AN ASSESSMENT OF THE ECONOMIC VIABILITY OF SOLAR PANEL RECYCLING FOR UTILITY-SCALE PROJECTS IN THE UNITED STATES

by

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(Under the Direction of David Gattie)

ABSTRACT

The deployment of solar panels continues to grow, putting pressure on the back side of this industry related to decommissioning and disposal. At end-of-life, solar panels are often disposed of in landfills but with significant waste volume. Though there have been Levelized Cost of Electricity (LCOE) studies conducted to analyze the effects of adding panel recycling methods, this study will focus on a comparison of solar photovoltaic (PV) panel LCOE with and without solar panel recycling in two regions of the United States: Pennsylvania-New Jersey-Maryland (PJM) and California Independent System Operator (CAISO). This research explores the driving factors for cost differences across the United States for solar PV and its effects on the potential adoption of solar panel recycling. It will further undergo an analysis with a range of interest rates due to fluctuating market variability and its impact on the economic feasibility of solar panel recycling.

INDEX WORDS: LCOE, Solar panel recycling, Utility-scale

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RECYCLING FOR UTILITY-SCALE PROJECTS IN THE UNITED STATES

by

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CHAPTER 1

INTRODUCTION

1.0 Overview of US Growth in Solar

The United States has made significant strides in clean energy. In 2023, the United States installed 31 GW of solar capacity, which was roughly a 55 percent increase from 2022 [1]. Overall, the country is at 161 GW of installed solar capacity, enough to provide approximately 5 percent of the nation's electricity as stated by the Solar Energy Industries Association (SEIA) [1]. Furthermore, battery storage systems that are often installed with solar arrays have exceeded in Q3 those of all of 2022 with a projected growth of twice the capacity in 2024 [1]. The growth can be viewed in Figure 1 from 2021 to 2024 for utility-scale energy capacity additions in the U.S., which includes renewable energy sources as well as fossil fuels for comparison.

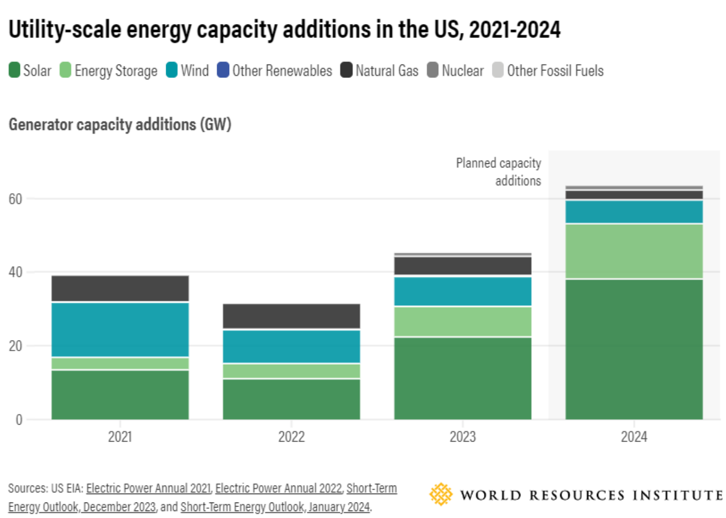


Figure 1: Utility-scale Energy Capacity Additions in the U.S. from 2021-2024 [1].

For these large strides to occur, policy development became a critical part in the process. Federal policies such as the Investment Tax Credit and the Inflation Reduction Act allowed interested parties to adopt solar with lesser financial burdens. States also passed climate and clean energy policies as federal policies alone would not suffice [1]. These policies are further discussed in this study.

Though solar energy has greatly increased in recent years, there are upcoming and ongoing issues that are imperative to address. Beginning June 2024, President Biden's two-year pause on solar tariffs will expire, potentially subjecting solar modules with imported components to trade duties [1]. Due to the rising interest rates, the amount of upfront capital required will continue to impact clean energy projects.

Beyond financial concerns for clean energy, there is a major issue with transmission capacities and necessary grid upgrades for electricity generation and use. There are more transmission installation projects than there is demand for them due to crossing state borders and how long it takes to build them [1]. Grid upgrades are necessary to meet the required demand for other clean energy sources [1].

Despite these rising issues, there is still legislation such as the Inflation Reduction Act's Greenhouse Gas Reduction Fund to combat costs of future spikes [1]. To resolve the issues that may inhibit the growth of solar and achieve goals, decision makers, manufacturers, developers, and policymakers, and many more, must come together to continue the expansion of solar and clean energy in the United States.

Another impending issue is the end-of-life management of solar panels. Most solar panels are placed in landfills. It is predicted that the United States alone will have around one million total tons of solar panel waste by 2030 [2]. Currently, there are some end-of-life management practices, but there is a need for more advancements as solar continues to grow.

The SEIA created the National PV Recycling Program in 2016 to gather companies that would offer recycling and refurbishment opportunities for solar panels [3]. There are approximately 12 partners for this program including METech Recycling, SolarCycle, Echo Environmental, FabTech Solar Solutions, First Solar, ERI, OKON Recycling, We Recycle Solar, Revive PV, Ontility, SolarPanelRecycling.com, and OnePlanet Solar Recycling [3]. The end-of-life recycling of solar panels is still in the beginning stages of development but has the potential to provide more economic growth.

1.1 Solar PV Panels

Solar PV panels can be broken down into three categories: monocrystalline, polycrystalline, and thin-film [4]. Table 1 summarizes the types of panels and their respective efficiencies.

Table 1: Solar PV Panel Categorization with Efficiency and Summary [4,5].

Panel	Efficiency	Summary
monocrystalline	17-22 %	Made from highest grade silicon; most commonly deployed but higher cost compared to the other categories; single-crystalline
polycrystalline	15-17 %	Made from multi-crystalline silicon; lower cost and can be produced faster; shorter lifespan

thin-film	7-18 %[16]	Lightweight and flexible, cheaper than both crystalline panels; becoming more efficient and comparable to crystalline panels as advancements are made

[16]Referenced from American Solar Energy Society

Though these three categories are currently the most sought out in the market, there are new solar cell types under development, including the organic solar cell, perovskite solar cell, amorphous Si solar cell, CdTe solar cell, dye-sensitized solar cell (DSSC), and more [4]. Figure 2 below shows the advancements in cell efficiency research conducted over the years allowing solar cell efficiency to grow from 5-47 percent.

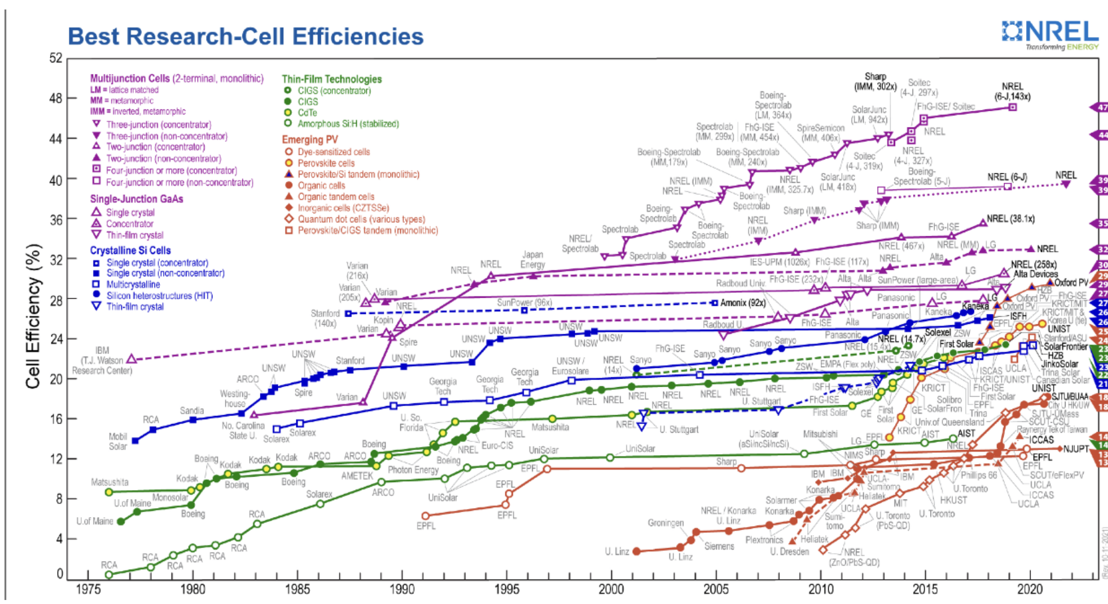


Figure 2: Research-Cell Efficiency from Approximately 1976 to 2021 through NREL [4].

Solar PV is used by commercial and residential customers and utilities. Commercial and residential building owners look to install rooftop solar as an independent system or a grid-connected system [4]. Utilities often look to ground solar and have large solar farms [4]. Since ground solar does require more land coverage, it can be more costly than rooftop solar depending on many factors, such as whether the site needs to be graded, whether the rooftop can hold additional loads from solar, and more.

1.2 Solar Panel Waste Projections

Even though there is a transition to renewable energy, waste is still accumulated after the technology is used. End-of-life management of solar panels needs policy action. This is due to the projected estimations of decommissioned solar panels around the world. Studies have been conducted to estimate two different scenarios for solar panel waste: regular-loss scenario and early-loss scenario. The time frame is from 2016-2050. Regular-loss scenario is when the panel is decommissioned at its expected life expectancy of 30 years without any issues prior, whereas early-loss scenario is when the panel unexpectedly meets its end before the 30-year lifespan [6]. These projections can be viewed in Figure 3.

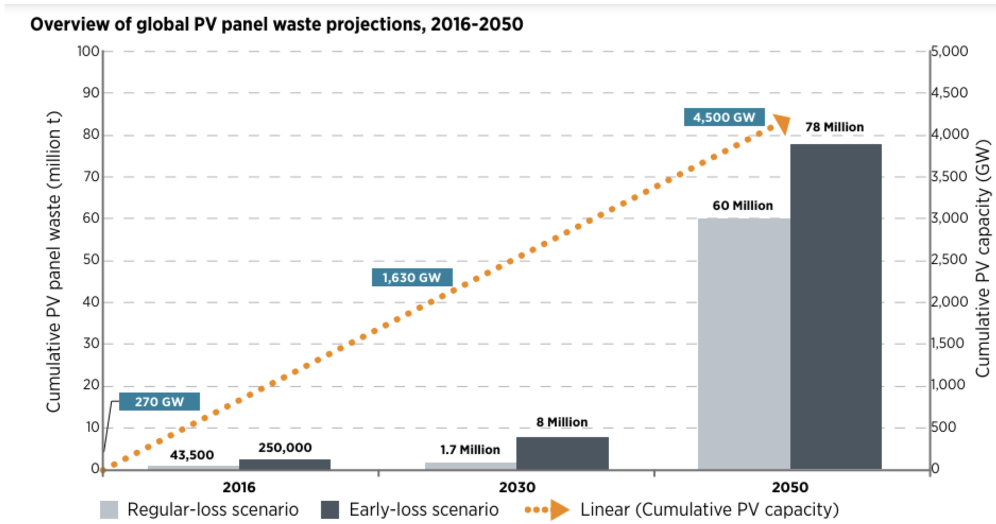


Figure 3: Global Solar PV Panel Waste Projections from 2016-2050 [6].

Specifically in the U.S., it is projected that by 2050, there would be an early-loss scenario of 10 million PV panels and a regular-loss scenario of 7.5 million PV panels [6]. This is shown in Figure 4.

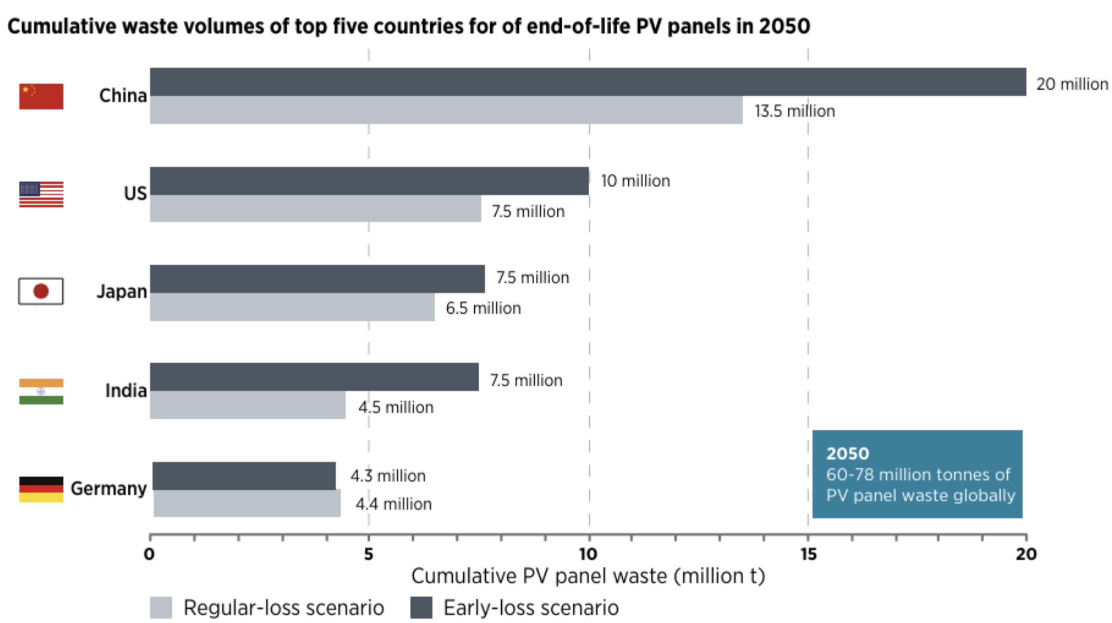


Figure 4: Waste Volumes of Top Five Countries for End-of-Life PV Panels in 2050 [6].

To decrease the number of PV panels for waste management, there are several categories that are being researched including reducing, reusing, and recycling.

1.3 Current Solar Panel Recycling Methods

Currently, there are companies that recycle various parts of solar panels in the United States. Some sources for possible recycling options can be found through the Department of Energy Solar Energy Technologies Office U.S. Solar Photovoltaic Manufacturing Map, Earth 911, or SEIA. However, it is best to review how solar panels are recycled before looking into current technologies and policies.

In the solar PV panel market, crystalline-silicon is the most used [7]. Figure 5 displays the components that make up a PV panel. The glass, aluminum frame, copper wire, and plastic junction box can all be recycled [7]. Materials such as silver and internal copper are more difficult to recycle, and there are various toxic metals that may be present in the solar panel [7]. Furthermore, critical materials such as aluminum, tin, tellurium, and antimony may be found in solar panels [7]. For thin-film modules, there may be gallium and indium [7].

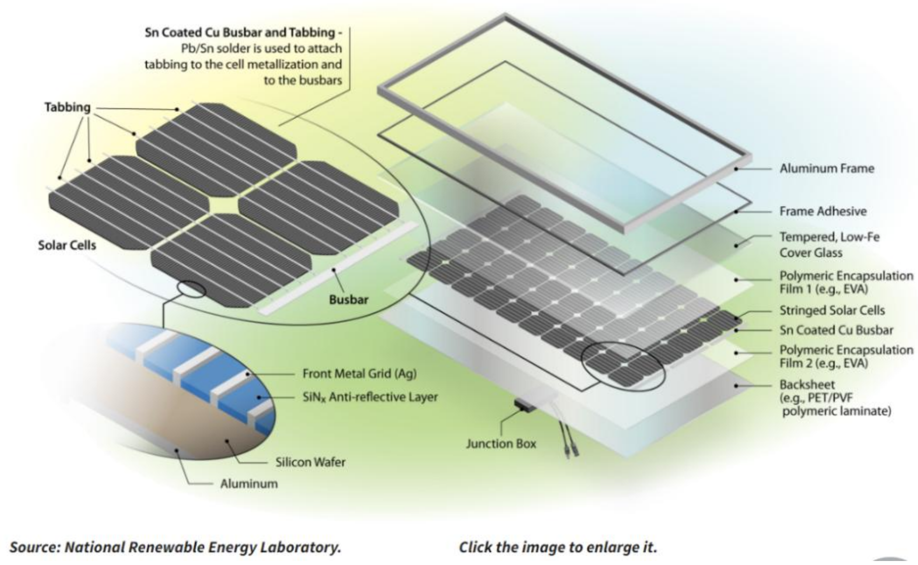


Figure 5**:** Components of a Solar Panel [7].

Critical materials are identified as "non-fuel mineral or mineral material that is essential to the economic and national security of the United States, that has a supply chain vulnerable to disruption, and that serves an essential function in the manufacturing of a product, the absence of which would have significant consequences for the economy or national security" [8]. There are thirty-five identified critical materials in the U.S., and a shortage of these minerals can pose a threat on supply chain. Political issues may arise if the critical mineral is imported.

Due to the use of critical minerals and general minerals for solar panels, there is importance in retrieving the minerals for reuse or using less raw materials for the panels. Before diving into the recycling process, it is important to note that the panels alone are not the only components that make up a solar energy system. Other components include inverters, racking, and battery storage systems, but they may be recycled through electronic waste, similar scrap metals, and battery recycling programs respectively [7]. The focus for recycling in this study, however, is solar PV panels.

Solar panels are recycled in one to three generalized steps:

> "1. Removal of the frame and junction box;
>
> 2. Separation of the glass and the silicon wafer through thermal, mechanical or chemical processes; and/or
>
> 3. Separation and purification of the silicon cells and specialty metals (e.g., silver, tin, lead, copper) through chemical and electrical techniques" [7].

Recycling has yet to be commercialized for solar panels, but facilities are available to recycle solar panels and the system's components [7].

1.4 Current Regulations and Legislation in the United States – Solar Panels

As end-of-life disposal of solar products is newer to industry, there are few regulations enforced. One U.S. regulation that addresses solar is the Federal Resource Conservation and Recovery Act (RCRA). It gave the Environmental Protection Agency (EPA) the power to handle hazardous waste from cradle to grave [9]. The RCRA itself is too broad for solar panels because it just ensures that the panels would be safely recycled or disposed of if it is hazardous waste. Thus, it can be concluded that there are currently no national policies in the U.S., but there are some policies at the state level.

As of 2022, approximately 11 states have passed legislation to address end-of-life solar panels: Hawaii, Illinois, Indiana, Maine, Montana, New Jersey, Ohio, South Carolina, Tennessee, Virginia, and West Virginia [10]. California's Code of Regulations addresses solar panel decommissioning, but it falls under state executive agencies and not state legislation [10]. Summaries of the state legislation for the eleven states are shown in Table 2.

Table 2: Enacted Legislation Regulating End-of-Life Solar Panel Care [10].

State	Bill Number	Summary of Relevant Content
Hawaii	House Bill 1333	Commissions the Hawaii Natural Energy Institute and Department of Health to study and determine best practices for recycling or disposing of solar panels and related equipment. The study is to include information on the type, composition and number of solar panels that will be disposed of; best practices for decommissioning to maximize environmental and economic benefits; and an assessment of potential solar panel disposal fees to support state efforts.
Illinois	Senate Bill 3790	Establishes a 15-member Renewable Energy Component Recycling Task Force to develop recommendations by July 2025 for the executive, legislative and private sector on end-of-life management strategies for renewable energy generating equipment, including that used to gather and store solar energy (e.g., identification of

		needed infrastructure, regulatory requirements of other jurisdictions and the safest/most effective methods of disposal).
Indiana	Senate Bill 411	Requires commercial solar facilities and commercial solar energy systems to submit a security bond equal to 25% of the cost of decommissioning prior to commercial operation. By the 10^{th} anniversary of operation, the owner of a commercial solar facility must post 100% of decommissioning costs as a security bond. Facilities must notify authorities of the intent to decommission the solar facility 60 days prior to decommissioning and adhere to a one-year decommissioning timeline or risk being fined.
Maine	House Policy 1184/Legislative Document 1595	Prohibits disposal of solar equipment, including solar panels, in landfills and dumps as electronic waste. Purchased panels will incur a $125 fee, $25 for tracking and $100 for recycling. Decommissioned panels must be recycled at a site designated by the Department of Environmental Protection. Any property harboring solar panels

		must retain insurance that covers the cost of recycling should a catastrophe make it necessary.
Montana	Senate Bill 93	Requires that new commercial solar facilities capable of producing more than two megawatts of energy submit a decommissioning plan and security bond within 12 months of beginning operations. Existing facilities must produce decommissioning plans and security bonds for retroactive application. Allows the Department of Environmental Quality to seize bonds and commence decommissioning on abandoned facilities and directs resources to a pre-existing wind and solar decommissioning account
New Jersey	Senate Bill 601	Establishes the New Jersey Solar Panel Recycling Commission to develop strategies that could be implemented by the executive, legislative or private sector to manage end-of-life solar panel recycling and produce a public report. Authorizes the state Department of Environmental Protection to utilize its authority under the Administrative Procedures Act to set rules and regulations regarding end-of-life solar panel care.

Ohio	Senate Bill 52	Requires that “large solar facilities” submit an engineer-approved decommissioning plan of less than 12 months duration for disposing of solar panel equipment and restoring land prior to constructing the facility. Plans must be updated every five years and applicants for large solar facilities must post a performance bond to ensure they will be able to fund the decommissioning of their facility.
South Carolina	House Bill 525	Directs the South Carolina Department of Health and Environmental Control to develop guidelines on decommissioning standards for photovoltaic modules and energy storage system batteries for solar farms exceeding 13 acres; new solar farms over 13 acres must submit end-of-life plans for technology.
Tennessee	Senate Bill 2797	Directs the Tennessee Advisory Commission on Intergovernmental Relations to oversee a study on the viability of large-scale solar development in the state. The study must include information on federal regulation of solar equipment decommissioning, a survey of state statutory

		regulations and an examination of owner and operator financial obligations in solar panel decommissioning.
Virginia	Senate Bill 499	Establishes a task force involving the Virginia State Corporation Commission, Department of Energy and Department of Environmental Quality to analyze best practices for end-of-life care of solar panels, including liability for decommissioning costs and feasibility of recycling projects.
West Virginia	Senate Bill 492	Requires that commercial solar facilities capable of producing one megawatt of energy submit a bond sufficient to decommission solar panels and related equipment should the equipment be abandoned. Establishes a fee of $100 per new application and $50 per application modification to be paid to a pre-existing wind and solar decommissioning account. Allows the Department of Environmental Protection to seize bonds from abandoned solar facilities and establish necessary regulations.

Certain bills (Senate Bill 52 and Senate Bill 93) require that solar panel decommissioning plans must be created within a set time frame whether prior or within several months of construction and installation. Others legislation require more studies to be conducted for best management practices for decommissioning. Even though states have various legislation policies and goals, all are in favor of end-of-life management of solar panels.

1.5 Purpose

This study is crucial in sustainably expanding solar capacity in the United States. Understanding the relationships between policies, technologies, financial and environmental aspects and solar panel recycling will allow for the solar industry to grow in a circular economy.

1.6 Motivation and Structure

With previous and future experiences in solar and growing conversations surrounding solar panel recycling, this study demonstrates the feasibility and the constraints of this potential industry. The structure of this study incorporated a literature review on a solar photovoltaic (PV) module, supply chain of solar panels, an overview for levelized cost of electricity, battery energy storage systems, and an economic review of the costs associated with constructing and maintaining solar farms, where solar panel recycling would add additional factors. The third section provided the methodology of economic calculations completed via excel sheets. The results section organized the levelized cost of electricity data (LCOE) and its variations dependent on original and new factors. The final section of this study discussed the results, potential and constraints of this industry, and concluding remarks going forward.

CHAPTER 2

LITERATURE REVIEW

2.0 Research Objective

The primary objective of this study was to identify the feasibility of recycling solar panels in the United States by identifying factors that would affect the levelized cost of electricity ($/kWhr). The second objective was to identify the supply chain of solar panels and investigate the potential for a circular economy with the addition of solar panel recycling.

2.1 Utility-Scale Solar

A solar farm is considered utility-scale if it has at least 1 MW of electricity–generation capacity [11]. There are two primary types that are used, which are solar photovoltaic (PV) panels and concentrated solar power (CSP), but solar PV was the focus for this study.

2.1.1 Solar PV

Solar PV panels convert energy from the sun called photons into direct current (DC) electricity [12]. A PV cell is made up of glass, n-type layer, junction, and p-type layer as shown in Figure 6 [12].

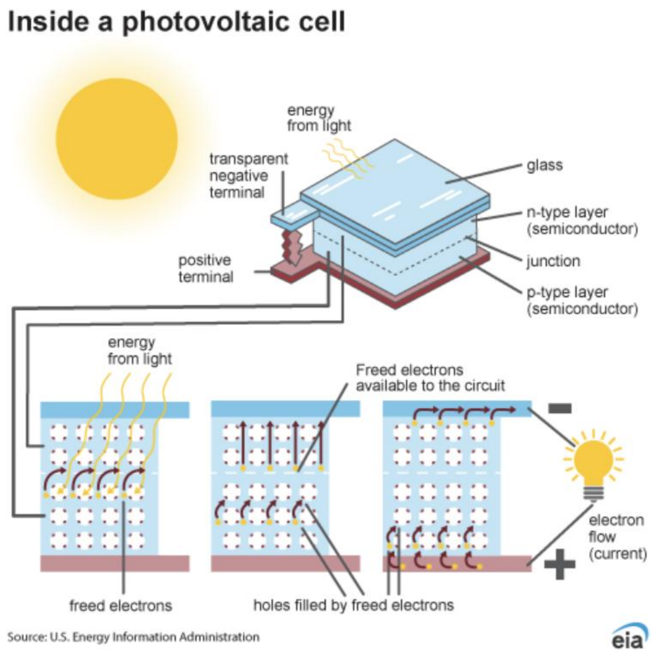


Figure 6: Solar PV cell Composition and Function [12].

The n-type layer is made up of silicon with excess electrons due to the presence of another atom that has an additional electron in the outer level such as phosphorus [13]. Thus, there is a roaming electron. In the p-type silicon layer, there are holes created due to the pairing of an atom with one less electron in the outer energy level such as boron or gallium [13]. Therefore, when a photon is absorbed, there are excited electrons that move into the holes between the n-type and p-type layer where positive ions and negative ions create an electric field inside, generating electricity when connected to a metallic wire [13]. This is the utilized technology for this study.

2.2 Solar Panel Supply Chain

In the current state, supply chain on a global scale is required for solar panel production. This is due to the limited number of raw materials harvesting locations and the need for production processes for assembly. Figure 7 below shows a broad overview of the supply chain for solar panels. Recycling is a section of the supply chain that is potentially added to create a circular economy for this industry.

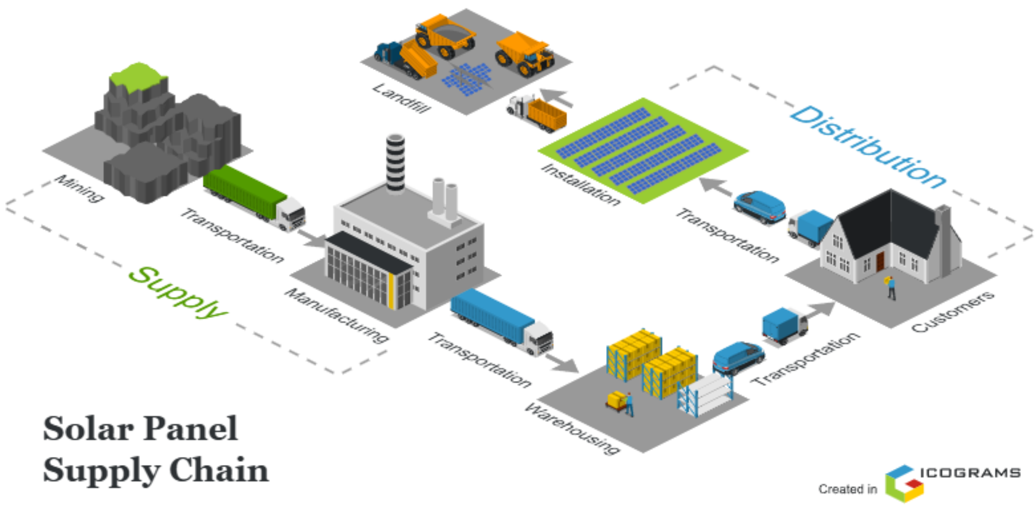


Figure 7: Solar Panel Supply Chain.

A circular economy aids with the issue of climate change, as it takes the materials that have been used and utilizes it for the same product, or for other products for as long as possible [14]. It is often tied to terms such as reduce, redesign, and recycle, since it is not just the recycling aspect that makes a circular economy but improved components in all aspects to minimize the effects and use of the materials. The figure below shows the connected cycle through the recycling facility.

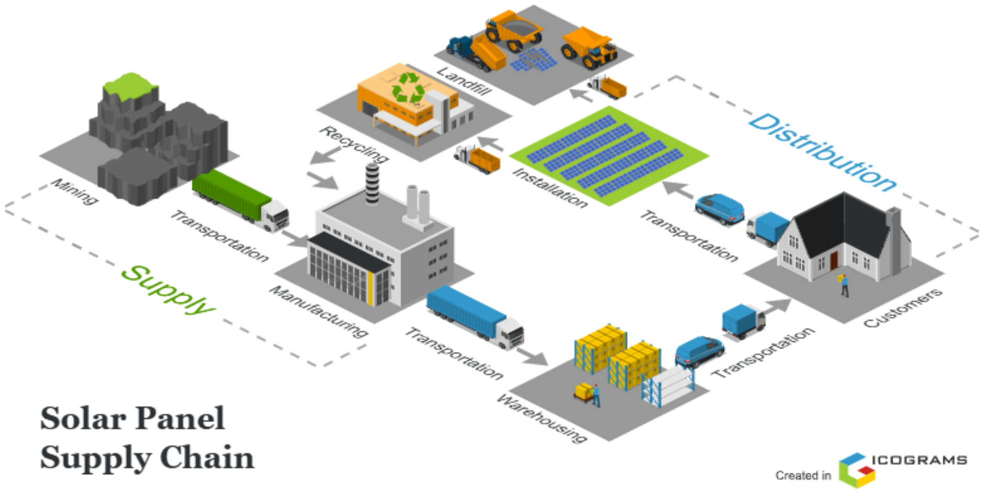


Figure 8: Solar Panel Supply Chain with Recycling.

Going into the specifics of a solar PV module, a base outline of a solar PV supply chain is displayed in Figure 9. The focus of this supply chain will be on crystalline silicon (c-Si) PV modules but may overlap with cadmium telluride, which is another type of PV technology. Though there are mounting and inverters in the supply chain, an analysis was done from polysilicon to module since the other costs would be addressed further in the study.

Figure 9: Solar PV Supply Chain [15].

2.2.1 Solar PV Supply Chain Process: How c-Si Modules are Made

High-grade quartz is used to produce a material called metallurgical-grade silicon (MGS) or silicon metal [15]. MGS is the input for polysilicon, and it is melted to grow monocrystalline silicon ingots that would be sliced into thin wafer cells [15]. The wafers are processed to make the cells that are layered appropriately to make c-Si modules [15].

2.2.2 Solar PV Manufacturing

China has an overwhelming manufacturing capacity compared to the rest of the world. It exceeds 80 percent in its share in all the manufacturing stages from polysilicon to modules [16]. This is represented in Figure 10.

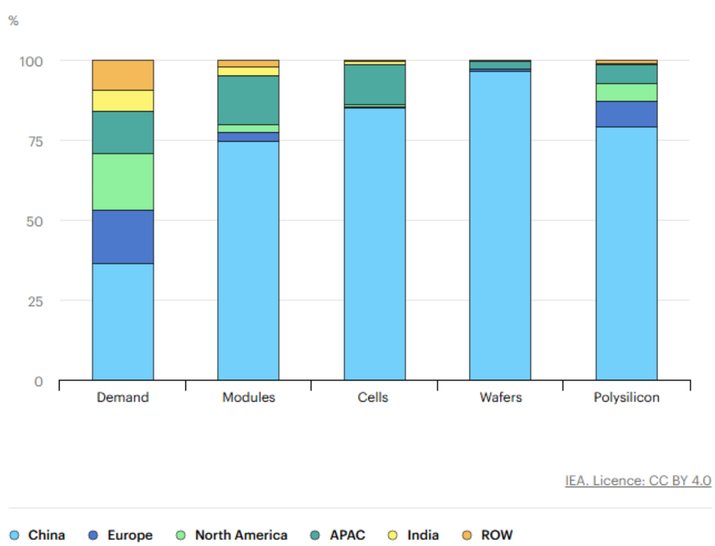


Figure 10: Solar PV Manufacturing Capacity by Country and Region 2021 [16].

The United States continues to rely heavily on imports from Chinese subsidiaries and other countries but has made significant progress in growing domestic manufacturing capacity for polysilicon, c-Si wafer, c-Si cells, PV modules, and more as expressed in Figure 11.

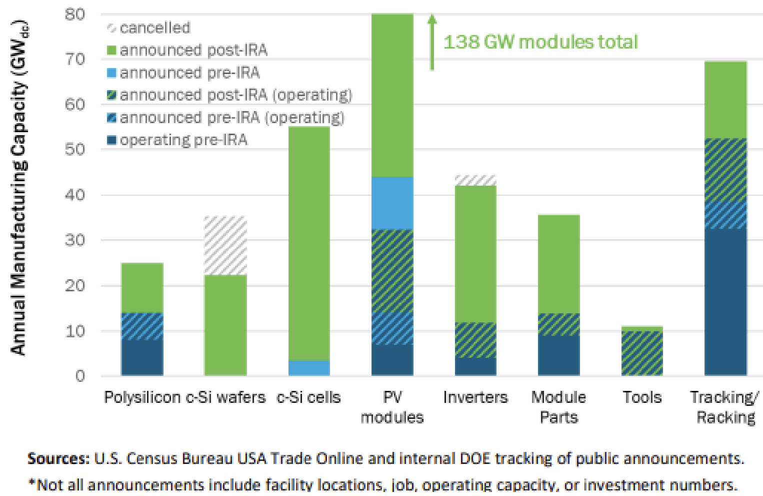


Figure 11: Current Manufacturing Announcements by Supply Chain Segment [17].

It was due in part to the tax credit benefits from the Inflation Reduction Act (IRA) for manufacturing in the solar industry. In terms of production, the United States only produces c-Si modules and thin-film modules [17]. It is significantly cheaper to manufacture components of the module in China compared to the United States and to purchase them from Chinese subsidiaries rather than domestically. However, this can pose a future risk due to geopolitics and trade. If domestic supply chains continue to grow, costs may decrease due to lower transportation costs along with continued tax credits.

2.3 Landfills and Solar PV Recycling Costs

A solar PV module is deemed at its end-of-life (EOL) when it falls below 20 percent of its original capacity [17]. When comparing the landfill to recycling costs for solar PV, it is much cheaper to place them in landfills, which is often done. The landfill fee is around $1 to $5 per module, whereas it is $15 to $45 per module for recycling without accounting for transportation costs [17]. In $/ton for landfilling, it ranges between \$30/ton to \$70/ton [17]. There is a third option for solar PV modules, which is to reuse them by selling them to customers interested in pre-owned modules; however, it is a very small market [17]. This is because the panels will perform at a lower efficiency, and the warranty may have expired for the module by the time it is deemed it is end-of-life. There may be some PV modules that may have extended warranties for the next owner [18].

2.4 Chemical, Physical, and Thermal Processes for Solar PV Recycling

With current technology for solar PV recycling, 95 percent can be recycled, and 99 percent is non-hazardous [18]. There are three processes for solar PV recycling, which include chemical, physical, and thermal as shown in Table 3.

Table 3: Physical, Chemical and Thermal Process Comparison for PV Modules [19].

Process	Physical process	Chemical process	Thermal process
Techniques	Comminution, shockwaves, sonication, electrostatic separation, wire saw,hot knife device, mechanical grinding of wafer	Organic solvents dissolution of polymers, acid and base leaching of metals, electrowinning, effluent treatment	Pyrolysis, Laser rays, hot knife, wire saw, microwave, melting and casting
Advantages	Time and cost saving Handle huge waste on industrial scale Easy process and machineries No use of Chemicals Expertise not required to operate	Metals recovery from wafer surface Availability of numerous leaching reagents and their combinations Well established leaching process Numerous organic solvents availability for EVA removal	Quick and clean recovery of materials Intact silicon wafer recovery Traces of polymers after physical and chemical process can be removed For delamination of Tedlar layer
Disadvantage	High emissions and energy consumption Contamination of recycle materials Not suitable for toxic element treatment Recovered down cycling materials	Decreasing of silicon wafer thickness Required hazardous chemicals Time taking process compared Effluent generation Emission of toxic gases and fumes Need expertise and arrangement	Energy intensive Loss of materials due to thermal degradation Generate huge amount of hazardous emission and increase CO_2 emission Oxidation and defects generation in materials
Recent progress	Optical separation, density separation Multistage crushing and milling for delamination Vacuum refining	Solvothermal swelling added with thermal decomposition Simulation studies for high recovery and purity.	Laser irradiation followed by mechanical peeling Optimization of time with respect to temperature of pyrolysis
Scope of improvement	Automation of process to minimize human interaction Minimize material loss and emission Improvement in material selectivity	Categorized organic solvents on the bases of cost and toxicity Effluent treatment process and recycling of effluent Minimize chemical use by combination with thermal and physical process	Treatment process for emission gases Use of polymer combustion energy Optimized process with respect to time and temperature

Depending on whether the module is silicon or CdTe thin film, there are different components that require to be removed and separated as shown in Figure 12.

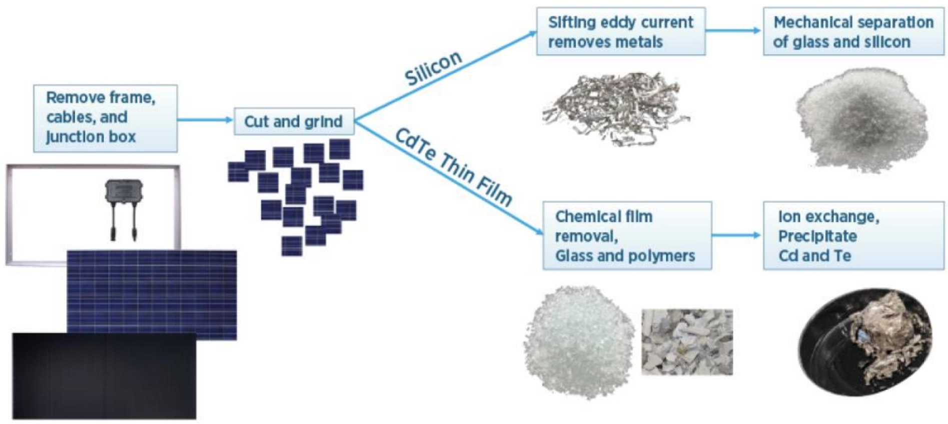


Figure 12: Commercial Module Recycling Process [20].

Focusing on technologies for recovering silicon from crystalline silicon PV modules, it includes chemical treatment, centrifugation separation, phase-transfer separation, two-step heating processes, and electrostatic separation [21]. Chemical treatment has shown to be the most effective with 90 percent pure silicon recovery rate compared to the other technologies analyzed as shown in Table 4.

Table 4: PV Cell Recycling Technologies According to the Purity of Silicon [21].

Refs.	Technologies	Year	Purity of Si (%)
[11]	Centrifugation separation	2010	74.1%
[12]	Phase-transfer separation	2010	71.1%
[13]	A heating procedure involves both acidic and alkaline treatments	2016	62%
[14]	Chemical treatment	2022	90%
[21]	Electrostatic separation	2023	48.9%

In the chemical treatment process, silicon wafers are removed from decommissioned PV cells, and any surrounding materials on the wafers are removed [21]. Various chemical processes are conducted to isolate the pure silicon through acidic solutions or other specialized chemicals [21]. Once the silicon is separated, it goes through a process called milling where it is mechanically crushed into small particles to result in pure silicon powder [21]. Other procedures may be conducted to ensure a high-level purity of silicon powder [21]. Figure 13 displays the recycling process of silicon from a PV module.

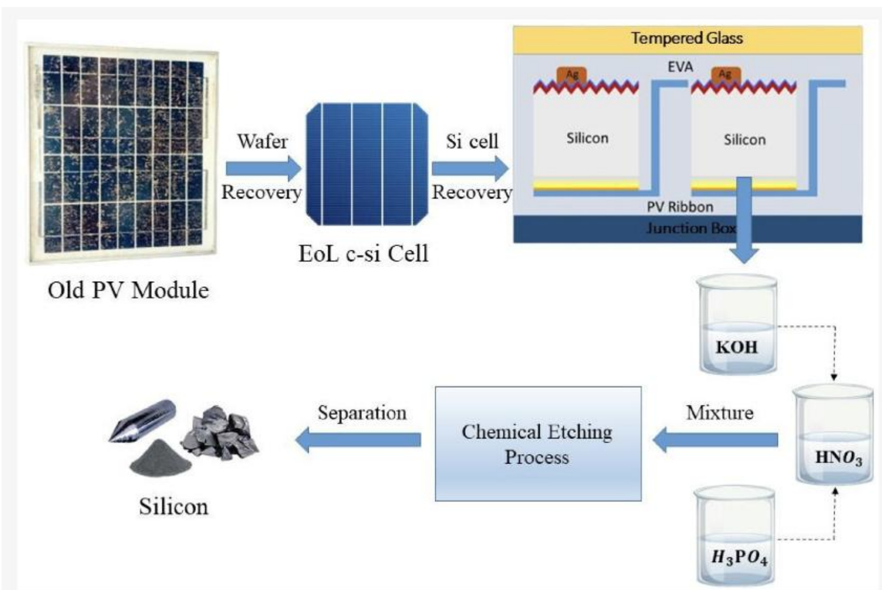


Figure 13: Crystalline Si Cell Recycling Process (Chemical Base) [19].

2.5 Levelized Cost of Electricity (LCOE)

Levelized cost of electricity is an economic value in price per unit of energy ($/kWhr, $/MWhr, etc.) that is used to analyze the cost-competitiveness of a power-producing system and aid in decision-making for development of the system itself. Three key purposes of LCOE are listed below:

1. "Measures lifetime costs divided by energy production
2. Calculates present value of the total cost of building and operating a power plant over an assumed lifetime
3. Allows the comparison of different technologies (e.g., wind, solar, natural gas) of unequal life spans, project size, different capital cost, risk, return, and capacities [22]."

LCOE incorporates capital costs, operation and maintenance costs, annual electricity generation, discount rate, and the lifespan of a system. Fuel costs are exempt, since solar plants do not need fuel to generate electricity. It is important to note that LCOE does not account for all factors including policy changes and considerations to ensure system reliability, and it only accounts for the cost to build and operate a plant [23].

2.5.1 Average LCOE in the United States without Tax Credits

From 2010-2023, the average LCOE decreased 80 percent due to technological advancements such as making solar panels more efficient, competitive growth in the solar industry, lower capital costs, lower operation and maintenance costs, and incentives and policies from the government [24]. Figure 14 displays the levelized cost of solar energy (LCOE) trend for utility-scale solar PV without the tax credit benefits and battery storage.

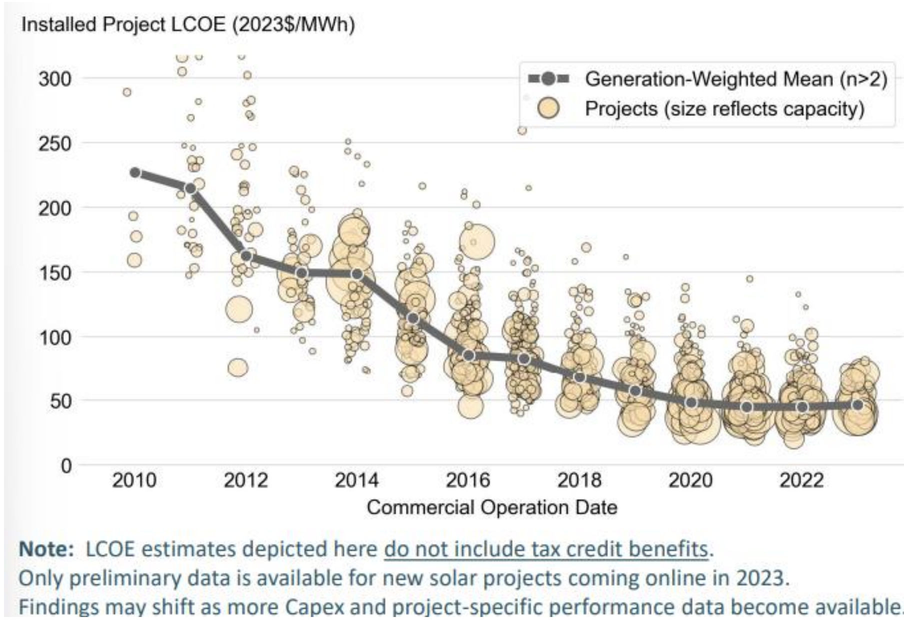


Figure 14: LCOE Trend for Utility-Scale Solar PV [24].

This is based on a sample size project totaling 66.3 GW_{AC} across the U.S where the LCOE averaged $45/MWh in 2022 and $46/MWh in 2023, but it is significantly lower than in 2010 where it was over $200/MWh [24].

There are also capacity-weighted average LCOE costs displayed for 10 regions per year. Figure 15 shows the costs depending on the year, and some are not displayed due to data collection limitations for 2023. Though there are three major grid regions (Eastern Interconnection, Western Interconnection, and Texas Interconnected system) as stated by the EPA, the Berkeley Laboratory does its analysis with more detailed region designations based on the operating company for interconnection or transmission organization for electricity management (independent system operator or ISO), or no independent system operator [25].

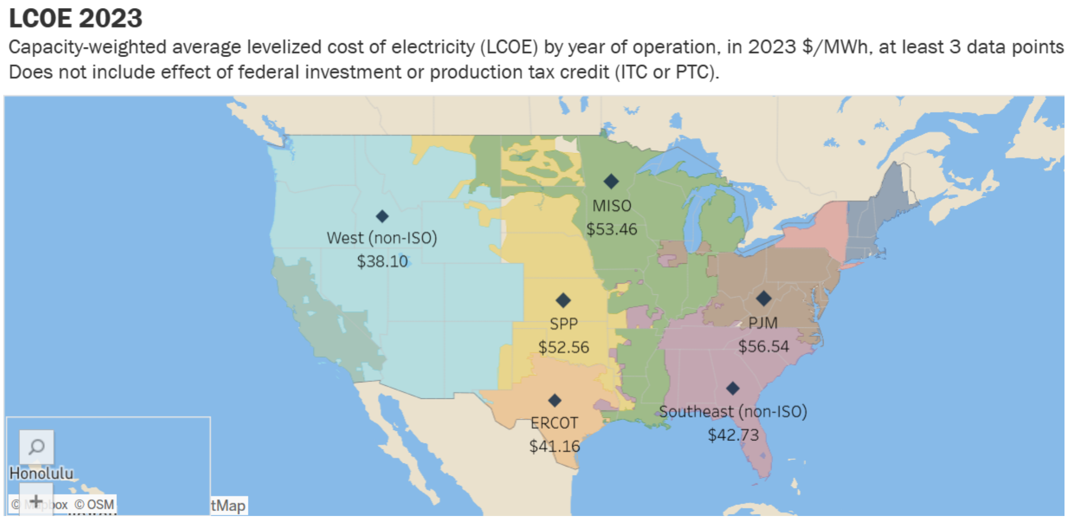


Figure 15: Capacity-Weighted Average LCOE 2023 [25].

The nine regions include CAISO, ERCOT, ISO-NE, MISO, NYISO, PJM, Southeast (non-ISO), SPP, and West (non-ISO). The West (non-ISO) region is lower in price compared to the eastern region such as PJM due to its value affected by the type of technology of fixed or tracking solar, solar resource quality, and transmission congestion [24].

2.5.2 Average LCOE in the United States with Tax Credits

For solar LCOE averages in the United States with tax credits, there are two main ones that are accounted for which are the Production Tax Credit (PTC) and the Investment Tax Credit (ITC). Furthermore, there is a specific contract that affects the LCOE costs called Power Purchase Agreements (PPA), especially for utility-scale projects.

Since the PTC is a federal tax incentive, it allows for a credit per kWh of electricity generated and is available for ten years after it is in service [26]. This is ideal for different regions based on various conditions. For example, in the West (non-ISO) region, it may be better to go with PTC because the utility-scale project would be in very sunny areas that would produce a lot of electricity and may be eligible for bonus tax credit (Domestic Content Bonus and Energy Community Bonus) [26]. However, the cost of the project is important to consider too.

ITC is also a federal tax incentive that is ideal for projects with high initial costs, a location with less sun, and bonus tax credits (Domestic Content Bonus and Energy Community Bonus) [26]. A few of the expenses that qualify for this incentive include solar PV panels, installation costs, energy storage equipment, and more [26]. The ITC percentage that contributed towards a project is set to lower in the future, which is shown in Figure 16.

Summary of Investment Tax Credit (ITC) and Production Tax Credit (PTC) Values Over Time

			Start of Construction						
			2006 to 2019	2020 to 2021	2022	2023 to 2033	The later of 2034 (or two years after applicable year[a])	The later of 2035 (or three years after applicable year[a])	The later of 2036 (or four years after applicable year[a])
ITC	Full rate (if project meets labor requirements[b])	Base Credit	30%	26%	30%	30%	22.5%	15%	0%
		Domestic Content Bonus				10%	7.5%	5%	0%
		Energy Community Bonus				10%	7.5%	5%	0%
	Base rate (if project does not meet labor requirements[b])	Base Credit	30%	26%	6%	6%	4.5%	3%	0%
		Domestic Content Bonus				2%	1.5%	1%	0%
		Energy Community Bonus				2%	1.5%	1%	0%
	Low-income bonus (1.8 GW/yr cap)	<5 MW projects in LMI communities or Indian land				10%	10%	10%	10%
		Qualified low-income residential building project/Qualified low-income economic benefit project				20%	20%	20%	20%
PTC for 10 years ($2022)	Full rate (if project meets labor requirements[b])	Base Credit			2.75 ¢	2.75 ¢	2.0 ¢	1.3 ¢	0.0 ¢
		Domestic Content Bonus				0.3 ¢	0.2 ¢	0.1 ¢	0.0 ¢
		Energy Community Bonus				0.3 ¢	0.2 ¢	0.1 ¢	0.0 ¢
	Base rate (if project does not meet labor requirements[b])	Base Credit			.55 ¢	0.55 ¢	0.4 ¢	0.3 ¢	0.0 ¢
		Domestic Content Bonus				0.1 ¢	0.0 ¢	0.0 ¢	0.0 ¢
		Energy Community Bonus				0.1 ¢	0.0 ¢	.01 ¢	0.0 ¢

a "Applicable year" is defined as the later of (i) 2032 or (ii) the year the Treasury Secretary determines that there has been a 75% or more reduction in annual greenhouse gas emissions from the production of electricity in the United States as compared to the calendar year 2022.

b "Labor requirements" entail certain prevailing wage and apprenticeship conditions being met.

Figure 16: Summary of ITC and PTC Values Over Time [26].

For both the PTC and the ITC, there are different rates for credit prices and percentages which are dependent on the project qualifications.

PPAs for utility-scale projects often involve a developer and a consumer, which can be a large consumer or the utility-grid [27]. This type of agreement is entered into due to the accountability that falls on the developer rather than the utility-grid for the solar farm installation, operation and maintenance, and financing. Furthermore, there is a negotiated set price for electricity to negate concerns for the fluctuating market over a set period and is often lower than the cost of electricity from other sources [27]. The developer benefits from the ability to save further from any tax credits and income once the threshold is met [27].

Figure 17 shows LCOE and levelized PPA price for a sample size of 1,266 projects totaling 66.3 GW_{AC}. From the graph, the levelized PPA price followed the trend of both LCOE trends with and without tax credits depending on the timeline. From 2010-2016, LCOE without tax credits was followed, and from 2016-2023, LCOE with tax credits was more closely followed and even fell below the line in more recent years.

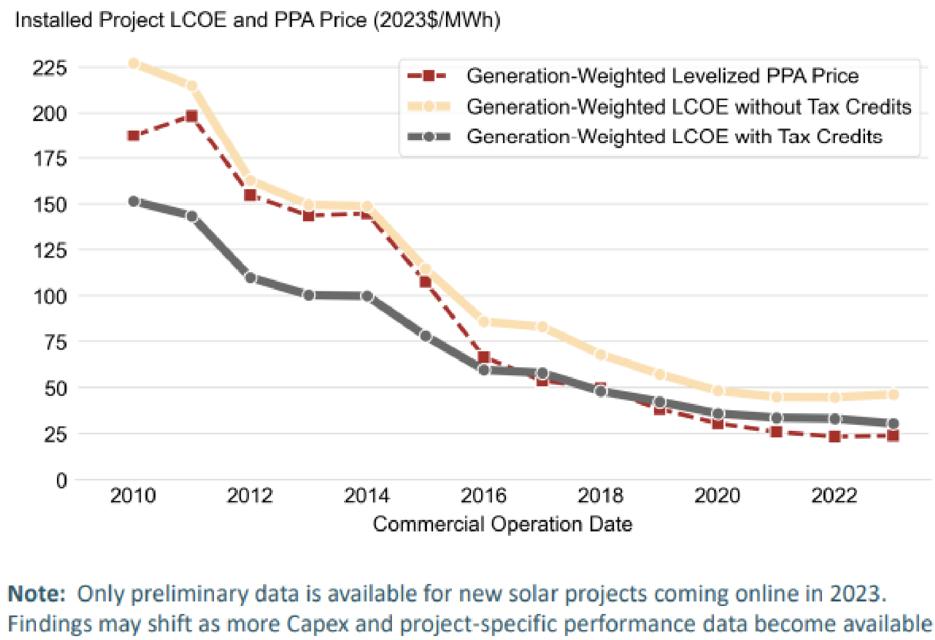


Figure 17: LCOE and PPA Price Trend from 2010-2023 [24].

It is important to consider that the PPA prices can be beneficial or harmful in terms of profitability. If the PPA price is higher than the LCOE, profit can be generated. If the PPA price is lower than the LCOE, it is unprofitable. Finally, if it is the same as LCOE, it is likely that the project would break even and is not profitable [28]. Comparing and contrasting PPA prices to LCOE allows for reasonable calculations for budgeting, cost transparency, etc.

2.6 Economics for Solar

As there are many costs that can be excluded or included in LCOE calculations, the relevant variables were addressed for the purpose of this study. They were summarized in three categories: capital costs, operational expenses (OpEx), and incentives and savings. These costs were further broken down in the 'methodology' section of this study.

2.6.1 Capital Costs

Capital costs include all the fees that are needed to construct a system. The costs "to engineer, procure, construct, and commission all equipment within the plant facility fence line, as well as interconnections to electrical transmission and fuel distribution networks, as applicable" fall within these costs [29].

These costs can be placed in categories including:

- Module
- Inverter
- Energy storage system (ESS)
- Structural balance of system components (SBOS)
- Electrical balance of system (EBOS)
- Fieldwork
- Officework
- Other [30].

The categories listed above are known as hardware costs for the first five and soft costs for the last three, and each category has fixed and variable costs that depend on the scale of the project and what is needed [30].

2.6.1.1 Solar PV Panels

Solar PV panels have variability due to the type, lifespan, efficiency, and degradation rates. Utility-scale solar PV panels were said to have a lifespan of 25 to 30 years, but it is closer to 30 years now [31]. The efficiency of solar modules ranges from 7-22 percent depending on whether they are monocrystalline, polycrystalline, and thin-film as found in the 'background' of this study. However, thin-film can be excluded as this study focuses on solar PV, changing the range to 15-22 percent. Degradation of solar modules is 0.5-1 percent each year [31].

2.6.1.2 Energy Storage Systems (ESS)

Energy storage systems serve as support for power grids by using electricity or another source to charge the system and are discharged to generate electricity when needed [32]. The power capacity is given in kW, MW, or GW, and an energy capacity is given in kWh, MWh, or GWh [32]. Additional information is usually given such as the number of hours (storage duration), which indicates how long the storage can be discharged before the energy is depleted and needs to charge [32]. The energy capacity is "the total amount of energy that can be stored in or discharged from the storage system" [32]. They are either stand-alone, co-located or paired with other power generating plants to improve efficiency, reliability, and stability [32].

There are five types of ESSs:

- Pumped-storage hydroelectric
- Batteries (electro-chemical)
- Solar electric with thermal energy storage
- Compressed-air storage
- Flywheels [32].

ESSs are often paired with a renewable energy power plant, which are mostly battery energy storage systems (BESS). They are paired to reduce curtailment from renewable energy plants. Curtailment occurs when a renewable energy plant produces more than the grid can handle, there is not enough demand, or there is grid congestion, so the electricity is wasted.

There are different types of BESS including:

- Lithium-ion
- Lead-acid
- Flow [33].
- Sodium
- Nickel-based [34].

Utility-scale lithium-ion batteries are mainly used in the United States due to high-cycle efficiency, fast response times, and high energy density [32]. Furthermore, the round-trip efficiency of batteries averages 82 percent [35]. This meant that, of the electricity that is stored in the BESS, 82 percent could be retrieved when needed.

2.6.2 Operational Expenses

OpEx consists of costs that are needed for everyday performance of a system. It encompasses several categories as listed:

- Operation and maintenance (O&M)
- Land lease
- Security
- Insurance
- Asset management [36].

These are just a few of the many other costs that may be included in cost calculations; however, it is dependent on the study that is conducted to account for any or all variables.

2.6.3 Incentives and Savings

Incentives and savings costs consist of any federal, state, and regional tax incentives that may contribute to a decrease in total solar farm costs. There may be other factors that may incur savings costs too such as credits.

CHAPTER 3

METHODOLOGY

3.0 Overview

Two regions of the United States were studied: Pennsylvania-New Jersey-Maryland (PJM) and California Independent System Operator (CAISO). Within each region, a state(s) was selected for calculations: Maryland, Virginia and California. These ISO regions were selected to minimize variability, as an analysis between two non-ISO regions would include more variability and may be more difficult in gathering necessary data.

It was assumed that the solar farm size was 150 MW_{AC} with single-axis tracking for all systems even when paired with an ESS. The solar farm assumed 500-W, 1500-V monocrystalline, bifacial solar modules [39]. They were also ground-mounted. The ESS was assumed to be a 200 MWh lithium-ion battery storage that was AC-coupled [39]. It was assumed that the lithium-ion battery was lithium iron phosphate (LFP) based on the size of the solar farm and commonality of its use currently.

All the calculations were completed on an excel spreadsheet.

3.1 Annual Generation

Annual generation (MWh) was calculated by multiplying the capacity of the solar farm (MW), the annual capacity factor (ACF), and the hours equivalent to one year. The ACF was sourced from US Energy Information Administration by region from 2023 [40]. Solar panels' generation decreased each year due to degradation, so an assumed average degradation rate of 0.5 percent was applied to another table for final calculations [45]. The annual generation was calculated for a solar PV farm.

Equation 1: Annual Generation

$$Annual\ Generation = Capacity*ACF*8760$$

Table 5: Annual Generation for States in PJM and CAISO Region with Solar PV Only.

State	ACF	Capacity (MW)	Hours	Annual Generation (MWh)
Maryland	0.194	150	8,760	254,916
Virginia	0.203	150	8,760	266,742
California	0.256	150	8,760	336,384

Equation 2: Total Generation

$$Total\ Generation = Annual\ Generation*[(1\text{-}r)^n / (1\text{-}r)]$$

r = degradation rate

n = lifetime of plant in years

Table 6: Total Generation Accounting for Degradation with Solar PV Only.

State	Initial Generation (MWh)	$(1\text{-}r)^n$	(1-r)	$(1\text{-}r)^n/(1\text{-}r)$	Total Generation (MWh)
Maryland	254,916	0.8604	0.995	0.8647	220,427
Virginia	266,742	0.8604	0.995	0.8647	230,653
California	336,384	0.8604	0.995	0.8647	290,873

For battery energy storage systems, it was assumed that the round-trip efficiency (RTE) was 82 percent [35]. This was used to calculate the energy loss in MWh/yr. The annual discharge was calculated by multiplying the capacity of the BESS by the number of days in a year, which was 365.

Equation 3: Annual Discharge

$$Annual\ Discharge = Capacity_{BESS}*365$$

Equation 4: Storage after RTE

$$Storage\ after\ RTE = Annual\ Discharge*RTE$$

$RTE = 0.82$

The energy loss (MWh/yr) of the BESS was calculated by subtracting the Storage after RTE from the Annual Discharge.

Equation 5: Energy Loss

$$Energy\ Loss = Annual\ Discharge - Storage\ after\ RTE$$

Table 7: Electricity Lost from BESS.

State	Capacity (MWh)	Annual Discharge (MWh/yr)	Storage after RTE (MWh/yr)	Energy Loss (MWh/yr)
Maryland	200	73,000	59,860	13,140
Virginia	200	73,000	59,860	13,140
California	200	73,000	59,860	13,140

Table 8: Total Generation for BESS Only.

State	ACF	Capacity (MW)	Hours	Annual Generation (MWh)	Total Generation (MWh)
Maryland	0.194	150	8,760	254,916	241,776
Virginia	0.203	150	8,760	266,742	253,602
California	0.256	150	8,760	336,384	323,244

The adjusted generation for solar PV with BESS needed to be calculated for another scenario for LCOE comparison. It was calculated using the equation below. The values used for Equation 6 were from Table 6 and Table 7.

Equation 6: Adjusted Generation

$$\textit{Adjusted Generation} = \textit{Total Generation}_{PV} - \textit{Energy Loss}$$

Table 9: Adjusted Generation for PV+BESS.

State	Adjusted Generation (MWh)
Maryland	207,287
Virginia	217,513
California	277,733

3.1.1 Capacity

The capacity of a solar farm is the maximum amount of electricity that can be generated; it does not operate at max capacity realistically due to underlying conditions that cannot be controlled such as weather, amount of sun, failures, and efficiencies of the modules. As this applied to solar PV panels, the values were calculated in either AC or

DC but were specified as needed. The capacity used was 150 MW_{AC}, since the values used from EIA were based on that system size [39].

3.1.2 Annual Capacity Factor

The annual capacity factor was not calculated but sourced from EIA. The capacity factor in Maryland was 0.194, Virginia was 0.203 and 0.256 in California in 2023 for utility-scale solar PV [40].

3.1.3 Hours

As annual generation was calculated over a year, 8,760 hours were utilized.

3.1.4 Lifespan of Utility-Scale Solar Farm

The decided lifespan of a utility-scale solar farm was between 25-30 years, and 30 years was assumed for calculations.

3.2 Capital Cost

The capital cost or overnight cost was pulled from the United States Energy Information Administration (EIA) for 2023. The solar farms were either solar PV with tracking or solar PV with storage. The values were based on a solar farm with a capacity of 150 MW_{AC} [41]. The values for the total overnight cost ($/$kW_{AC}$) differed depending on the region. Based on the selected states, the total overnight capital costs were found without investment tax credits. The selected electricity market module regions were 13 PJMD, 11 PJMW, and 21CANO as shown below.

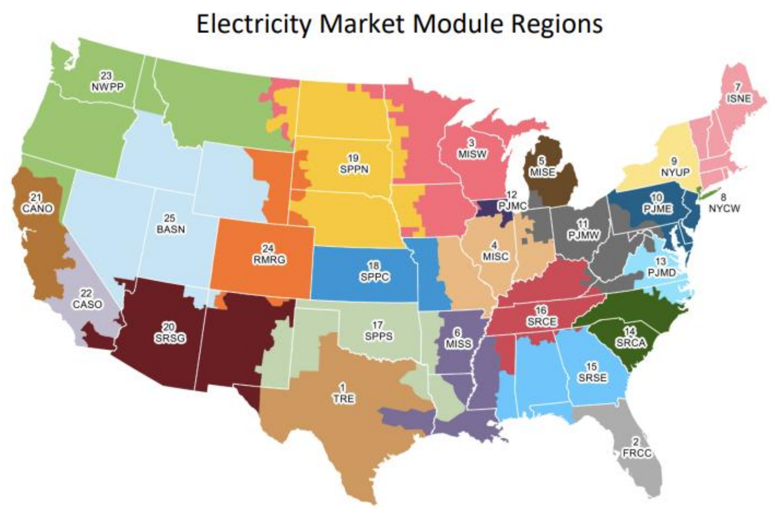


Figure 18: Electricity Market Module Regions [44].

The capital cost was multiplied by the capacity to get the principal cost for each state. The interest rate varied for 3, 5, 7, and 10 percent scenarios. The annual capital cost was found using the equation below.

Equation 7: Annual Capital Cost

$$Annual\ Capital\ Cost = (P*i*(1+i)^n) / ((1+i)^n - 1)$$

n = lifespan

P = principal cost

i = interest rate

It was assumed that the total overnight costs for the regions would apply to the states selected for the study [41].

Table 10: Total Overnight Capital Costs by Region/State (2022$/$kW_{AC}$).

Region	Solar PV with Tracking	Solar PV with Storage
13 PJMD / MD	1,436	1,842
11 PJMW / VA	1,440	1,780
21 CANO / CA	1,579	1,969

Table 11: Annual Capital Cost (2022$) Solar PV Only.

State	Principal Cost	$(1+i)^n$	$((1+i)^n)-1$	$P*i*((1+i)^n)$	Annual Capital Cost
Maryland	215,400,000	4.32	3.32	46,547,319	14,012,079
Virginia	216,000,000	4.32	3.32	46,676,977	14,051,109
California	236,850,000	4.32	3.32	51,182,602	15,407,432

Table 12: Annual Capital Cost (2022$) Solar PV + BESS.

State	Principal Cost	$(1+i)^n$	$((1+i)^n)-1$	$P*i*((1+i)^n)$	Annual Capital Cost
Maryland	276,300,000	4.32	3.32	59,707,633	17,973,711
Virginia	267,000,000	4.32	3.32	57,697,930	17,368,733
California	295,350,000	4.32	3.32	63,824,284	19,212,941

In both Tables 11 and 12, they were calculated with a 5 percent interest rate for the values shown. In the excel sheet, the interest rate could be changed so that it would reflect the values for the targeted interest rates.

3.3 Operation and Maintenance Cost

For O&M costs, there were no variable costs because solar farms did not need fuel. Fixed O&M costs were used from EIA [41]. They were assumed to be the same for all three states analyzed.

Table 13: Fixed O&M Costs for Solar PV with and without Storage (2022$/kWy$_{AC}$).

Solar PV with Tracking ($/kW$_{AC}$)	**Solar PV with Storage ($/kW$_{AC}$)**
17.16	32.42

The O&M costs were found by multiplying the value in Table 13 with the capacity of the plant. This was done for both solar PV only and solar PV with storage.

Table 14: O&M Cost ($) PV Only.

State	**Annual O&M**
Maryland	2,574,000
Virginia	2,574,000
California	2,574,000

Table 15: O&M Cost ($) PV + BESS.

State	**Annual O&M**
Maryland	4,863,000
Virginia	4,863,000
California	4,863,000

3.4 Total Revenue

The PPA price was found by looking at LevelTen's energy PPA price index report for Q1 2023. The market-averaged continental index price was $49.52/MWh [43]. Since PPA values for each region were not listed specifically but provided on a graph, it was roughly estimated values that were used. The values were $66/MWh for PJM and $42/MWh for CAISO [43]. It should be noted that the report presented the PPA prices based on the most competitive 25th percentile offer price [43]. The graph was provided below for reference.

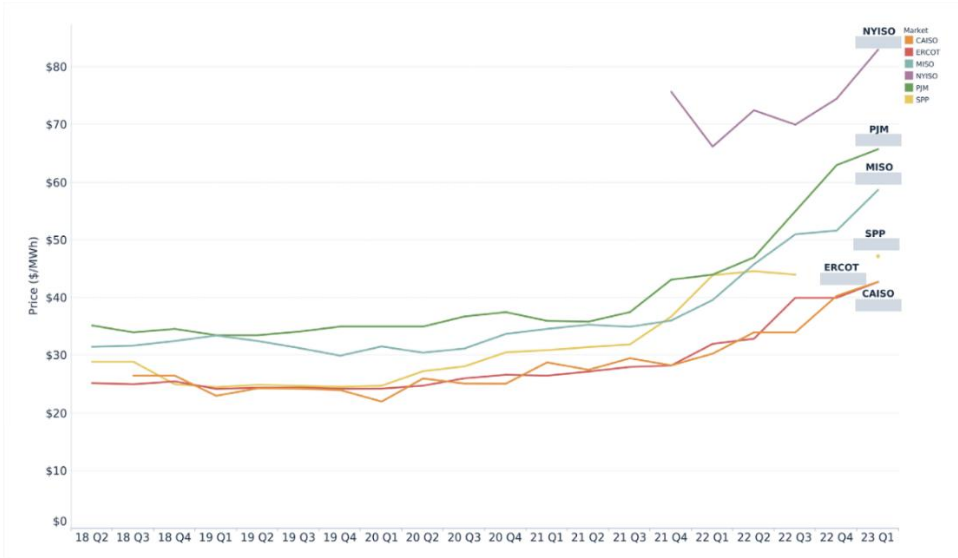


Figure 19: Solar P25 PPA Price Indices by ISO from Q2 2018 – Q1 2023 [43].

The assumption for the PPA was that it was fixed, so there would not be variations for the contract limit. The total revenue ($) was found by multiplying total generation and the PPA price for each state for solar PV and solar PV with BESS.

Table 16: Total Revenue ($) for Solar PV Only.

State	Total Generation (MWh)	PPA Price ($/MWh)	Total Revenue ($)
Maryland	220,428	66	14,548,237
Virginia	230,654	66	15,223,155
California	290,874	42	12,216,702

The total revenue ($) for solar PV with BESS was calculated by using adjusted generation from Table 9 and multiplying it by the PPA price. The PPA price differed between Table 16 and Table 17 because there was a PPA price for BESS that was added to the PPA price for solar PV. The PPA price for BESS was assumed to be $35/MWh [49].

Table 17: Total Revenue ($) for Solar PV+BESS.

State	Adjusted Generation (MWh)	PPA Price ($/MWh)	Total Revenue ($)
Maryland	207,288	101	20,936,071
Virginia	217,514	101	21,968,901
California	277,734	77	21,385,506

3.5 Decommissioning Cost

Decommissioning cost was based on a sample list of decommissioning tasks and estimated costs for a 2 MW solar installation and scaled up to fit the 150 MW solar installation [47]. It was assumed that the costs from the sample would be representative of cost estimates in the three states. The project owner was assumed to oversee the decommissioning costs [47].

Table 18: Sample List of Decommissioning Tasks and Estimated Costs for a 2 MW Solar Installation [47].

Tasks	Estimated cost
Remove rack wiring	$2,459
Remove panels	$2,450
Dismantle racks	$12,350
Remove electrical equipment	$1,850
Breakup and remove concrete pads or ballasts	$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)	**$98,900**

Source: New York State Energy Research and Development Authority

The scaling factor was calculated to be 75 because 150 MW capacity was used for the study and Table 18 used a 2 MW solar installation.

Table 19: Decommissioning Scaling Factor Solar PV.

Scaling Factor
75

The scaling factor was multiplied by the value $60,209 because it was the unrounded current total provided in Table 18 to find the cost estimate. The cost estimate was then divided by the lifetime of the solar plant in the study, which was assumed to be 30, to get the cost/yr.

Table 20: Decommissioning Cost Solar PV Only.

Total Cost Estimate ($)	**Cost/yr**
4,515,675	150,523

The decommissioning cost for the BESS was sourced from the United States Department of Energy (USDOE) of $59/kWh [50]. This included preparation, battery module, balance of battery system and container, balance of plant, and post-site work costs [50]. The BESS decommissioning cost was multiplied by the capacity of the BESS in the study (200,000 kWh or 200 MWh) to get the total decommissioning cost.

Table 21: Decommissioning Cost BESS.

BESS Decommissioning cost ($/kWh)	**Capacity (kWh)**	**Decommissioning Cost ($)**
59	200,000	11,800,000

The decommissioning cost for solar PV with BESS was calculated by adding the respective costs together. It was divided by the lifetime of the solar plant, which was 30 years.

Table 22: Decommissioning Cost Solar PV+BESS.

Total Decommissioning Cost	543,856

3.6 Battery Storage System Cost

Battery storage system costs varied depending on whether it was AC coupled, or DC coupled. AC coupled was selected for the PV + storage scenario in this study. It was assumed the PV + storage scenarios were hybrid due to size and commonality [49].

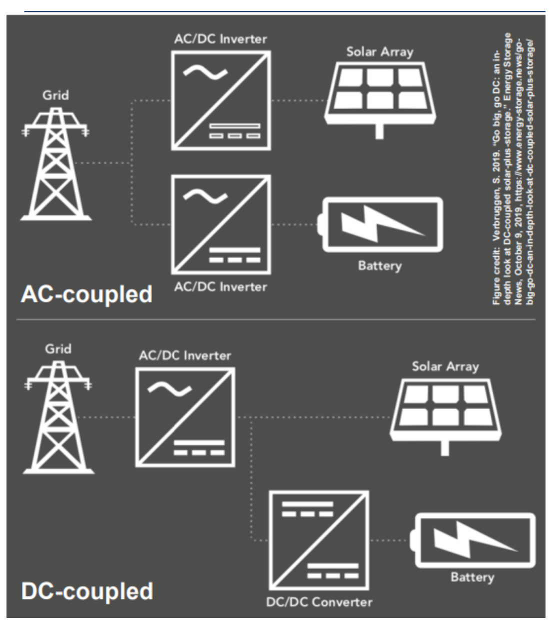


Figure 20: AC- and DC-Coupled PV+Storage Farm [49].

The PPA price of ~$35/MWh-PV was added to the PPA price of just solar PV so that the PPA price accounted for the BESS [49]. A BESS degrades over time and needs replacement while co-located with a solar PV farm. The cost of BESS replacement was incorporated into the calculations. It was assumed that the BESS would need a replacement after year nine of the lifetime of the plant. This was calculated by subtracting the solar PV with BESS principal cost from the solar PV principal cost. The replacement cost was then divided by the remaining years of operation of the solar PV farm, which was 20.

Table 23: Cost of BESS Replacement.

State	PV	PV + Storage	Replacement	Replacement/yr
Maryland	215,400,000	276,300,000	60,900,000	3,045,000
Virginia	216,000,000	267,000,000	51,000,000	2,550,000
California	236,850,000	295,350,000	58,500,000	2,925,000

3.7 Solar PV Panel and BESS Recycling Cost

The recycling cost for Solar PV was based on the “Literature Review” section about the recycling costs. It was $15 to $45 per module and the 150 MW system was assumed to have 390,000 modules [17,39]. An assumed average of $30 per module for recycling was used because it was the median value for the provided range.

The total number of modules for this study was multiplied by the recycling cost per module to get the recycling cost. It was then divided by the lifetime of the solar farm, which was 30 years, to get the recycling cost per year.

Table 24: Recycling Cost Solar PV Modules.

Modules	Cost per Module ($)	Recycling Cost	Recycling each yr
390,000	30	11,700,000	390,000

The table below was referenced for estimating costs for recycling a lithium BESS offsite. The column regarding 'equipment recycling' was the focus.

Table 25: Lithium Container Offsite Dismantling Cost Estimate [51].

Estimated System Cost for Offsite Dismantling and Disposal of Balance of Lithium Battery System and Container (Costs displayed as positive numbers, end-of-life values are displayed as negative numbers)				
Item (Description)	On-Site Dismantling and Packaging for Shipment	Transportation	Equipment Recycling	Subsystem Total
Container Housing				**$26,085.00**
Base Container (Concrete built enclosure.)	$2,880.00	$6,500.00	$13,000.00	
Modifications (Lighting, Flooring, venting, etc.)	$2,880.00	$175.00	$650.00	
Battery System Components				**$17,962.00**
Battery Racks (Estimated based on 82.5 kWh Racks. 19 per unit with 247 total racks.)	$5,760.00	$500.00	-$188.50	
Battery BMS (19 per unit, for 247 total BMS units)	$2,880.00	$150.00	$5,460.00	
Battery Connector Cables (Electrical and Communication Cables.)	$2,880.00	$150.00	$370.50	
System Controls and Communications				**$20,935.00**
Storage Management System (Master Computer, Communication Hardware, Metal housing.)	$7,760.00	$175.00	$13,000.00	
HVAC Thermal Management System				**$12,220.00**
HVAC Equipment (Each unit has four 5-ton systems for redundancy.)	$2,880.00	$500.00	-$1,560.00	
Refrigerant (Requires special handling and removal.)	$0.00	$0.00	$10,400.00	
Fire Suppression System				**$6,666.75**
Fire Suppression System Controls (Sensor and response box.)	$1,440.00	$150.00	$0.00	
Fire Suppression Tank and Agent (FM 200 Tank)	$1,440.00	$500.00	$1,300.00	
Piping Dispersion System (Metal piping for dispersion.)	$1,440.00	$400.00	-$3.25	
Additional Equipment				**$5,030.00**
Additional Equipment (Main Switch, Cables, Breakers, Fuses, etc.)	$2,880.00	$200.00	$1,950.00	
Subtotals	$35,120.00	$9,400.00	$44,378.75	
Total Estimated System Disposal and Recycling Cost				**$88,898.75**

Source: EPRI Estimates

It was assumed that the costs in Table 25 would be reasonable cost estimates for the BESS in this study. Each cost was recalculated based on the number of items the actual system for this study would likely need. The assumptions of the BESS itself were mentioned prior to this section of the study [39].

Assuming each rack for the 200 MWh BESS was 82.5 kWh, an estimated 2,424 items would be needed for battery rack, battery BMS, and battery connector cables. It was assumed that 4 HVAC systems would be needed for 80 containers and 320 HVAC thermal management system items would be needed.

After each cost was estimated, they were totaled. It was important to note that the values in parentheses in Table 26 indicated a negative value. This was because there was revenue from recycling certain items. This helped reduce the BESS recycling cost. Finally, the sum total was divided by the lifetime of the solar farm, which was 30 years.

Table 26: BESS Recycling Cost

Item	**Cost/item**	**# of items**	**Total**
Base container	13,000	80	1,040,000
Modifications	650	80	52,000
Battery rack	(188.5)	2,424	(456,924)
Battery BMS	5,460	2,424	13,235,040
Battery connector cable	370.50	2,424	898,092
System controls and comm	13,000	1.00	13,000
HVAC thermal mgmt system	(1,560.0)	320.0	(499,200.0)
Fire suppression tank	1,300	1.00	1,300
Piping dispersion system	(3.25)	1.00	(3.25)
Refrigerant	10,400	1.00	10,400
		Sum Total	14,293,705
		Annual Cost	476,457

3.8 Tax Incentives

It was assumed that the full rate is applied to the scenarios for ITC calculations. The full rate for ITC was 30 percent, as taken from Figure 16. It was assumed that the project met all the requirements.

The ITC was applied to the capital cost for year 1 of the solar farm. The ITC discount was calculated by multiplying 30 percent by the capital cost for year 1. The net principal cost was then calculated by subtracting the ITC discount from the capital cost in year 1.

Table 27: Net Principal Cost for Solar PV with ITC.

State	Capital Cost yr 1	ITC	ITC Discount	Net Principal Cost
Maryland	215,400,000	0.30	64,620,000	150,780,000
Virginia	216,000,000	0.30	64,800,000	151,200,000
California	236,850,000	0.30	71,055,000	165,795,000

The net principal cost was used as the new principal cost to calculate the annual capital cost for solar PV.

Table 28: Annual Capital Cost (2022$) for Solar PV with ITC.

State	Principal Cost	$(1+i)^n$	$((1+i)^n)-1$	$P*i*((1+i)^n)$	Annual Capital Cost
Maryland	150,780,000	4.32	3.32	32,583,124	9,808,455
Virginia	151,200,000	4.32	3.32	32,673,884	9,835,777
California	165,795,000	4.32	3.32	35,827,822	10,785,203

The same steps were followed but for solar PV with BESS to apply the ITC.

Table 29: Net Principal Cost for Solar PV+BESS with ITC.

State	Capital Cost yr 1	ITC	ITC Discount	Net Principal Cost
Maryland	276,300,000	0.30	82,890,000	193,410,000
Virginia	267,000,000	0.30	80,100,000	186,900,000
California	295,350,000	0.30	88,605,000	206,745,000

Table 30: Annual Capital Cost (2022$) for Solar PV+BESS with ITC.

State	Principal Cost	$(1+i)^n$	$((1+i)^n)-1$	$P*i*((1+i)^n)$	Annual Capital Cost
Maryland	193,410,000	4.32	3.32	41,795,344	12,581,598
Virginia	186,900,000	4.32	3.32	40,388,551	12,158,113
California	206,745,000	4.32	3.32	44,676,999	13,449,059

3.9 Levelized Cost of Electricity

The following equation was used to calculate the LCOE.

Equation 8: LCOE

LCOE = (Capital Cost + O&M + Decommissioning + Recycling) / Total Generation

Depending on the scenario, the LCOE variables in the numerator differed. The values were given for 3 percent, 5 percent, 7 percent, and 10 percent interest rates to analyze effects on the LCOE values. Furthermore, the LCOE values were conducted on a generation basis. The following LCOE tables were for each scenario that was conducted, but only the 5 percent interest rates were shown for calculation example purposes.

Table 31: LCOE Calculations Solar PV Only (Capital Cost+O&M).

State	Total Overnight Capital Cost	Total O&M Cost	Total Generation	LCOE
Maryland	14,012,079	2,574,000	220,428	75.24
Virginia	14,051,110	2,574,000	230,654	72.08
California	15,407,432	2,574,000	290,874	61.82

Table 32: LCOE Calculations Solar PV+BESS (Capital Cost+O&M).

State	Total Overnight Capital Cost	Total O&M Cost	Total Generation	LCOE
Maryland	17,973,712	4,863,000	207,288	124.86
Virginia	17,368,733	4,863,000	217,514	113.93
California	19,212,941	4,863,000	277,734	97.22

Table 33: LCOE Calculations Solar PV Only Including Decommissioning.

State	Total Overnight Capital Cost	Total O&M Cost	Total Generation	Total Decommissioning Cost	LCOE
Maryland	14,012,079	2,574,000	220,428	150,523	75.93
Virginia	14,051,110	2,574,000	230,654	150,523	72.73
California	15,407,432	2,574,000	290,874	150,523	62.34

Table 34: LCOE Calculations Solar PV+BESS Including Decommissioning.

State	Total Overnight Capital Cost	Total O&M Cost	Total Generation	Total Decommissioning Cost	LCOE
Maryland	17,973,712	4,863,000	207,288	543,856	127.48
Virginia	17,368,733	4,863,000	217,514	543,856	116.43
California	19,212,941	4,863,000	277,734	543,856	99.18

Table 35: LCOE Calculations Solar PV Only Including Recycling.

State	Total Overnight Capital Cost	Total O&M Cost	Total Gen.	Total Decomm. Cost	Recycle Cost	LCOE
Maryland	1.40E+07	2.57E+06	220,428	150,523	390,000	77.70
Virginia	1.41E+07	2.57E+06	230,654	150,523	390,000	74.42
California	1.54E+07	2.57E+06	290,874	150,523	390,000	63.68

The recycling cost of the solar PV and BESS were calculated separately and added together for Table 36, since the LCOE is for solar PV with BESS.

Table 36: LCOE Calculations Solar PV+BESS Including Recycling.

State	Total Overnight Capital Cost	Total O&M Cost	Total Gen.	Total Decomm. Cost	Recycle Total	LCOE
Maryland	1.80E+07	4.86E+06	207,288	543,856	866,457	131.66
Virginia	1.74E+07	4.86E+06	217,514	543,856	866,457	120.42
California	1.92E+07	4.86E+06	277,734	543,856	866,457	102.30

Table 37: LCOE Calculations Solar PV Only Including ITC.

State	Total Overnight Capital Cost	Total O&M Cost	Total Gen.	Total Decomm. Cost	Recycle Cost	LCOE
Maryland	9,808,455	2,574,000	220,428	150,523	390,000	58.63
Virginia	9,835,777	2,574,000	230,654	150,523	390,000	56.15
California	10,785,203	2,574,000	290,874	150,523	390,000	47.79

Table 38: LCOE Calculations Solar PV+BESS Including ITC.

State	Total Overnight Capital Cost	Total O&M Cost	Total Gen.	Total Decomm. Cost	Recycle Total	LCOE
Maryland	12,581,598	4,863,000	207,288	543,856	866,457	105.65
Virginia	12,158,113	4,863,000	217,514	543,856	866,457	96.46
California	13,449,059	4,863,000	277,734	543,856	866,457	81.54

To graph the results, the LCOE was calculated for each scenario and for each year of the lifetime of the solar farm. This was then averaged in three periods: years 1-10, years 11-20 and years 21-30. The values were in ($/MWh).

CHAPTER 4

RESULTS

4.0 Overview

The results for the LCOE calculations for the state of Maryland, Virginia, and California were provided in ($/MWh). They were provided as line graphs or bar graphs as needed for solar PV and solar PV with BESS at different interest rates (3%,5%,7%,10%) for different scenarios as described in each section.

4.1 LCOE with Recycling vs. No Recycling Across States

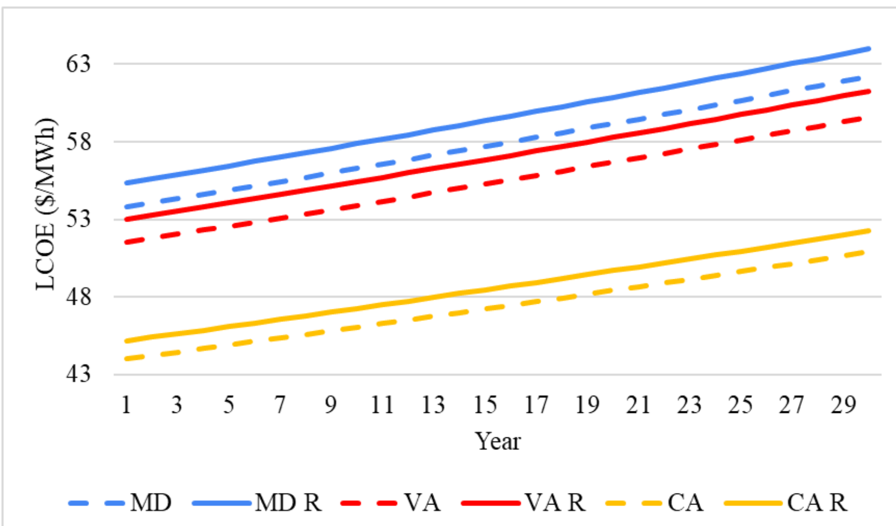


Figure 21: LCOE ($/MWh) of Recycling vs. no Recycling Across States over 30 Year Lifespan with 3% Interest Rate for 150 MW Solar PV Farm.

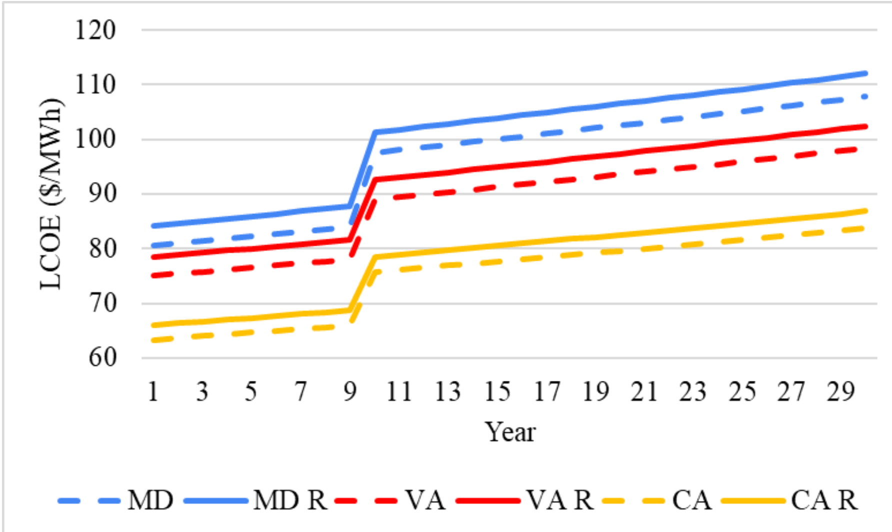


Figure 22: LCOE ($/MWh) of Recycling vs. no Recycling Across States over 30 Year Lifespan with 3% Interest Rate for 150 MW Solar PV Farm+200 MWh BESS.

4.2 LCOE by State for Recycling vs. No Recycling and System Type at Interest Rates

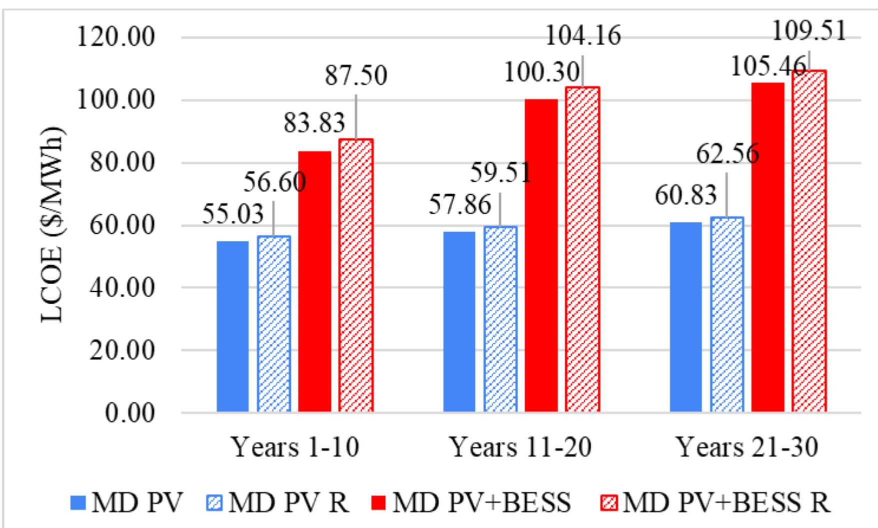


Figure 23: LCOE ($/MWh) of Recycling vs. no Recycling over 10 Year Increments with 3% Interest rate for 150 MW Solar PV Farm and 150 MW Solar PV Farm+200 MWh BESS in Maryland.

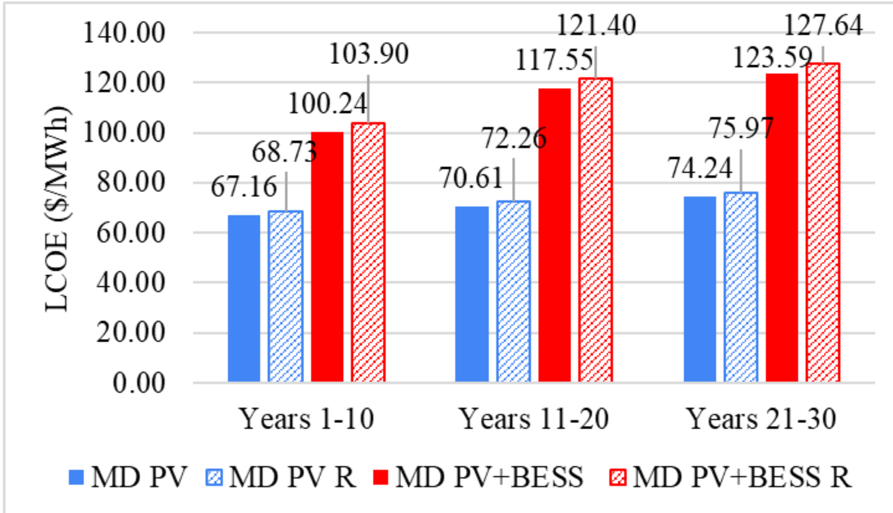


Figure 24: LCOE ($/MWh) of Recycling vs. no Recycling over 10 Year Increments with 5% Interest rate for 150 MW Solar PV Farm and 150 MW Solar PV Farm+200 MWh BESS in Maryland.

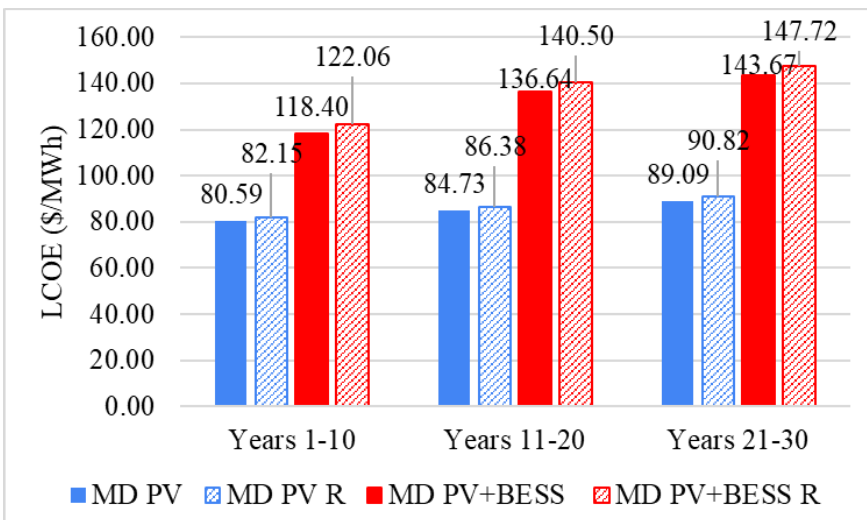


Figure 25: LCOE ($/MWh) of Recycling vs. no Recycling over 10 Year Increments with 7% Interest rate for 150 MW Solar PV Farm and 150 MW Solar PV Farm+200 MWh BESS in Maryland.

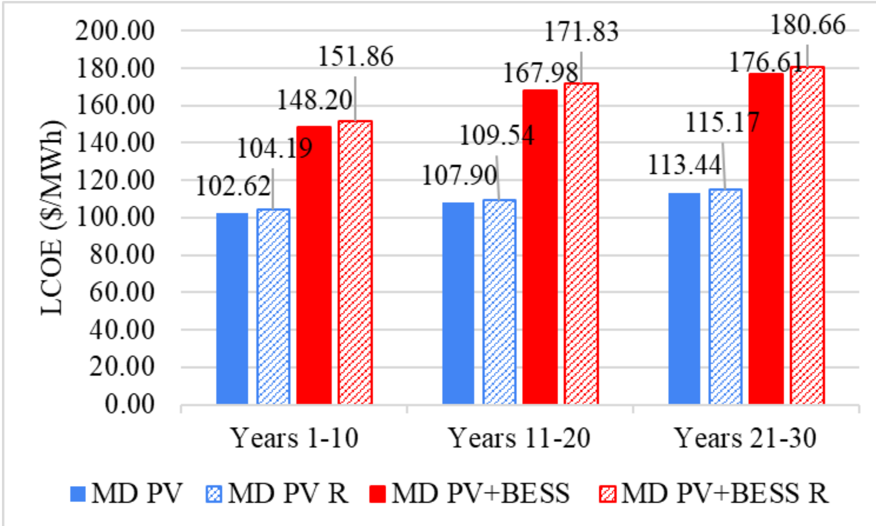


Figure 26: LCOE ($/MWh) of Recycling vs. no Recycling over 10 Year Increments with 10% Interest rate for 150 MW Solar PV Farm and 150 MW Solar PV Farm+200 MWh BESS in Maryland.

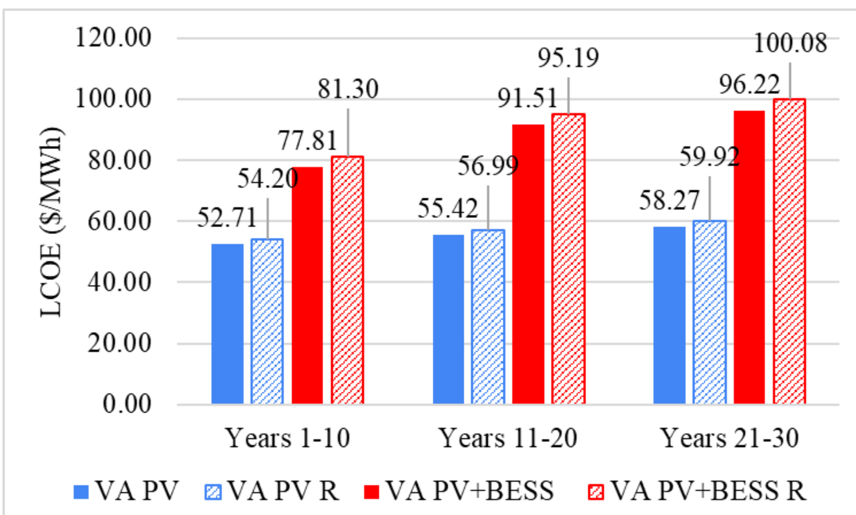


Figure 27: LCOE ($/MWh) of Recycling vs. no Recycling over 10 Year Increments with 3% Interest rate for 150 MW Solar PV Farm and 150 MW Solar PV Farm+200 MWh BESS in Virginia.

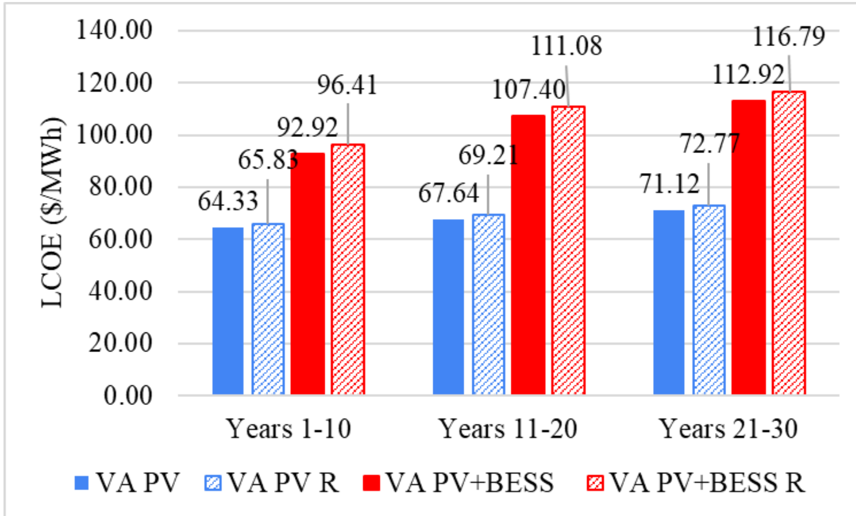


Figure 28: LCOE ($/MWh) of Recycling vs. no Recycling over 10 Year Increments with 5% Interest rate for 150 MW Solar PV Farm and 150 MW Solar PV Farm+200 MWh BESS in Virginia.

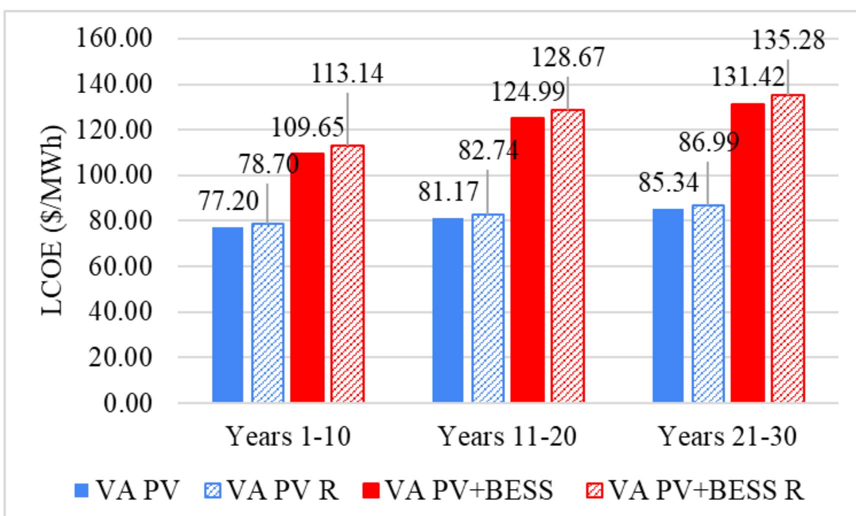


Figure 29: LCOE ($/MWh) of Recycling vs. no Recycling over 10 Year Increments with 7% Interest rate for 150 MW Solar PV Farm and 150 MW Solar PV Farm+200 MWh BESS in Virginia.

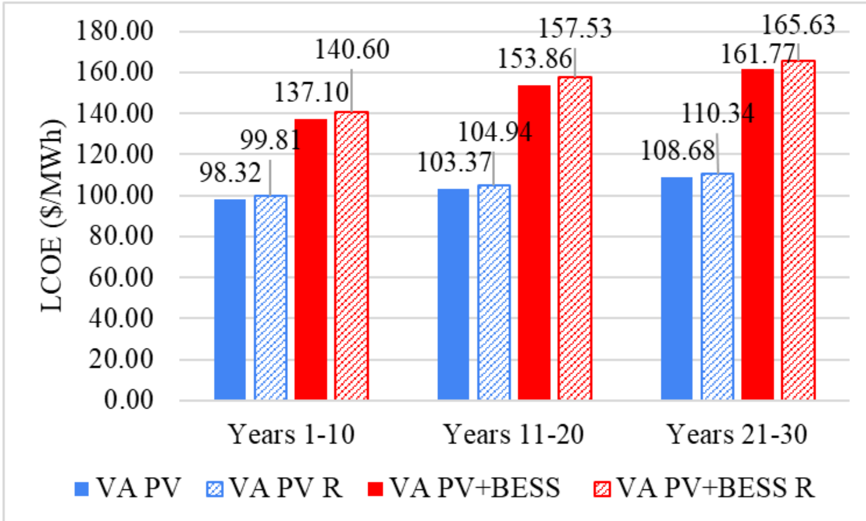


Figure 30: LCOE ($/MWh) of Recycling vs. no Recycling over 10 Year Increments with 10% Interest rate for 150 MW Solar PV Farm and 150 MW Solar PV Farm+200 MWh BESS in Virginia.

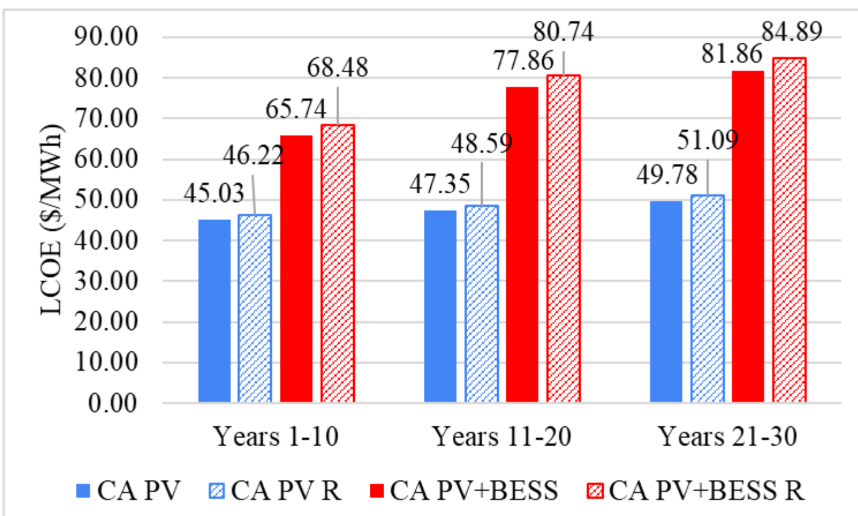


Figure 31: LCOE ($/MWh) of Recycling vs. no Recycling over 10 Year Increments with 3% Interest rate for 150 MW Solar PV Farm and 150 MW Solar PV Farm+200 MWh BESS in California.

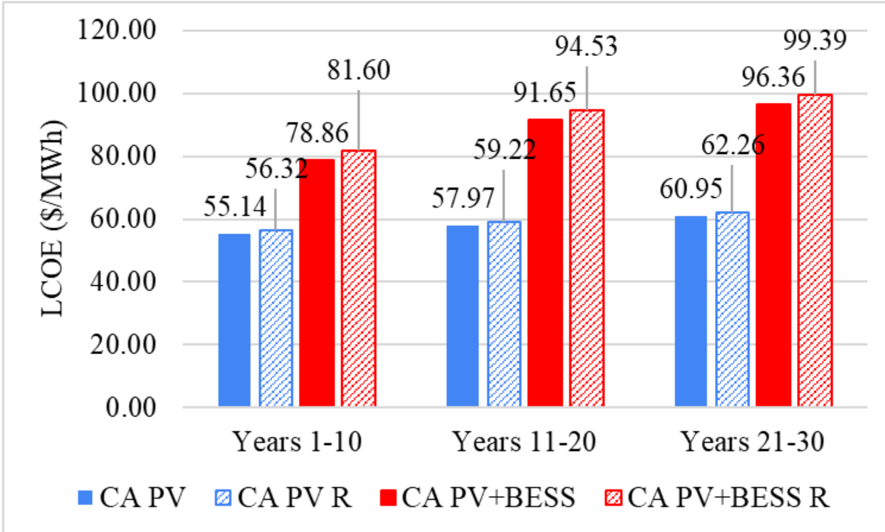


Figure 32: LCOE ($/MWh) of Recycling vs. no Recycling over 10 Year Increments with 5% Interest rate for 150 MW Solar PV Farm and 150 MW Solar PV Farm+200 MWh BESS in California.

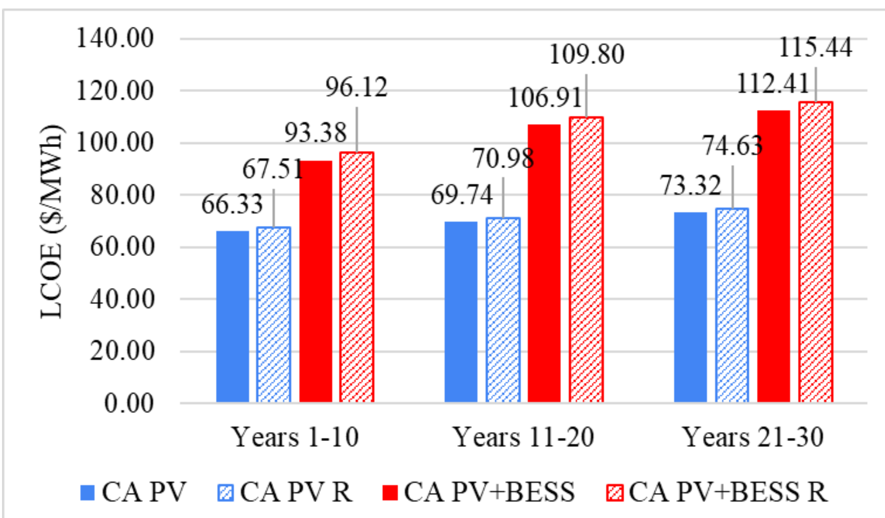


Figure 33: LCOE ($/MWh) of Recycling vs. no Recycling over 10 Year Increments with 7% Interest rate for 150 MW Solar PV Farm and 150 MW Solar PV Farm+200 MWh BESS in California.

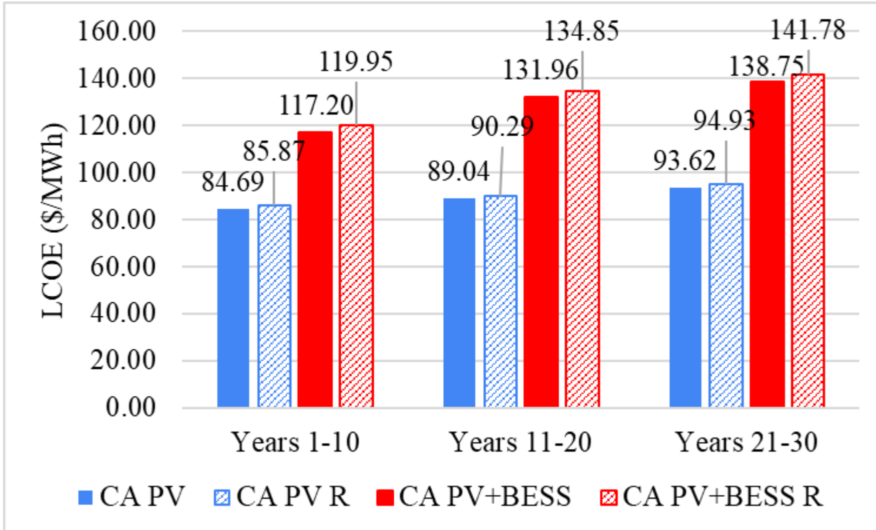


Figure 34: LCOE ($/MWh) of Recycling vs. no Recycling over 10 Year Increments with 10% Interest rate for 150 MW Solar PV Farm and 150 MW Solar PV Farm+200 MWh BESS in California.

4.3 Recycling Impact on Decommissioning Costs

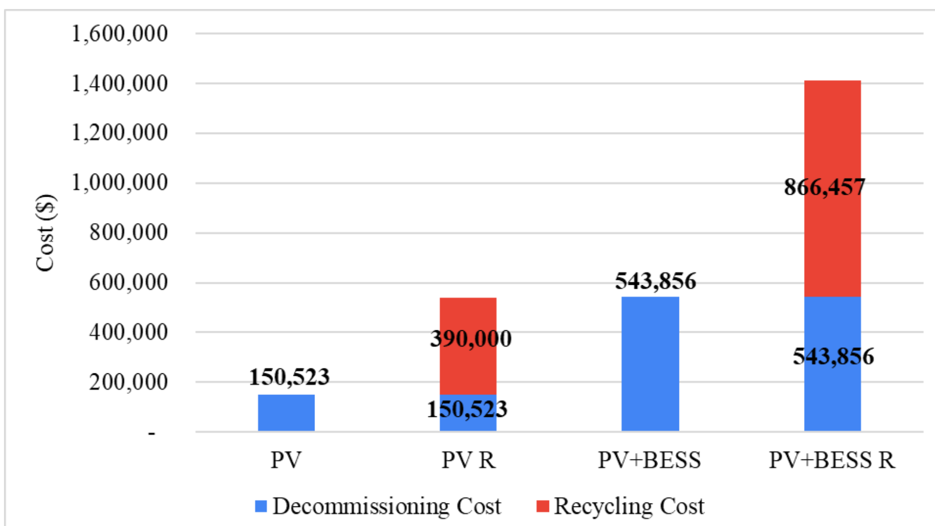
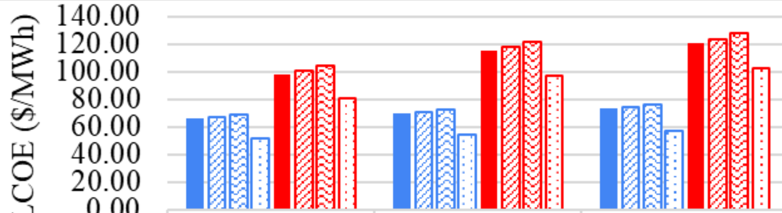


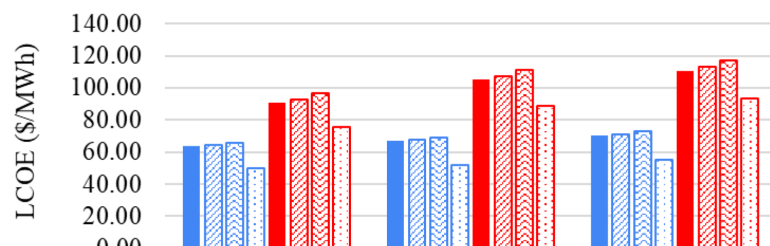
Figure 35: Recycling Impact on Decommissioning Cost for All States at 5% Interest Rate for 150 MW Solar PV Farm and 150 MW Solar PV Farm+200 MWh BESS.

4.4 LCOE All Scenario Comparison for each State at 5% Interest Rate



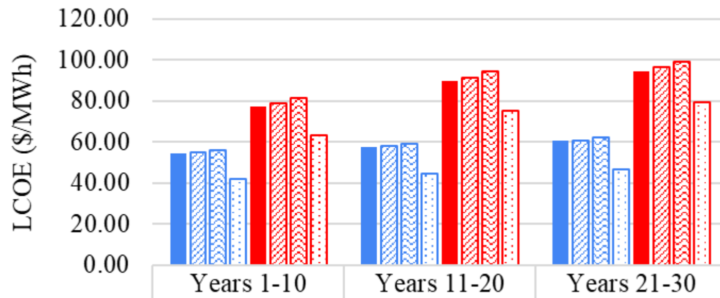
	Years 1-10	Years 11-20	Years 21-30
PV	66.56	69.98	73.57
PV Decomm	67.16	70.61	74.24
PV R	68.73	72.26	75.97
PV ITC	51.86	54.52	57.33
PV+BESS	97.94	115.13	121.05
PV+BESS Decomm	100.24	117.55	123.59
PV+BESS R	103.90	121.40	127.64
PV+BESS ITC	81.09	97.42	102.43

Figure 36: LCOE Scenario Comparison at 5% Interest Rate for 150 MW Solar PV Farm and 150 MW Solar PV Farm+200 MWh BESS in Maryland.



	Years 1-10	Years 11-20	Years 21-30
PV	63.76	67.03	70.48
PV Decomm	64.33	67.64	71.12
PV R	65.83	69.21	72.77
PV ITC	49.66	52.22	54.90
PV+BESS	90.72	105.10	110.50
PV+BESS Decomm	92.92	107.40	112.92
PV+BESS R	96.41	111.08	116.79
PV+BESS ITC	75.40	88.98	93.55

Figure 37: LCOE Scenario Comparison at 5% Interest Rate for 150 MW Solar PV Farm and 150 MW Solar PV Farm+200 MWh BESS in Virginia.



	Years 1-10	Years 11-20	Years 21-30
PV	54.68	57.78	60.60
PV Decomm	55.14	57.97	60.95
PV R	56.32	59.22	62.26
PV ITC	42.27	44.44	46.73
PV+BESS	77.14	89.84	94.46
PV+BESS Decomm	78.86	91.65	96.36
PV+BESS R	81.60	94.53	99.39
PV+BESS ITC	63.36	75.35	79.23

Figure 38: LCOE Scenario Comparison at 5% Interest Rate for 150 MW Solar PV Farm and 150 MW Solar PV Farm+200 MWh BESS in California.

4.5 LCOE Scenario Comparison with ITC

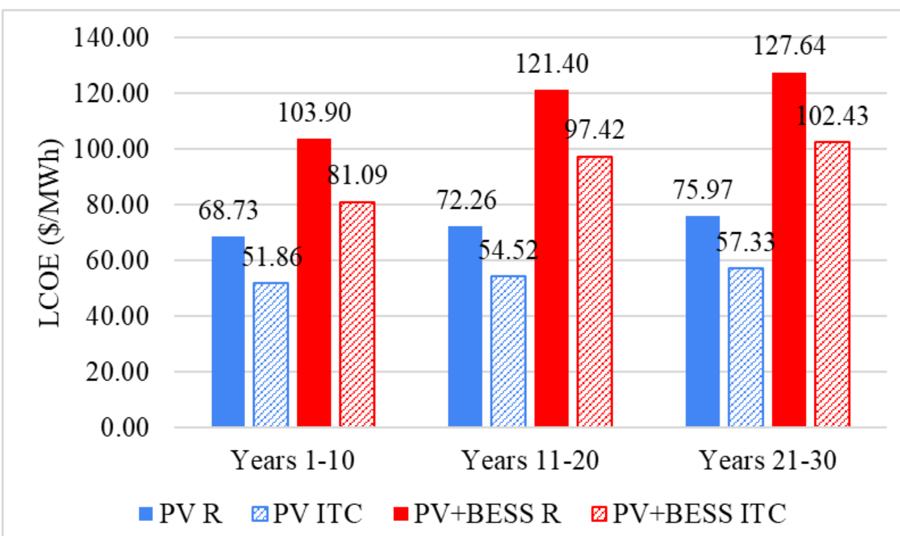


Figure 39: LCOE Recycling Scenario Comparison of ITC at 5% Interest Rate for 150 MW Solar PV Farm and 150 MW Solar PV Farm+200 MWh BESS in Maryland.

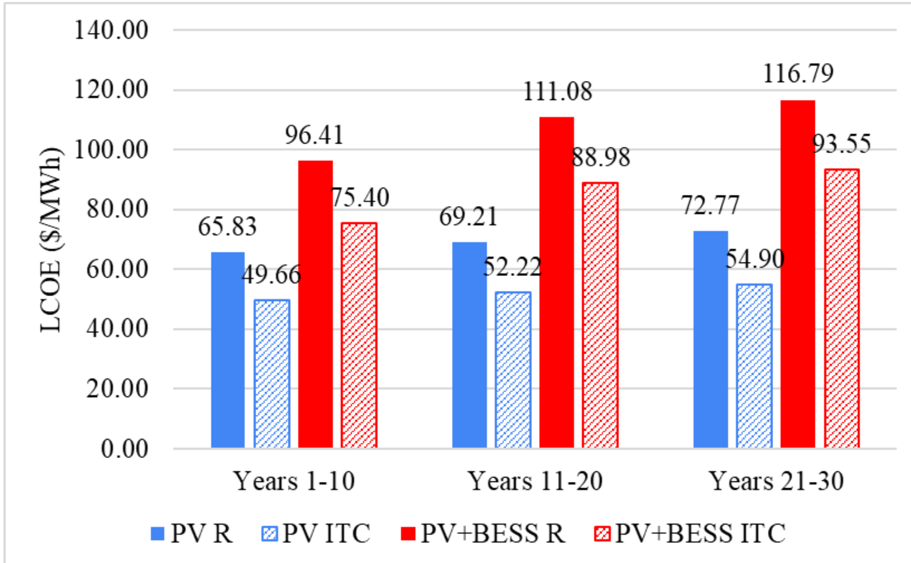


Figure 40: LCOE Recycling Scenario Comparison of ITC at 5% Interest Rate for 150 MW Solar PV Farm and 150 MW Solar PV Farm+200 MWh BESS in Virginia.

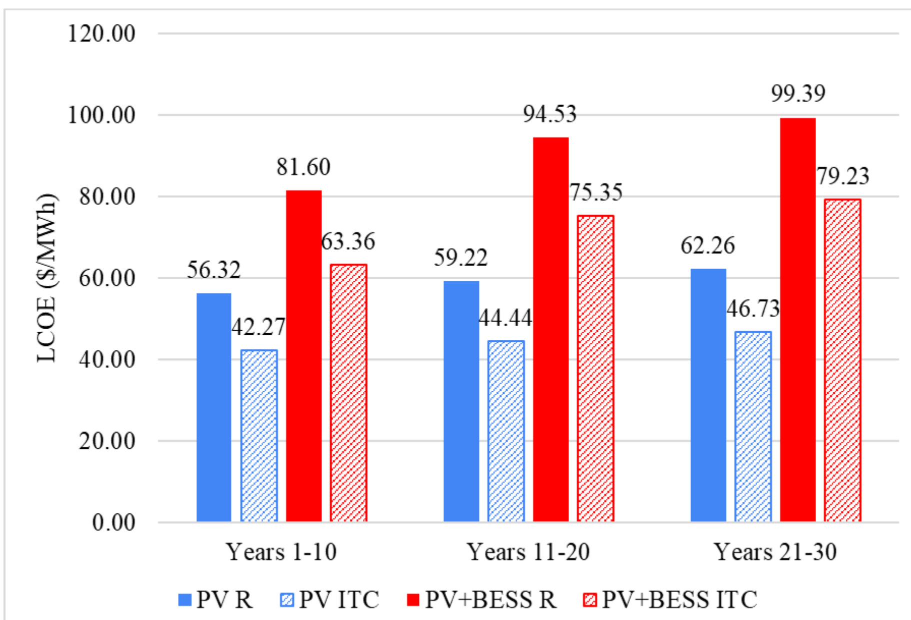


Figure 41: LCOE Recycling Scenario Comparison of ITC at 5% Interest Rate for 150 MW Solar PV Farm and 150 MW Solar PV Farm+200 MWh BESS in California.

CHAPTER 5

DISCUSSION & CONCLUSION

5.0 Overview

The objective of this study was to identify the feasibility of recycling solar panels in the United States by incorporating a cost for recycling into the levelized cost of electricity ($/MWhr). The discussion conducts an analysis on the graphs from the 'Results' chapter of this study.

5.1 Result Analysis

The general trend for all LCOE scenarios and interest rates used in this study was to increase over its lifespan. This was likely due to the degradation rate, which affected the denominator in the LCOE equation. The smaller the generation of the solar farm, the higher the LCOE value was. This was shown in Table 39 for years 1-6.

Table 39: LCOE and Generation Decreases for Maryland Years 1-6.

Year	**Generation Maryland**	**LCOE MD**
1	254916	65.06
2	253641	65.39
3	252373	65.72
4	251111	66.05

5	249856	66.38
6	248607	66.72

Next, Figure 21 and 22 provided an LCOE with and without recycling for solar PV and solar PV with BESS. It was evident that the scenarios with solar PV and BESS were higher overall. This was due to the additional costs from co-locating or having a hybrid system of BESS. Figure 22 has a sharp increase at year 10 due to the replacement cost for the BESS. It was assumed that the BESS would need to be replaced after 10 years due to degradation and would not be efficient. The panels did not have to be replaced because they have a longer lifespan, which was between 25-30 years.

Figure 23 through 34 analyzes the effects of the interest rate changes for each state and scenario. The interest rate only affected the capital cost because it was used to calculate the annual capital cost. The other costs including O&M, decommissioning, and recycling were kept constant. It was apparent that the LCOE increased as the interest rate increased. If the study had other variables in the numerator of the LCOE equation that were affected by the interest rate, there would be a more realistic understanding of its effects on the LCOE value. Since the analysis was conducted for a utility-scale system, lower interest rates would be ideal but are dependent on the region.

Looking at Figure 35, the recycling impact on decommissioning costs was high. It added more to the decommissioning cost as expected (390 thousand for solar PV only and 866,457 for solar PV with BESS). This was because recycling panels are costly and the system size for this study was large. For the combined solar PV and BESS costs, the

BESS did have some savings as shown in Table 40, but it was not enough to lower the LCOE costs nor decommissioning costs.

Table 40: BESS Recycling Equipment Cost.

Item	**Cost/item**	**# of items**	**Total**
Base container	13,000	80	1,040,000
Modifications	650	80	52,000
Battery rack	-188.5	2,424	-456,924
Battery BMS	5,460	2,424	13,235,040
Battery connector cable	370.5	2,424	898,092
System controls and comm	13,000	1	13,000
HVAC thermal mgmt. system	-1,560	320	-499,200
Fire suppression tank	1,300	1	1,300
Piping dispersion system	-3.25	1	-3.25
Refrigerant	10,400	1	10,400

Sum Total	14,293,704

Figures 36 through 38 showed that the solar PV system alone was cheaper than having a co-located or hybrid system. Looking at the different LCOE numerator combinations, it was apparent that there were not a lot of changes for all the solar PV farm only scenarios, but more variability in the prices for solar PV with BESS. This was due to the need for multiple systems that would aid in stability and reliability.

Figures 39 through 41 showed the significance of tax incentives for solar projects. The ITC reduced the capital cost by 30 percent, since it was assumed that the project qualified for the full rate. This greatly reduced the LCOE costs for both the solar PV farm and solar PV with BESS. For example, looking at Figure 39, the solar PV with BESS before the ITC was included was $103.90 per MWh, but after the ITC was applied, it was $81.09 per MWh as an average from years 1-10.

5.2 Recommendations for Future Work

For future studies, it is recommended that appropriate rates are used to understand a more realistic approach for LCOE calculations including recycling rather than linear cost approaches. Furthermore, this is just one of many studies that have been conducted to understand LCOE calculations and estimates. The framework for every study is different and comparing results across multiple sources may not prove to be helpful. Thus, a standardized cost list for each variable of the LCOE would be ideal for residential, commercial, and utility-scale levels. Standardization of the costs requires collaborative efforts between researchers, experts, and policymakers to ensure more accurate and comparable studies in the future.

5.3 Conclusion

The three states that were analyzed in this study had significant differences in the LCOE cost. Maryland and Virginia were similar, but California was significantly lower. Factors that would have contributed to the lower LCOE would be the amount of sun, capacity factor, rates, and incentives. From the selected states, incorporating recycling would be most economically feasible in California. It could have been as low as $47.79 per MWh for solar PV only with ITC and $81.54 per MWh for solar PV with BESS and ITC; however, further analysis needs to be completed to ensure the values reflect the current and future market. As the LCOE comparisons did not show a drastic increase in the cost compared to other scenarios, it could be concluded that adding recycling to LCOE is economically feasible but would need more consideration in financing to lower costs.

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