Wales)	New South Wales	Solar	Recycle	Circular Solar Grants Program	2021	Hybrid	Initiative	Funding
Australia	Australia (Australian Capital Territory)	Australian Capital Territory	Solar	Recycle	Notice Paper No. 18	2021	Government-led	Pending	Recycling or
Australia	Australia (Australian Capital Territory)	Australian Capital Territory	Storage	Recycle	Notice Paper No. 18	2021	Government-led	Pending	Recycling or
China			Storage	Recycle	Law of the People's Republic of China	2020	Government-led	Regulation/Statute-	EPR
China			Storage	Recycle	Interim Measures for the	2018	Government-led	Regulation/Statute-	EPR
China			Storage	Recycle	Technical Specification of Pollution	2022	Government-led	Regulation/Statute-	Guidelines
China			Storage	Recycle	Interim Provision on the Management	2018	Government-led	Regulation/Statute-	Labelling
France			Storage	Recycle	Decree 1139 of September 2009	2009	Government-led	Regulation/Statute-	EPR
France			Solar	Recycle	Decree 2014-928, Implementing EU	2014	Government-led	Regulation/Statute-	EPR
Germany			Storage	Recycle	Batteriegesetz ("BattG")	2009	Government-led	Regulation/Statute-	EPR
Germany			Storage	Recycle	BattG2	2021	Government-led	Regulation/Statute-	EPR
Japan			Storage	Recycle	Act on the Promotion of Effective	2015	Government-led	Regulation/Statute-	EPR
Japan			Solar	Reuse	Next Energy Blockchain	2021	Hybrid	Initiative	Funding
Japan			Solar	Reuse	Solar Panel Re-sale Guidelines	2021	Hybrid	Initiative	Guidelines
Japan			Storage	Recycle	Waste Management and Public	1970	Government-led	Regulation/Statute-	Guidelines
Saudi Arabia			Solar	Recycle	Saudi Green Initiative	2021	Government-led	Pending	Guidelines
Turkey			Storage	Recycle	Regulation on Waste Batteries and	2005	Government-led	Regulation/Statute-	EPR

Appendix E: Secondary and Circular Economy Market Analysis

Table E.1 Recycling Vendor Database

Vendor Name	City	State	Address	Website
First Solar	Tempe	AZ	350 West Washington Street, Suite 600	https://www.firstsolar.com/
First Solar	Tempe	AZ	350 West Washington Street, Suite 600	https://www.firstsolar.com/Modules/Recycling
R3E Waste	Phoenix	AZ	4202 E Elwood St, Suite 12	https://www.r3ewaste.com/
R3E Waste	Tuscon	AZ	2055 East 17th Street	https://www.r3ewaste.com/
ERI	Fresno	CA	3243 South East Avenue, Building 108	https://eridirect.com/sustainability/products-we-recycle/solar-panels/
Recycle1234	Union City	CA	33548 Central Ave	https://recycle1234.com/
Surplus Service	Fremont	CA	3090 Osgood Court	https://surplusservice.com/surplus-electronics/dont-let-solar-panels-go-waste-energy-industry/
Eco Cycle Center for Hard-to-Recycle Material:	Boulder	CO	6400 Arapahoe Rd	https://www.ecocycle.org/charm
ERI	Aurora	CO	3250 Abilene Street	https://eridirect.com/sustainability/products-we-recycle/solar-panels/
CompuPoint	Lawrenceville	GA	111 Fredrix Aly	https://www.compupointusa.com/
Mr. K's Recycle Redemption	Hilo	HI	815 Kinoole St	https://www.mrksrecyclehawaii.com/
Recycle Boise	Boise	ID	4725 N Glenwood St	https://www.recycleboise.com/
Interco	Madison	IL	10 Fox Industrial Dr	https://intercotradingco.com/
ERI	Plainfield	IN	3100 Reeves Rd.	https://eridirect.com/sustainability/products-we-recycle/solar-panels/
Earthworm Recycling	Somerville	MA	65 Inner Belt Rd.	http://www.earthwormrecycling.org/index.html
ERI	Holliston	MA	510 Ryerson Rd., Suite #2	https://eridirect.com/sustainability/products-we-recycle/solar-panels/
Cleanlites Recycling	Mason	MI	1623 Wildwood Ave.	https://cleanlites.com/
Cleanlites Recycling	Lakeville	MN	7650 215th Street West	https://cleanlites.com/
Green Lights Recycling	Blaine	MN	10040 Davenport Street NE	https://www.glrnow.com/
ERI	Badin	NC	293 NC 740 Hwy., #134.	https://eridirect.com/sustainability/products-we-recycle/solar-panels/
Green River Professional Consulting	Tioga	ND	10 Dakota St N	http://greenriverpro.com/
ERI	Lincoln Park	NJ	89 R Cross Street	https://eridirect.com/sustainability/products-we-recycle/solar-panels/
Cleanlites Recycling	Cincinatti	OH	7806 Anthony Wayne Ave	https://cleanlites.com/
Cleanlites Recycling	Cincinatti	OH	419 Northland Blvd.	https://cleanlites.com/
Cleanlites Recycling	Wauseon	OH	715 Linfoot St.	https://cleanlites.com/
Green Century Recycling	Portland	OR	2950 NW 29th Ave	https://greencenturyonline.net/
Cleanlites Recycling	Spartanburg	SC	195 Ben Abi Road	https://cleanlites.com/
ERI	Flower Mound	TX	Lakeside Trade Center, Building 1	https://eridirect.com/sustainability/products-we-recycle/solar-panels/
R3E Waste	Austin	TX	2216 Rutland Drive Suite B	https://www.r3ewaste.com/
ERI	Sumner	WA	3901 150th Ave. Ct. East, Suite 200	https://eridirect.com/sustainability/products-we-recycle/solar-panels/
Green Century Recycling	Tacoma	WA	10733 A St. S Suite A	https://greencenturyonline.net/

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