UNIVERSITY OF HAWAI‘I SYSTEM REPORT

REPORT TO THE 2022 LEGISLATURE

Interim Report from the Hawai‘i Natural Energy Institute to Provide
Recommendations on Waste Management of
Clean Energy Products in Hawai‘i

Act 92, SLH 2021

December 2021

Hawaiʻi Natural Energy Institute

School of Ocean and Earth Science and Technology
University of Hawaiʻi at Mānoa

INTERIM REPORT: Act 92, Session Laws of Hawaiʻi 2021

FORWARD

The Hawaiʻi Natural Energy Institute at the University of Hawaiʻi at Mānoa has been tasked, in collaboration with Department of Health and Hawaiʻi State Energy Office, to report on the best practices for disposal, recycling, or secondary use of clean energy materials resulting from our transition to renewable energy. This document is the requested interim report on progress, due 20 days prior to the convening of the regular session of 2022. Per legislation, a final report will be delivered twenty days prior to the convening of the first regular session of 2023.

The material contained herein is intended, primarily, to show the scope of the study and methodology used for the analysis. This is a work in progress and does not constitute a report of findings or recommendations to be acted upon or used in any manner other than for informational purposes. Data from a wide variety of sources has been included but, in some cases, that data has not been fully analyzed or fully vetted for accuracy or completeness so should be taken only as a representation of progress made to date. Due to time constraints, initial priority has been given analysis of those elements considered most important, PV modules and battery materials. Some of the sections deemed less critical or for which data were not readily available are incomplete. These materials may be updated, removed, adjusted, or modified in preparation of the final report. Additional materials will also be developed as appropriate.

INTRODUCTION

The 2021 Hawaiʻi State Legislature passed and the Governor enacted Act 92, Session Laws of Hawaiʻi 2021 (HB 1333, House Draft 1, Senate Draft 1, Conference Draft 1), relating to energy. This law required "the Hawaiʻi Natural Energy Institute (HNEI), in consultation with the Department of Health, to conduct a comprehensive study to determine best practices for disposal, recycling, or secondary use of clean energy products in the State."

Specifically, the law required HNEI to address and evaluate:

1. The amount of aging photovoltaic and solar water heater panels in the State that will need to be disposed of or recycled;
2. Other types of clean energy materials expected to be discarded in the State in significant quantities, including glass, frames, wiring, inverters, and batteries;
3. The type and chemical composition of those clean energy materials;
4. Best practices for collection, disposal, recycling, or reuse of those clean energy materials;
5. Whether a fee should be charged for disposal or recycling of those clean energy materials; and
6. Any other issues that the Hawaiʻi Natural Energy Institute and Department of Health consider appropriate for management, recycling, and disposal of those clean energy materials.

Per the legislation's requirement, this report serves as the interim report in which HNEI has provided, to the extent possible, the requested information. The report is divided into five sections.

- Section 1 provides background information related to the three types of clean energy materials under evaluation; solar photovoltaics systems, energy storage systems, and solar hot water systems. This information is not meant to be exhaustive, but rather serves as an overview of characteristics of each technology being considered under Act 92. Section 1 is also used to narrow the focus of the evaluation to specific technologies, within these three categories, to those either already deployed or expected to be deployed in Hawaiʻi in the near term. An initial review of the literature was conducted to assess and quantify waste streams from each technology, on a standardized basis (per kw_p of PV module or per kwh of storage, for example) for use in later sections. Estimates of waste will include not only the primary components (photovoltaic panels, energy storage batteries, and solar hot water panels) but also key ancillary components within each system.

- Section 2 is intended to quantify the deployment of the three technologies to date and to provide an estimate of future potential deployment through the year 2030. While a variety state agency and utility resources are used to estimate both existing and expected future deployment, these numbers and associated timelines are preliminary and will be updated in the final report.

- Section 3 uses the information from Sections 1 and 2, along with projected estimates of lifetimes of the various components to estimate projections of the waste streams in future years. In the final report interactive spreadsheets will be made available allowing the user to explore the impact of changes in deployment and projected lifetimes on the expected waste streams. Due to the relatively long life of components and the expected significant increases in deployment in future years, significant waste streams are not expected for a decade or more.

- Section 4 provides information on the current regulations for the disposal of photovoltaics panels, energy storage batteries, and solar hot water systems. This section also provides a brief discussion on the state-of-the-art for recycling technologies. This section is included for preliminary information purposes only and should not be considered as recommendations for action.
- Section 5 identifies some initial comments addressing the question of requiring fees for disposal of these used materials and discusses some additional aspects of energy systems that should be considered that may be pertinent to the Act 92 request.

BACKGROUND

The following section provides some background technical information on the energy systems that are at issue for future disposal or recycling. This information is not meant to be exhaustive, but to provide a general overview on these systems and their characteristics.

1. Photovoltaics

This section provides a review of photovoltaic systems of interest for Hawaiʻi and a brief description of the ancillary equipment found in the typical installation. This sections also quantifies the expected waste streams on a standardized basis of weight of material per kw_p.

1.1. Panels

Photovoltaic (PV) panels are generally classified according to the structure of the active semiconductor cell used for power generation. Sometimes called first generation, solar cells made using mono-crystalline or poly-crystalline form [2] have dominated the rooftop market and represent a significant share of the utility scale systems. The active cells are made using high-purity Si wafers typically 160–190 µm in thickness [3]. A second generation of solar materials comprise thin films of one or more layers deposited on a substrate such as glass or stainless steel [4]. The most common materials used to produce the thin film cells include amorphous silicon (a-Si), cadmium telluride (CdTe), or various copper indium gallium alloys (CIG). Third generation *panels* comprise less commercially advanced technologies such as dye-sensitized, organic and hybrid solar cells [5]. While thin-film materials have seen some degree of commercial success, the vast majority of panels worldwide (> 95%) are fabricated using crystalline (single or poly). To our knowledge, there has been no significant deployment of any of the other module types in Hawaiʻi nor is any expected in the near-future.

The general structure of the crystalline PV panel (c-Si) includes (i) an aluminum (anodized or powder coated) frame, (ii) a transparent tempered glass or polymeric film, (iii) an ethylene vinyl acetate (EVA) sheet that encapsulates the semi-conductor electrodes, (iv) metal electrodes affixed to the solar cells for current collection, and (v), a plastic back sheet to protect from the environment, and (vi) the junction box (Figure 1a) [6]. The front of the PV Panel is shock resistant glass. The solar cell rests below the glass and under a protective layer of EVA (Ethylene Vinyl Acetate) that acts as an encapsulant for the solar cells. A back-sheet, typically made of polyvinyl fluoride (PVF) or a combination of PVF with polyethylene terephthalate (PTE), is attached at the backend of the panel. After these components have been mantled together, the panel is subjected to heating under vacuum to melt the EVA and fill the space between the front glass of the panel and the rear polyvinyl fluoride lamination sheet (to create a sealant). A junction box is then added at the rear of the panel to service output connections [7]. The final framing of the whole panel is done after an additional sealant in the aluminum profiles has been added (Figure 1b) [8]. In all cases the cells are combined to form the module or a panel (i.e. several modules pre-fabricated together in a unit). Modules or panels are aggregated to form arrays (Figure 1c). Recycle and or waste management will need to consider all these elements of the module.

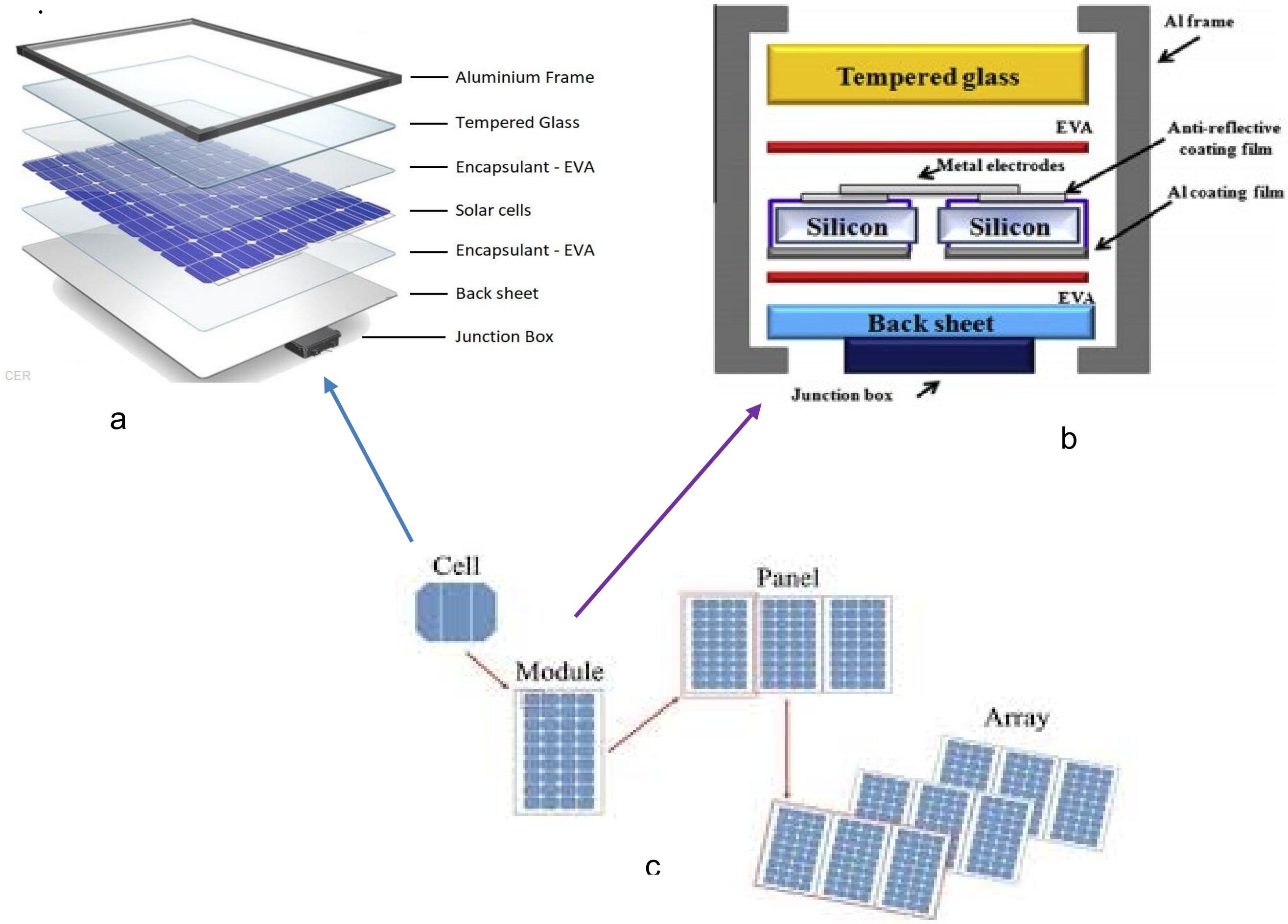


Figure 1. The general structure of the c-Si PV module

A number of studies [1, 10-17], most conducted in the past five years were evaluated to quantify to specific materials waste streams associated with potential recycle of the Si modules. Table 1 summarizes the reported compositions of silicon crystal (c-Si) panels. Values varied significantly and some studies did not report on all materials expected to be found in the module. Some, for example, did not even report Si. While further vetting of these reports needs to be conducted, average composition values are included in Table 1. The values included averages, for all materials are shown as per kilowatt rating at standard condition. In accordance with the general expectations of composition described above, the major elements are glass (~67%), aluminum (~15%, mostly frame), polymer (~7%, including back-sheet), high grade silicon (~3%), copper (0.6%) and an assortment of additional metals (~1.0%) including magnesium, aluminum (circuits), zinc, lead, tin, and silver. Copper is used extensively in wires and cables that connect the PV panels with ancillary components such as inverters. The composition of these materials, e.g. copper in cables was not included in Table 1. In addition, plastic can be used to house junction boxes that are often found on the underside of a solar panel. Junction boxes provide an easy way of connecting multiple panels together to form a single system.

.

Table 1: Chemical composition of c-Si PV panels.

Panel type	Peak power (Wp)	Panel weight	Panel total	Glass	Al - Frame	EVA	Backing - Tedlar	Cu	Ag	Sn	Pb	Si	Zn	Al	Mg	Si
	Watt	kg	**Kg/kW**	**Kg/kW**	**Kg/kW**	**Kg/kW**	**Kg/kW**	**Kg/kW**	**Kg/kW**	**Kg/kW**	**Kg/kW**	**Kg/kW**	**Kg/kW**	**Kg/kW**	**Kg/kW**	**Kg/kW**
c-Si	215	22	102.33	75.9	10.5	6.7	0.37	0.58	0.0102	0.1228	0.0716	3.56				3.07
c-Si	215	22.3	103.72	64.3	22.8	7.8	0.26	0.38	0.1433	0.1245	0.1228					
c-Si	250	19	76.00					0.51	0.0288		0.3040	2.28				2.05
c-Si	220	22	100.00	70.0	18.0	5.1	0.11	0.18	0.0530	0.0260	0.0260	3.56		0.5300		3.56
c-Si	225	24	106.67	69.8	17.6	6.9		0.78	0.0615	0.0062	0.0498	0.84	0.0008		0.5547	
c-Si	270	18.6	68.89	52.4	5.5	6.9		0.69	0.0689			3.44				3.44
c-Si	224	23	102.68		16.5			0.74			0.0049	0.79			0.0536	0.82
c-Si	175	2							0.0089			4.95	0.1057	0.0891		
c-Si	230	2								0.0243		2.48	0.1116	0.2661	0.0752	2.61
				65.8	16.6	6.5		0.73	0.0560	0.0001	0.0047	0.80	0.0000		0.5220	0.7950
AVE		21.56	94.326	66.358	15.363	6.644	0.247	0.573	0.054	0.051	0.083	2.523	0.055	0.295	0.301	2.336
AVEDEV		1.58	12.504	5.524	4.193	0.559	0.089	0.163	0.029	0.049	0.074	1.205	0.054	0.157	0.237	0.954

Table 2: Chemical composition of PV inverters. Values estimated per kW rating of inverter

Inverter type	Power	Inverter weight	Panel total	Cu	Steel	Ag	Ni	Au	Sn	Pb	Fe	Zn	Al	Mg	Mn	Ta
	Watt kW	kg	**Kg/kW**	**Kg/kW**	**Kg/kW**	**Kg/kW**	**Kg/kW**	**Kg/KW**	**Kg/kW**	**Kg/kW**	**Kg/kW**	**Kg/kW**	**Kg/kW**	**Kg/kW**	**Kg/kW**	**Kg/kW**
ac	500			6.78E-01	2.88E+00	7.40E-04	3.20E-04	1.02E-03	4.00E-05	3.60E-03	1.00E-04	1.00E-03	2.62E-01	2.00E-05	2.00E-06	4.00E-05
ac	500			1.95E+00		2.30E-03	9.20E-04	2.90E-03	6.00E-05	1.04E-02	2.90E-04	2.30E-03	7.53E-01	6.00E-06	1.00E-05	1.20E-04
AVE				1.31E+00	2.88E+00	1.52E-03	6.20E-04	1.96E-03	5.00E-05	7.00E-03	1.95E-04	1.65E-03	5.08E-01	1.30E-05	6.00E-06	8.00E-05
AVEDEV				6.36E-01	0.00E+00	7.80E-04	3.00E-04	9.40E-04	1.00E-05	3.40E-03	9.50E-05	6.50E-04	2.46E-01	7.00E-06	4.00E-06	4.00E-05

1.2. PV ancillary components

Other than wiring and cabling, the only significant additional ancillary component in a PV system is the inverters. Inverters convert the DC power supply generated by the PV panel to alternating current (AC). Most inverters fix frequency to the grid frequency although some are frequency fixing. There are several types of inverters: micro, string, multi string, and central. The micro-inverter connects to an individual solar panel (Figure 2a). Each microinverter is about the size of an internet router, typically has a lifetime of 25-year warranties, and is installed underneath the solar panel. String inverters have higher power ratings and are used to convert the energy from an array of DC connected modules to AC (Figure 2c). The multi-string inverter is a further development of the string inverter wherein several strings are interfaced with their own dc–dc converter to a common dc–ac inverter (Figure 2d). In this case, each PV string is connected to a single string inverter at the DC side and all AC outputs of all inverters are combined and connected to the utility grid. Central inverters are effectively large string inverters used to connect to a large number of PV modules where the strings are connected to the DC side of a single inverter and the AC output is connected to the utility grid (Figure 2b).

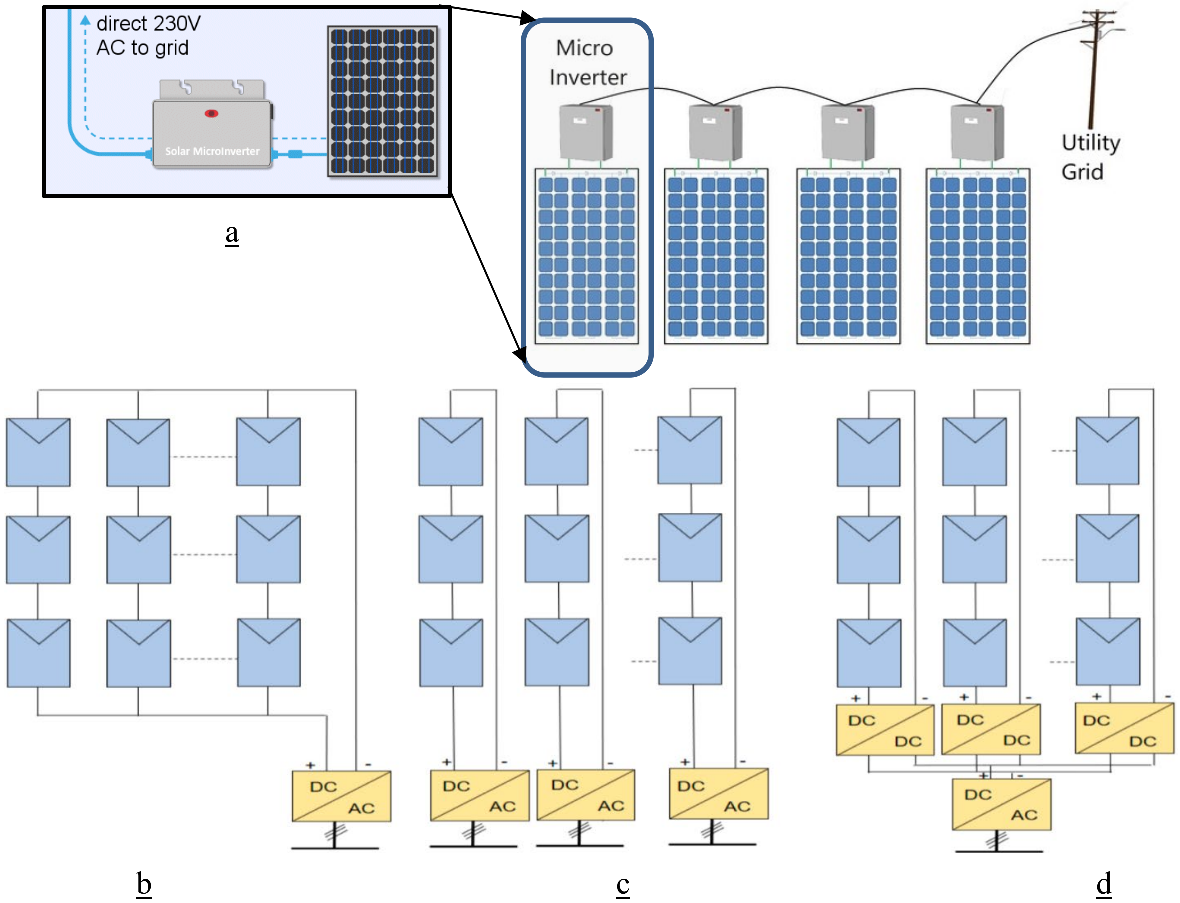


Figure 2: Microinverter and topology (a), central inverter and topology (b), string inverter and topology (c), multi-string inverter and topology (d).

While utility scale solar farm systems have traditionally used centralized inverter architectures [9], string inverter architectures (single string or multi-string) are widely used in utility-scale solar farms although the topologies of utility scale PV inverters are also moving towards multilevel structure [10].

Table 2 lists a limited number of reported material compositions for inverters with averages. These data are not comprehensive and are reported for a 500 kw-ac inverter. The values, including averages, for all materials have been reported as mass per kilowatt (kg/kW). The largest contributors are steel and copper followed by a range of precious (Ag, Au), base and special (Al, Sn, Zn, Ta, Mn, Fe, Ni), toxic (Pb), and critical materials (Mg) [11]. The use of Table 1 in its current form would suggest these compositions are constant irrespective of the inverter power rating. A more extensive review the literature is required to verify as well as to ensure accurate determination of the material composition across small to large inverters. For example, while Cu and steel are the dominate materials by several orders, the next largest or close to it is lead. This compositional relationship needs to be verified in future work.

Solar PV photovoltaic cables are designed exclusively for interconnections in photovoltaic solar power systems. Solar cables interconnect solar panels and other electrical components of a photovoltaic system. These ancillary components connect the solar panel to the combiner box, inverter and transfer line. The two most common conductor materials used in PV cables is aluminum and copper [12]. Estimates of 0.64 kg of Cu per m^2 of PV (~ 3.36 kg/kW) have been presented [12] while others have suggested 4.712 kg per kW [13].

Mounting systems have been proposed to possess (kg/m^2 of panel area) aluminum (3.9), steel (7.5), and zinc (0.27) [12]. This translates to approximately 20.45 kg/kW (aluminum), 39.4 kg/kW (steel), and 1.42 kg/kW (zinc) (assuming 1.26 m^2 per 240 W panel). This is in relative agreement with another study that proposed 25.42 kg/kW (aluminum), 48.9 kg/kW (steel/iron), and 1.76 kg/kW (zinc) [13].

2. Energy storage systems

This section presents a review of energy storage systems of interest for Hawai‘i and a brief description of the ancillary equipment found in the typical installation. This sections also quantifies the expected waste streams on a standardized basis of *weight of material per kwh of energy storage.* While other storage technologies may be included in the final report, as appropriate, this report includes only battery storage technology as it is the dominant technology used for both EV and photovoltaic power system applications in Hawai‘i.

2.1. Batteries

Batteries are the dominate technology for application in electric vehicles (EV) and photovoltaic power systems. Numerous battery chemistries and configurations are available including well known ones such as Lead acid, nickel-cadmium, nickel-metal hydride, lithium polymer [14], and lithium ion [21]. In recent years [15], lithium ion batteries (LIBs) have become the dominant technology used in grid-connected energy storage system (ESS) deployments and in EV applications, and it is expected to remain so for the foreseeable future [1]. In Hawai‘i LIB technologies are the dominant technology used for EV, as well as for rooftop and proposed utility scale storage.

While there are a number of lithium ion battery chemistries (see Table 3), lithium nickel cobalt aluminum oxide (NCA) and lithium manganese cobalt oxide (NMC) batteries have, until recently, dominated the EV and power market sectors. More recently, however, lithium iron phosphate (LFP) batteries have also gained greater acceptance. While LFP batteries have lower energy densities in comparison to the NCA and NMC they exhibit several notable benefits including improved safety [16], use of nontoxic and easily accessible materials [17], better lifetime, lower cost, avoidance of supply-chain issues, and decreased environmental impact [18, 19].

Table 3: Estimated energy densities for the five major lithium ion chemistry

Abbreviation	Full name (chemical formula)	Range of energy density (Wh/kg)
NCA	Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$)	200-360
NMC	Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$)	150-220
LMO	Lithium Manganese Oxide ($LiMn_2O_4$)	100-150
LFP	Lithium Iron Phosphate ($LiFePO_4$)	90-120
LTO	Lithium Titanite ($Li_4Ti_5O_{12}$)	70-80

According to a new analysis from Wood Mackenzie [greentechmedia[1]], LFP batteries are poised to overtake NMC batteries as the dominant stationary storage chemistry within the decade, growing from 10% of the market in 2015 to more than 30% in 2030. Latest announcements from

---

[1] https://www.greentechmedia.com/articles/read/lfp-will-overtake-nmc-for-stationary-storage

some EV producers such as Ford[2], VW[3] and Tesla[4] indicates that they are also increasingly leveraging LFP for electric vehicle batteries, substituting for the more currently used nickel and cobalt formulations. Based on these industry trends, HNEI has, for purposes of estimating recycle needs considered only two battery chemistries NMC and LFP. Representative characteristics of each are shown in Table 4.

Table 4: Lithium ion battery parameters		
Parameters	LFP	NMC
Rated capacity (kWh)	28	28
Battery weight (kg)	230	170
Battery’s energy density (Wh/kg)	122	165
Quantity of battery cells	100	96

The four main components of a Li-ion battery cell are the cathode, anode, electrolyte and separator. Commercial batteries are named from the lithium-ion donator in the cathode, as this is the main determinant of cell properties. During charge, the lithium ions move from the cathode, through the electrolyte, to the anode, and move back during discharge. The electrolyte is a mixture of lithium salt and organic solvents. Common lithium salts include lithium hexafluorophosphate ($LiPF_6$), lithium perchlorate ($LiClO_4$) and lithium hexafluoroarsenate ($LiAsF_6$), with $LiPF_6$ becoming the most common. Common organic solvents include ethylmethyl-carbonate (EC), dimethyl-carbonate (DMC), diethyl-carbonate, propylene-carbonate and ethylene-carbonate. The separator is a component between the cathode and the anode, preventing direct contact, i.e. short-circuiting, while being permeable to lithium ions. The most common separator materials are polyethylene and polypropylene [15]. The recycling of Li-ion batteries must consider all these components and materials. Table 5, below, shows typical battery composition, by weight. The weight percentages can be converted to kg per kW by using values of gravimetric or energy density (see Table 4).

---

[2] https://www.autoevolution.com/news/ford-details-ev-strategy-ford-plan-includes-li-ion-lfp-solid-state-batteries-162005.html

[3] https://www.reuters.com/article/us-volkswagen-electric-ahome/column-volkswagen-powers-up-for-the-electric-vehicle-revolution-idUSKBN2BG2MN

[4] https://techcrunch.com/2021/10/20/tesla-earnings-iron-batteries-evs-globally/?guccounter=1&guce_referrer=aHR0cHM6Ly93d3cuZWNvc2lhLm9yZy8&guce_referrer_sig=AQAAABGCpJ0L4fQiR6b1eSITINrZNnSqU33EXON3QT3YdYZ1E_kT7FKjMgkd_oCcrKg-ABLi0vYgCIA81dJjMmWmTpLsDPWRJL0dqyU3qXM2vluC6OWGSXISci58k6205TNZ55ipU1quMeCilrAv4oQ9qs8zOiQq6VH7cCAoW2S9KAiG

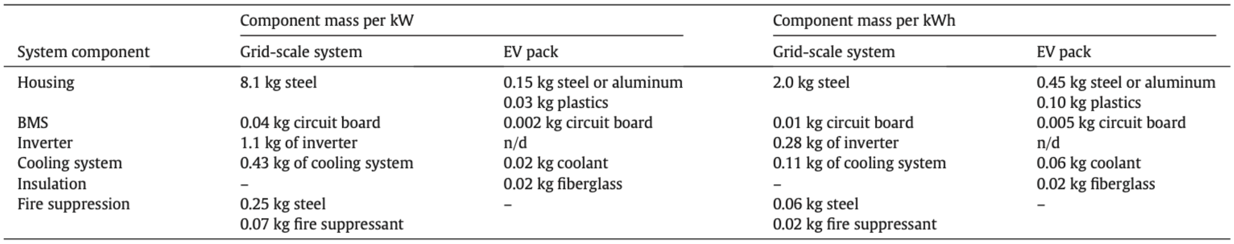
Table 5: Battery mass composition		
Battery components	**LFP**	**NMC**
Anode active materials	24.4%	28.2%
Graphite	15.2%	18.3%
Binder	2.1%	2.4%
Copper	12.4%	11.4%
Wrought aluminum	20.3%	19.7%
Electrolyte: $LiPF_6$	2.7%	1.9%
Electrolyte: EC	7.8%	5.4%
Electrolyte: DMC	7.8%	5.4%
Plastic: PP	1.9%	1.7%
Plastic: PT	0.3%	0.3%
Plastic: PET	1.3%	1.2%
Steel	1.5%	1.4%
Fiberglass	0.3%	0.4%
Coolant: glycol	1.0%	1.0%
Battery Management System (BMS)	1.0%	1.3%

2.2. Battery ancillary components

Battery systems or battery packs are composed of individual cells having a nominal voltage of 3-4 volts (depending on the chemical composition), organized in a series and parallel configurations to achieve the desired voltage and capacity [20]. To simplify assembly, individual cells are grouped into stacks called modules. Several of these modules are placed into a single pack. Within each module, the cells are welded together to complete the electrical path for current flow. Modules may require ancillary components such as cooling mechanisms, temperature monitors, and other devices such as a battery management system (BMS) which controls all aspects of the battery pack protection including Thermal Management and Energy Management [20].

The ancillary components (i.e. balance of system, BOS) differ for EV and photovoltaic power applications. As such their distinctive chemical compositions must also be assessed and accounted for [EPRI Recycling, 2017[5]]. Moreover, the designs of thermal management systems, pack construction, cell sizes and form factors can differ significantly between stationary (PV power) versus mobile (EV) applications. Stationary systems, for example, usually require fire suppression systems and often include conventional force-air HVAC systems [1]. A complete list of ancillary components (i.e. Balance of Plant, BOS) will also include physical infrastructure such as a container housing or concrete foundations, which are common for stationary lithium ion battery (LIB) energy storage systems (ESSs) but are not relevant for EV battery modules. Table 6 presents some representative example data for these ancillary components on a per kW or kWh basis.

Table 6: Example of ancillary components comparison for a representative hypothetical grid-scale LIB-ESS (1 MW, 4 MWh) and an EV battery pack (225 kW, 73 kWh, similar to the Tesla Model S battery pack) [1]



	Component mass per kW		Component mass per kWh	
System component	Grid-scale system	EV pack	Grid-scale system	EV pack
Housing	8.1 kg steel	0.15 kg steel or aluminum 0.03 kg plastics	2.0 kg steel	0.45 kg steel or aluminum 0.10 kg plastics
BMS	0.04 kg circuit board	0.002 kg circuit board	0.01 kg circuit board	0.005 kg circuit board
Inverter	1.1 kg of inverter	n/d	0.28 kg of inverter	n/d
Cooling system	0.43 kg of cooling system	0.02 kg coolant	0.11 kg of cooling system	0.06 kg coolant
Insulation	–	0.02 kg fiberglass	–	0.02 kg fiberglass
Fire suppression	0.25 kg steel 0.07 kg fire suppressant	–	0.06 kg steel 0.02 kg fire suppressant	–

Figure 3 presents a breakdown materials recycled from EV batteries taken from a 2017 study [21]. HNEI will continue to seek original sources for both EV and power sector batteries from which more extensive material composition tables will be developed. material composition tables These analyses, similar to those presented above for solar PV waste, will be used in conjunction with expected deployment numbers to estimate long-term yearly disposal loading rates.

---

[5] EPRI. Recycling and Disposal of Battery-Based Grid Energy Storage Systems: A Preliminary Investigation. 2017. EPRI, Palo Alto, CA. Report number 3002006911

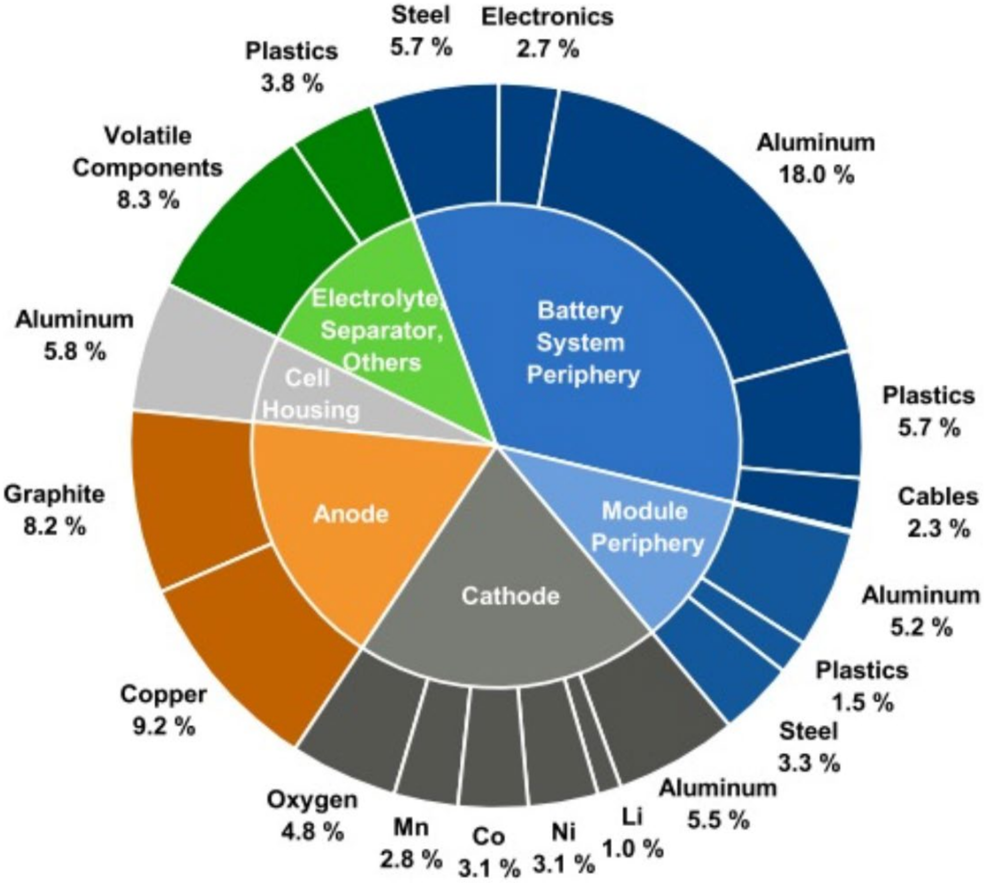


Figure 3: Generic composition of EV battery system

3.0 Solar hot water systems

Solar hot water systems comprise a storage tank and a series of solar collectors – mounted on the roof or otherwise. The solar collector collects and/or concentrates solar radiation from the Sun and is used for active solar heating and allow for the heating of water.

3.1. Solar hot water panels

There are many different types of solar collectors. Flat plate collectors are metal boxes that possess a transparent glazing cover that sits over top a dark-colored absorber plate over which pipes that contain the water to be heated sit (Figure 4). Evacuated tube collectors use a series of evacuated tubes to heat water.

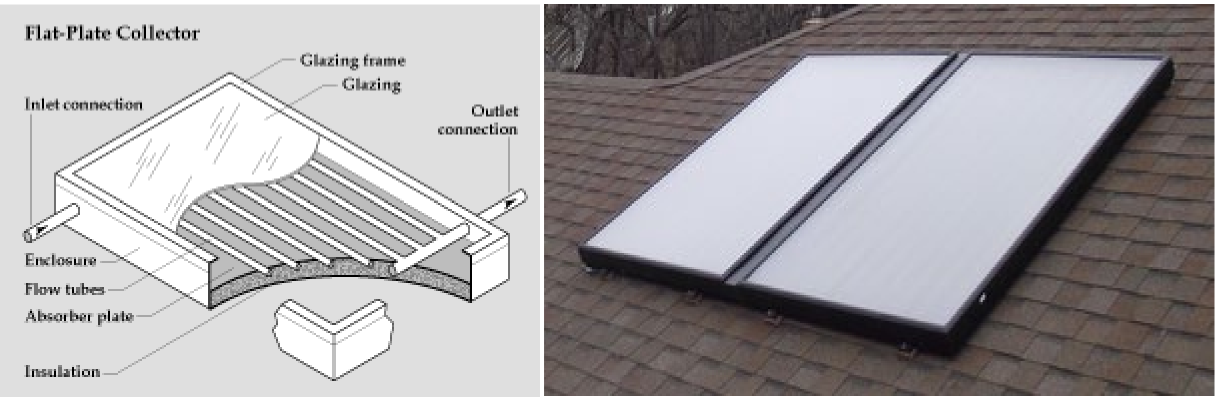


Figure 4. Solar water heater panel.

3.2 Solar hot water ancillary components

The hot water ancillary components include storage tanks or water heater, pumps, mounting hardware, racks, and advanced differential controls (Figure 5). Storage tanks will generally be ASME rated steel with options for lining material and insulation thickness. The controls are comprised of typical electronics. Mounting systems will be made of aluminum, stainless steel or a combination. Pumps will be comprised of copper, stainless steel, plastic, electronics and some glass.

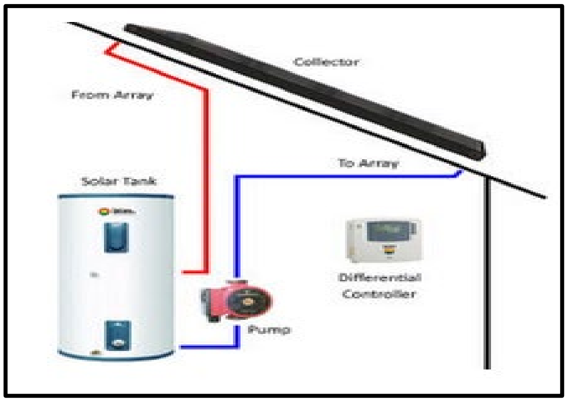


Figure 5. Ancillary components of solar water heater system.

ASSESSMENT OF PENETRATION IN HI

The objective of this section is to quantify the deployment of solar PV, battery storage and solar hot water systems through the year 2030. For this status report, in regard to PV, the current analysis includes all existing systems and those utility systems included in the utilities Stage 1 and Stage 2 procurements. However, we do anticipate additional future residential systems and potentially additional utility scale systems in that timeframe. These additional systems will be included in the final report.

In regard to battery storage, near-term deployment will be dominated by the storage included in the Stage 1 and Stage 2 utility scale systems. While rooftop storage, to date has been relatively small, applications for new permits for systems with storage have accelerated recently and those numbers will also be included in the final report.

With the slower rate of deployment of solar hot water panels and absence of critical materials, analysis of those has been deferred to the final report.

1.0. Photovoltaics

Estimates of PV deployments in Hawai‘i consider three categories of deployment: Residential, commercial, and utility scale. Residential PV systems refer to those at residences (generally roof-mounted, under 20kW). Commercial PV systems refer to those on businesses or serving businesses (roof-mounted and ground-mounted, 20kW to 500kW). Utility PV systems refer to those that sell power to the utility under a power purchase agreement or other PUC-approved program; i.e., Feed-In Tariff, Standard Interconnection Agreement (ground-mounted, over 500 kW).

Data for existing deployments of both residential and commercial have been obtained through Hawaiian Electric Company (HECO) websites or from Hawai‘i State Energy Office (HSEO) data bases. As noted, we have not projected future deployments in these categories for this report but intend to do so in the final. For this report, utility scale solar is based on the successful completion of Stage 1 and Stage 2 solar + storage projects on the HECO grids. Kaua‘i has considerable PV deployment relative to its grid size which is not yet included in this analysis. As appropriate we will address potential future solar developments beyond stage 2 in the final report.

Excluding the island of Kauaʻi, it is estimated that the cumulative installed residential and commercial PV is just under 1000 MW across the islands of Hawaiʻi, Maui, and Oʻahu [6]. This corresponds to approximately 3.5 million PV panels, a number estimated by using HECO assuming an average residential panel output of 250 kW and commercial panel output of 350 kW[7]. For context, the estimated cumulative US mainland installations totals 68,276 MW [22]. As such, Hawaiʻi penetration is approximately 1.5% that of the mainland US. As such, significant guidance on recycle should be available from the US mainland.

Additional detail on the current Hawaiʻi PV deployments is shown in Figures 6 through 9. Figure 6 shows total residential and commercial (combined Hawaiʻi, Maui, and Oʻahu) deployment by year from 2005 through 2020. Figures 7, 8 and 9 show comparable data by island for Hawaiʻi, Maui, and Oʻahu respectively[8].

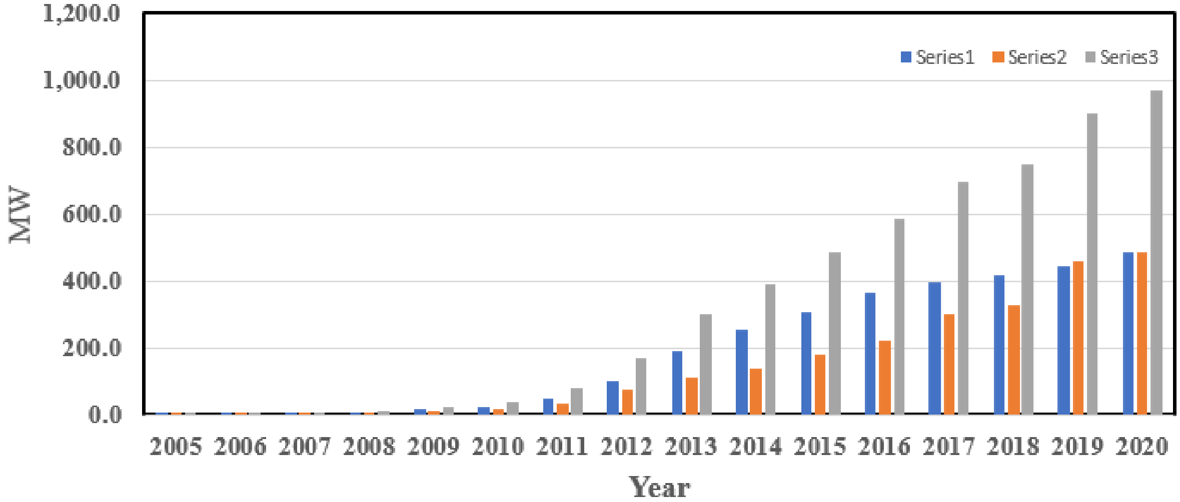


Figure 6. Cumulative installed residential or commercial PV capacity. Series 1 (blue): aggregate residential for the islands of Hawaiʻi, Maui, and Oʻahu; Series 2 (red): aggregate commercial for the islands of Hawaiʻi, Maui, and Oʻahu; Series 3 (grey): aggregate residential + commercial for islands of Hawaiʻi, Maui, and Oʻahu.

---

[6] HECO news release. https://www.Hawaiianelectric.com/2019-saw-21-percent-jump-in-solar-generation-capacity#:~:text=Total%20solar%20capacity%20surged%2021,tracking%20solar%20capacity%20in%202005.

[7] Personal communication: Bob Isler, VP of Power Supply, HECO, Yoh Kawanami, HECO.

[8] These presentations not include data from the Island of Kauaʻi which were not available for this progress report.

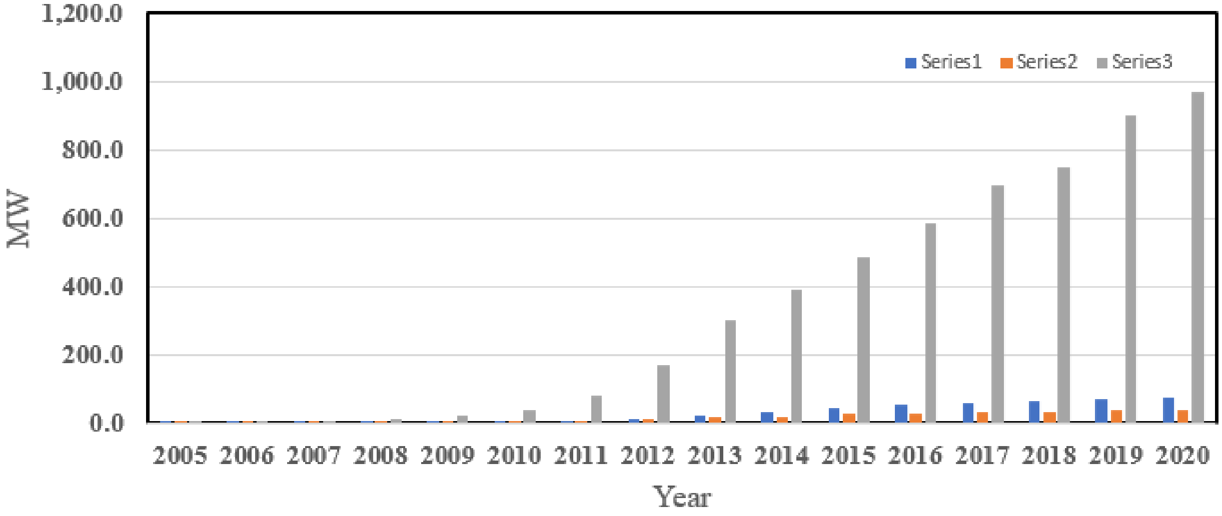


Figure 7. Cumulative installed residential or commercial PV capacity for Hawaiʻi. Series 1 (blue): residential; Series 2 (red): commercial; Series 3 (grey): aggregate residential + commercial for islands of Hawaiʻi, Maui, and Oʻahu.

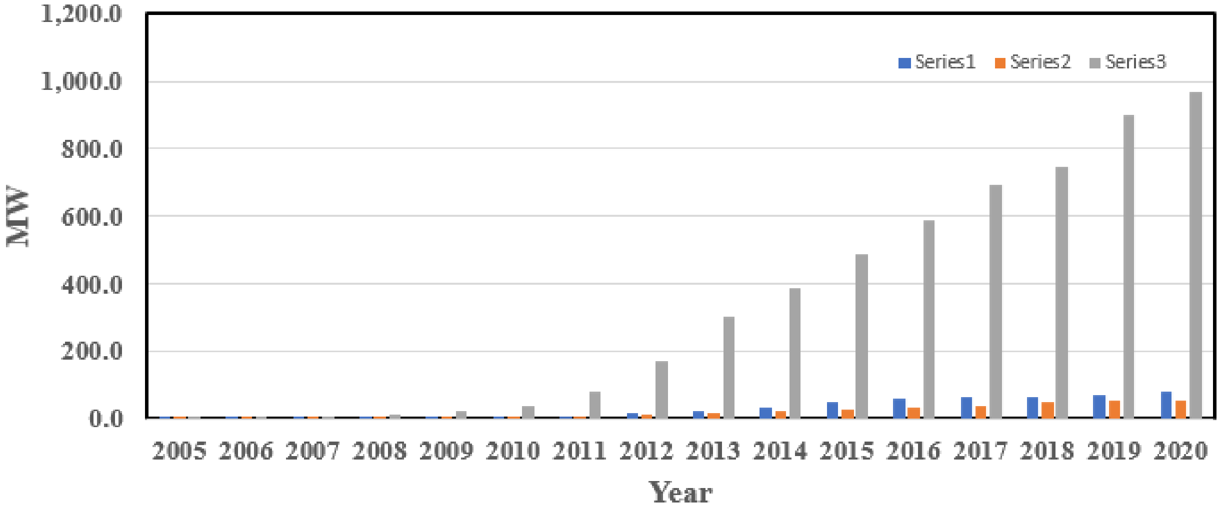


Figure 8. Cumulative installed residential or commercial PV capacity for Maui. Series 1 (blue): residential; Series 2 (red): commercial; Series 3 (grey): aggregate residential + commercial for islands of Hawaiʻi, Maui, and Oʻahu.

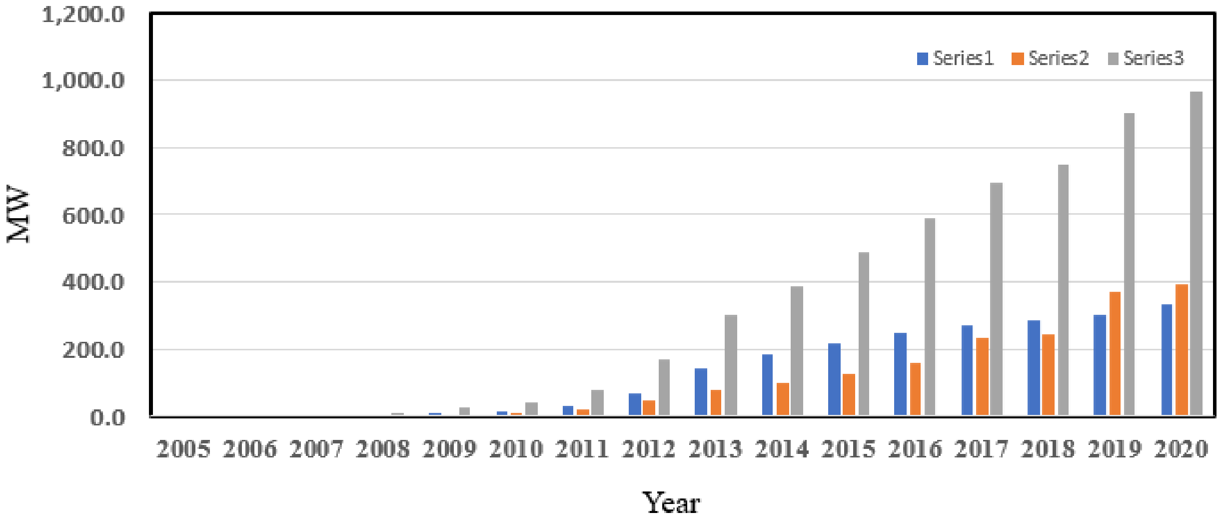


Figure 9. Cumulative installed residential or commercial PV capacity for O‘ahu. Series 1 (blue): residential; Series 2 (red): commercial; Series 3 (grey): aggregate residential + commercial for islands of Hawai‘i, Maui, and O‘ahu.

In recent years, the Hawaiian Electric Company has entered into a number of purchase power agreements (PPA) for utility scale solar projects. While most have been approved by the regulators, a few remain under review. The current status of these projects is summarized in Appendix A, which shows the pdf download from HECO's publicly available Renewable Project Status Board. The project size shown in this table is the nameplate capacity of the project, specified by the maximum output of the inverters. The DC –PV portion of these projects is typically 40% above the AC rating and each has approximately 4 hours of storage, again based on the inverter rating. A representative project schematic scaled to 1MW AC is shown in the Figure 10.

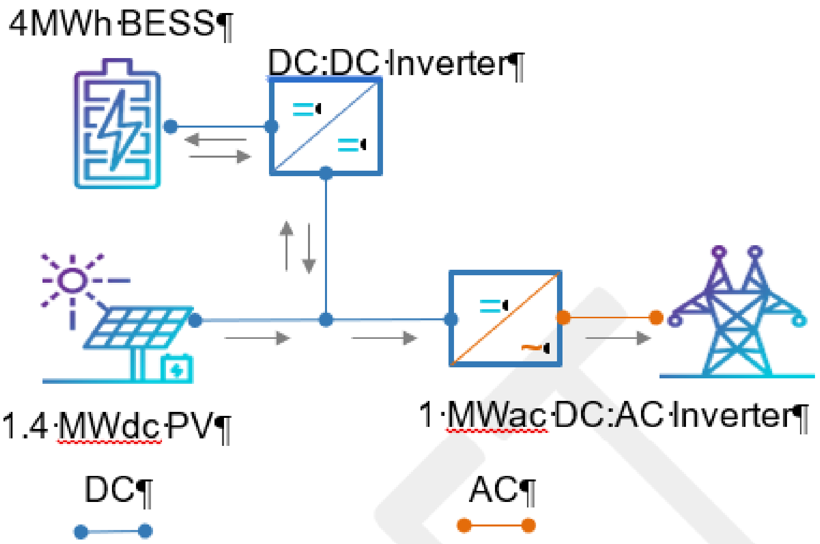


Figure 10: Representative schematic of HECO utility scale PPA

When completed these projects will include a total of 1,180 MW of PV production, more than all cumulative PV installation to date. As described in the next section, the energy storage associated with those projects, plus the 565MWh stand-alone battery at Kapolei on O‘ahu, as well as two smaller projects on Maui and Hawai‘i , will total approximately 3,290 MWh of battery energy storage, orders of magnitude more than currently deployed. A summary of PV capacity of all approved and reviewed utility scale projects is plotted, as a function of island[9], in Figure 11[10] by year of installation. The dates in Figure 11 reflect those shown in the HECO Project Status Board.

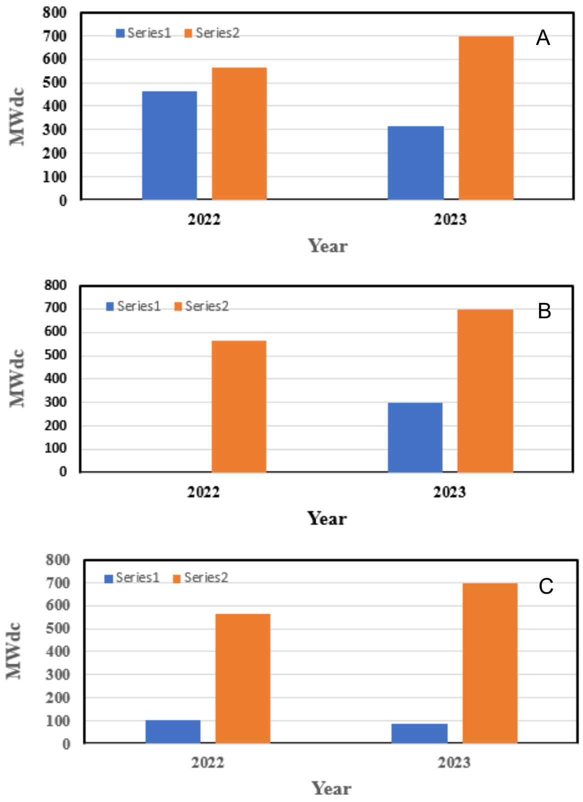


Figure 11. Approved and reviewed utility scale PV as a function of year. Blue: PV for O‘ahu (A); Maui (B); and Hawai‘i (C); Red: aggregate PV for O‘ahu + Maui + Hawai‘i.

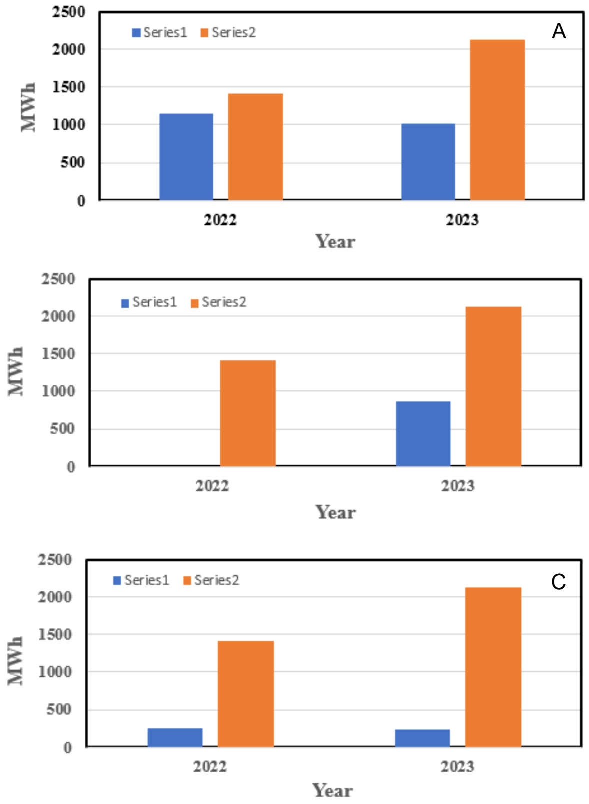


Figure 12. Approved and reviewed utility scale storage as a function of year. Blue: PV for O‘ahu (A); Maui (B); and Hawai‘i (C); Red: aggregate storage for O‘ahu + Maui + Hawai‘i.

---

[9] Data for the island of Kaua‘i is not included in this progress report.

[10] https://energy.Hawaii.gov/Hawaiian-electric-phase2

2.0 Batteries

As described in the previous section, all the new utility-scale PV projects under development include battery energy storage. A summary of storage capacity for all approved and reviewed utility scale projects are plotted, as a function of island[11], for the years 2022 and 2023 in Figure 12[12].

Pre-2017 residential and commercial installations were installed under net-metering agreements and installed photovoltaics and inverter only. HNEI has assumed the amount of battery storage installed with these systems is negligible. Post the termination of net metering agreements, however, residential and commercial installations are expected to include batteries. Permit records show that there has been a recent increase in the number of permits given for solar + storage behind-the-meter installations. As of the end of 2020, for example, 8087 permits were awarded for these installations. Future work will include an assessment of the amount of installed storage associated with these permits, as well as expectations going forward.

While Hawaiʻi ranks highly in the per capita registration of electric vehicles, to date it still represents a small fraction of total vehicles. It is estimated that the percentage of EVs currently on the road is less than one percent of the entire fleet of vehicles in Hawaiʻi. As of the end of 2019, the total number of vehicles was 1,308,344, with 97.8% (1.279,843) being automobiles. While it is difficult to make substantive assumptions about future automobile use, HECO continues to finalize its assumptions for their Integrated Grid Planning (IGP) docket that will project EV penetration for future years. Current IGP numbers forecast that 9% of all automobiles (118,000) will be EWV by 2030 although there is still ongoing debate about the rate of acceptance. HNEI will use the final IGP forecasts to evaluate battery recycle/waste needs from the EV sector. Given the projected lifetime of EV lithium-ion batteries, the significant impact of these vehicles' battery disposal will occur later in the 2030s.

3.0. Solar hot water systems.

Hawaiʻi has one of the most successful solar water heating programs in the country. Although not dominant, the market penetration of solar water heaters in Hawaiʻi is impressive. To date, about one in four single-family homes in Hawaiʻi use solar water heaters, with some estimates suggest 90,000 residential solar water heating systems are in operation in Hawaiian Electric service

---

[11] Data for the island of Kauaʻi is not included in this progress report.

[12] https://energy.Hawaii.gov/Hawaiian-electric-phase2

territories[13]. Moreover, in order to further promote the use of solar water heaters, in 2010 the Hawai‘i state legislature mandated the installation in all new homes [23].

---

[13] Estimate courtesy Hawai‘i Energy Efficiency Program. https://www.Hawaiianelectric.com/clean-energy-Hawaii/our-clean-energy-portfolio/renewable-energy-sources/solar.

QUANTITY AND TIMING OF DISPOSAL LOADING RATES

1.0. Photovoltaics.

Solar PV panels and associated ancillary components are predicted to become responsible for significantly higher amounts of waste per unit energy (kW) than any other source of electric energy generation [24]. PV panels are generally accepted to have a useful lifespan of approximately twenty-five years [7]. In Hawai‘i, most of the early net metering agreements will become void when panels are replaced[14]. This may reduce the incentive for those early panels being replaced until there are significant malfunction. Moreover, failure rates are estimated at approximately one percent per year[15]. These and other considerations have led to *estimated* lifetimes of 25 years[16]. Using this as a baseline, the predicted capacity of PV to be discarded can be estimated. As an example, Figure 13 presents estimated capacity to be discarded as a function of year. These values only consider currently installed residential and commercial PV although utility scale will be included in future reports.

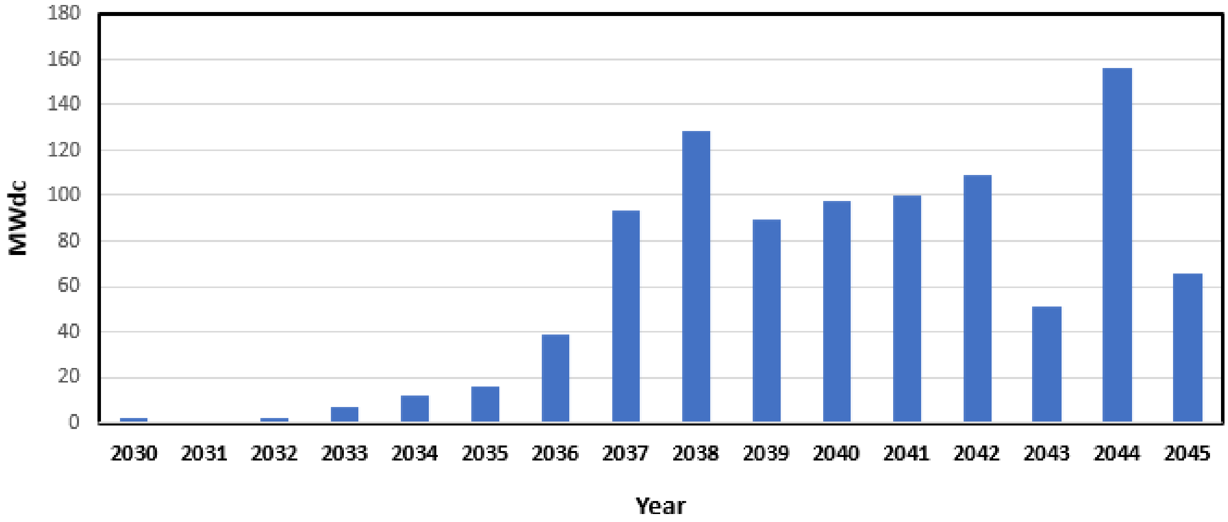


Figure 13. Estimated capacity loading rate through 2045.

The predicted MW disposal rate presented in Figure 13 can now be combined with the material compositions presented in Table 1 to predict the materials loading rate (i.e. waste disposal) as a

---

[14] Personal communication: Bob Isler, VP of Power Supply, HECO.

[15] Weaver, John. Recycling solar panels: Making the numbers work. PV magazine. September 21, 2021.

[16] Weaver, John. Recycling solar panels: Making the numbers work. PV magazine. September 21, 2021.

function of year. For example, relative loading rates for a broad range of PV material streams are presented in Figure 14. These estimates are based solely on installed PV and do not yet represent projected growth of photovoltaics and batteries for utility, commercial and residential scale development. This will be addressed in the final report. Most evident from Figure 14 is the dominant materials are glass, aluminum frame, EVA polymer and Tedlar backing, followed by an assortment of metals.

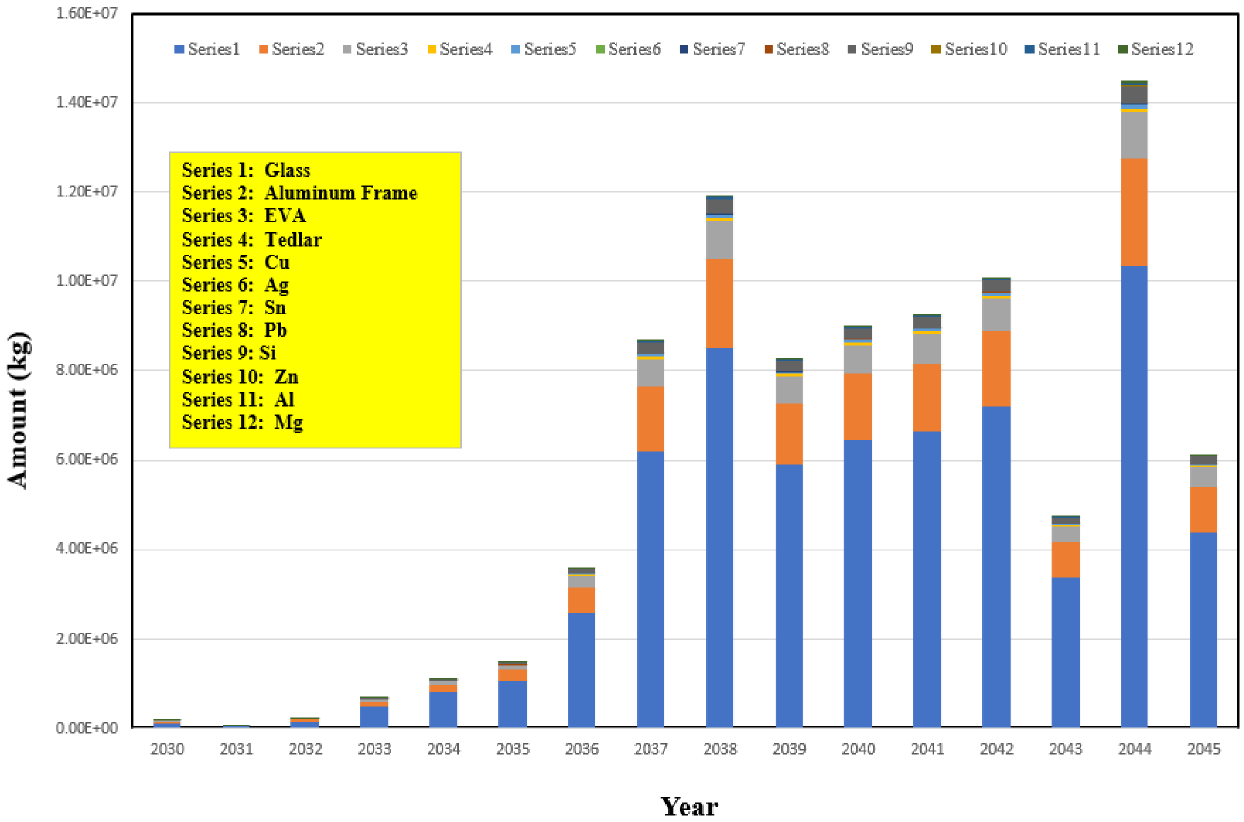


Figure 14. Estimated relative disposal loading rate of PV elements through 2045.

The data can be further broken down in any given year to more fully present the relative disposal loading rates and their contribution to the overall mass of all material disposed. A representation from the year 2040 is plotted in Figure 15. From this presentation it can be seen that that in this year some 71% of the aggregate mass disposed (~ 7 million kilograms) is glass, 17% is aluminum, 8% is EVA, 2% is silica and the remainder comprised of decreasing percentages of Tedlar, copper, magnesium, aluminum (from circuits), lead, zinc, silver and tin.

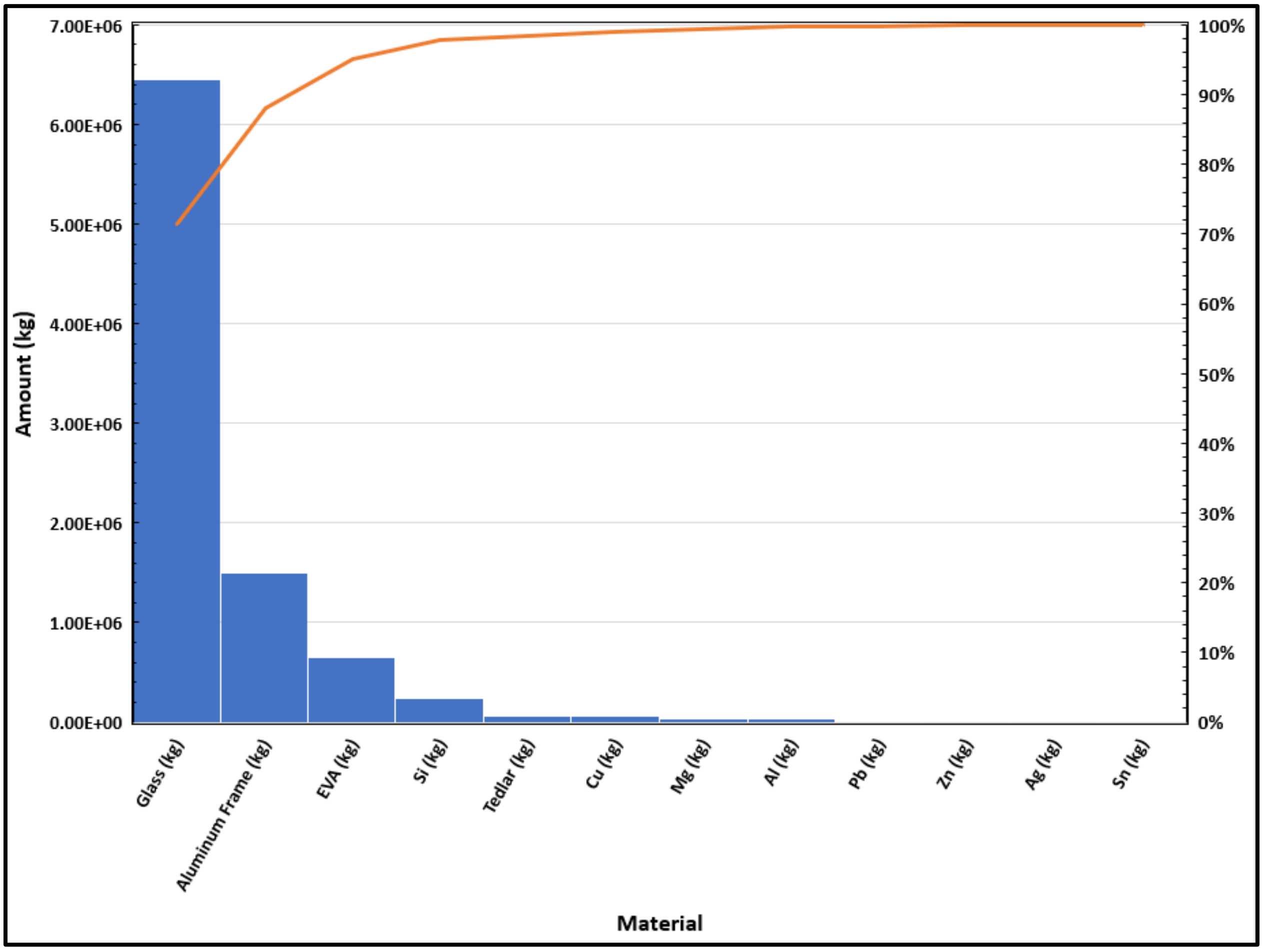


Figure 15. Estimated relative disposal loading rate of PV elements in the year 2040.

2.0. Battery Systems

Lithium ion batteries need to be replaced when the battery effectiveness depletes to below 70–80% of the initial capacity [25]. Lithium ion batteries have a lifespan of about 1 to 3 years for portable electronic devices and around 5 to 8 years for first-time use in electric vehicles [26]. The lifespan for PV system lithium ion batteries for energy storage systems (residential, commercial, and utility) is currently projected to be around 15 to 20 years.

In Hawaiʻi, there is a growing demand for electric vehicles and energy storage systems (both utility-scale and behind-the-meter). While this is a new phenomenon, there will be a significant need for either disposal or recycling options by the end of this decade. This demand will mirror similar demands in other regions. For example, Call2Recycle, an organization that supports the collection of lithium ion and other batteries for recycling, saw a 36% year-over-year increase in their lithium ion battery collection volume in 2019 [27]. In China, the number of lithium ion batteries produced in 2019 alone was 15.722 billion units, with that number projected to grow to 25 billion units in 2020 and a total weight of 500,000 tons [26].

3.0. Solar hot water systems

Estimating the disposal rate of solar hot water heaters is more challenging. These are off grid independent appliances and records of purchase and installation are spread over a vast array of installers. Lifetimes vary across manufacturers and disposal is often a personal decision of homeowners influenced by a variety of issues including maintenance, renovation, fault, and buyer incentive programs.

BEST PRACTICES FOR COLLECTION, DISPOSAL, AND RECYCLING OF CLEAN ENERGY MATERIALS

Under the Resource Conservation and Recovery Act (RCRA), anyone generating solid wastes must determine if they are hazardous waste (HW). A solid waste can be determined to be hazardous either because it is specifically listed as hazardous in the regulations, or because it exhibits a hazardous, characteristic (ignitability, corrosivity, reactivity, or toxicity).

1.0 Photovoltaics.

Solar PV panels in Hawaiʻi contain hazardous elements such as those listed in Table 1, which at certain concentrations are classified as hazardous waste [7]. Various reclaimable resources in PV waste such as silicon, glass, aluminum (Al), copper (Cu), and silver (Ag) are also present [28].

The disposer is required to perform a hazardous waste determination, using analytical test results or generator knowledge. If analytical testing is performed, then the U.S. EPA and the State of Hawaiʻi Hazardous Waste Program require the use of the Toxicity Characteristic Leaching Procedure (TCLP) to determine if a waste exhibits the characteristic of toxicity under the Resource Conservation and Recovery Act (RCRA). If the disposer uses generator knowledge, this knowledge must be from a legitimate and documented source, such as materials safety data sheets (MSDS) for the PV module waste. Rather than making a hazardous waste determination on each individual solar panel, a generator may decide to assume that all waste PV modules are hazardous and manage the waste panels as hazardous waste. In Hawaiʻi, PV panels may be managed as universal waste under chapter 11-273.1, HAR. Universal waste solar panels are prohibited from being commingled with other universal wastes, such as electronic items, due to the need to comply with the specific requirements associated with each waste stream. Each solar panel, container or pallet containing solar panels, or designated universal waste solar panel storage area demarcated by boundaries, must be labeled or marked clearly[17].

Not all PV modules will be hazardous. Analytical test results, using federal and California-specific toxicity test procedures, show that older PV modules have greater potential for the hazardous characteristic of toxicity due to the use of elements of concern, such as lead in solders and hexavalent chromium (Cr+6) in coatings. Cadmium telluride (CdTe) modules may also have hazardous characteristic of toxicity due to the cadmium; gallium arsenide (GaAs) modules due to

---

[17] with one of the following phrases: “Universal Waste—solar panel(s)”, or “Waste solar panel(s)”, or “Used solar panel(s)” [40 CFR section 273.14(h) and 273.34(h), as incorporated and amended in chapter 11-273.1, HAR].

arsenic; and thin film modules, such as copper indium gallium selenide (CIS/CIGS) modules due to copper and/or selenium. However, as discussed in Sections 1 and 2, nearly all of the current solar energy systems in Hawaiʻi are silicon-based crystalline cells (c-Si) and with no significant deployment of thin film technology other than for testing purposes.

1.1. Panels

The end of life treatment of PV panels requires the development of recycling processes for the main components: glass, silicon (Si), and aluminum (Al), along with less concentrated but still valuable elements such as silver (Ag) and copper (Cu) [28]. If the separation processes are inadequate, these and other toxic elements (e.g. lead (Pb), cadmium (Cd), and other elements) can leach into the environment [29]. The recycling of PV panels is complex and involves the dismantling of discarded panels that were vacuum sealed under mild heating to ensure that the plastic ethyl vinyl acetate polymer - used to ensure a seal between the front glass sheet and the rear polyvinyl fluoride lamination sheets – was fully melted (Figure 16) [4]. To that end, recycling of PV panels will generally comprise several steps: (i) collection, (ii) transport, (iii) dismantling, (iv) separation of non-compositional materials, and (v) refinement of such materials [7, 30].

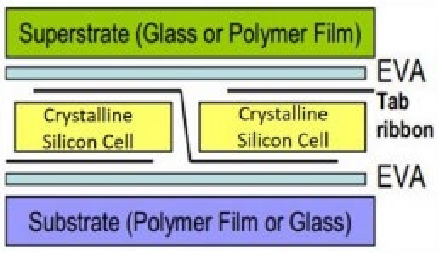


Figure 16. EVA layer.

Collection and transport refer to the collection of PV panels and their transfer to central process facilities. Dismantling involves separation of the junction box and frame from the solar cell. Separation of the non-compositional materials refers to various multi-step separation processes such as incineration (i.e. pyrolysis) or delamination (i.e. separation of the EVA polymer film from the solar cell) followed by metal extraction and purification [31]. The reason for either of these steps is because even when the glass layer is removed mechanically, the adhesive material remains glued to the semiconductor material, making its recovery difficult [6]. Incineration refers to the high temperature combustion of the panel (minus the junction box and frame) to gas emissions, hazardous fly ash and a bottom ash that is subjected to various treatments (sieving, filtration, electrolysis) to recover select elements such as scrap aluminum, silicon, silver and copper [30]. Delamination, by contrast, generally refers to (although variations will occur) a lighter application of thermal (or chemical with organic/inorganic solvents) treatment to remove/decompose the EVA polymer film prior to additional steps to recover the underlying valuable elements [32-34]. Other methods such as mechanical treatment (e.g. crushing) of the solar cell followed by various chemical recovery techniques have also been applied to PV modules [4, 31].

In Hawaiʻi, PV panels may be managed under the universal waste regulations[18]. While generators of PV panels may not landfill them, their management under universal waste regulations allows island-based recyclers/salvagers to collect, consolidate, and ship them to mainland recyclers (under an EPA identification number, EPID#) for recycling or hazardous waste disposal[19]. Universal waste handlers are required to contain PV modules in a manner that prevents breakage and release of any constituent of a PV module to the environment during transport and storage. Universal waste storage requirements are performance based and do not specify in the manner in which PV modules must be stored to prevent breakage and release, but examples include placing PV modules in containers or placing them on a pallet and shrink wrapping that pallet. Storage and transportation requirements are meant to protect the environment and human health by preventing harmful PV module constituents from potentially leaching into soil or water. Universal waste handlers are required to immediately clean up any PV module or PV module constituent(s) if the module is accidently or unintentionally broken, in order to prevent release of potentially hazardous constituents to the environment. Broken pieces must be cleaned up and containerized as to minimize the potential release and containers must be structurally sound and prevent releases under reasonably unforeseeable conditions.

Collection in Hawaiʻi will occur across islands and may require ocean transport to centralized collection points. Dismantling (i.e. separating the frame and junction box from the solar panel) would reduce shipping costs if conducted in Hawaiʻi. However, while removal of the junction box requires only a relatively simple step of detachment, removal of the frame requires a more aggressive mechanical step of breaking a sealant that cements the frame to the glass and backing sheet. Currently, removal of the frame and all subsequent steps are regulated as treatment that requires a hazardous waste permit [see chapters 11-264.1 and 11-270.1, HAR]. Separation of the non-compositional materials is a far more complex process based on physical treatments, chemical treatments, or a combination of both [30]. Although judged economically and technologically feasible in the US, these processes nonetheless require careful forethought, technical design, and business models [35]. In general, these processes implement some combinations of high

---

[18] PV panels are assumed to be characteristic hazardous waste based on testing that has been conducted and published. Some panels have tested high in heavy metals such as lead. Different panels from different manufacturers, may have different results. Managing all the panels as universal waste eliminates the cost of testing for each model line for each manufacturer.

[19] The reduced obligations of the universal waste regulations offer additional cost savings. Panels can be sent for recycling without using a uniform hazardous waste manifest and handlers can store the panels for up to a year to collect enough to make shipping them more economical.

temperature heat treatment (e.g. pyrolysis [36]), mechanical treatment (crushing and sieving [33]), and/or chemical treatments (solvents/acids/bases [37]) to recover targeted elements. Their implementation in Hawaiʻi is permissible under a hazardous waste management permit [see chapters 11-264.1 and 11-270.1, HAR]. That said, these processes are energy intensive and will require significant important and management of concentrated hazardous chemicals (shipping, transport, storage, waste treatment) [38].

Cabling and inverters are the principle ancillary components. In Hawaiʻi they will likely fall under a category of universal waste called "electronic items". As most electronic waste is hazardous waste (in Hawaiʻi, universal waste) it is expected that a hazardous waste determination will need to be made, and assuming all are hazardous will be managed as universal waste along the lines of the PV panels (discussed above).

2.0 Battery Systems

EPRI recently completed a survey of publicly available information on large-scale battery systems. From this, an approximate system framework and cost estimate for the decommissioning of a 1-MWh lithium nickel manganese cobalt oxide (NMC) battery-based grid energy storage system was outlined. That estimate was extrapolated to include various lithium ion chemistries, including lithium nickel cobalt aluminum oxide (NCA), lithium iron phosphate (LFP), lithium manganese oxide (LMO), and lithium titanate (LTO) on the modular level. Key regulatory requirements are summarized, and a brief description is provided on possible allocations of end-of-life responsibility. Significant results included:

- Total decommissioning cost for a 1-MWh NMC lithium ion battery-based grid energy storage system is estimated at $91,500.
- Cost breakdowns are as follows: roughly 40% of cost accrues to on-site dismantling and packaging, 30% to transportation costs, and 30% to recycling costs.
- Battery energy density is estimated to have a large impact on total decommissioning costs as a result of manual labor in dismantling and packaging as well as increased transportation and recycling costs.
- Module decommissioning costs range from $50,000–$150,000 depending on energy density and battery chemistry.
- U.S. federal regulations provide only for the transportation and correct packaging and labeling of lithium ion batteries, while state regulations vary.

- New York, California, and Minnesota have the most comprehensive battery recycling regulations, with battery manufacturers being largely responsible for battery collection and for provision of an accessible pathway for responsible disposal and recycling.
- Responsibility for managing end-of-life tasks should be consistent with various opportunities for increased efficiencies and reduced overhead depending on the capabilities of the parties involved.

Currently, lithium-ion batteries (LIBs) are regulated under federal and, in California, state waste rules. Under the Resource Conservation and Recovery Act (RCRA), anyone generating solid wastes must determine if they are hazardous waste (HW). LIBs can be managed as universal waste under the special RCRA HW provisions at 40 CFR Part 273. These provisions are intended to promote safe management of specific HWs (batteries, pesticides, etc.) using simplified management standards, while still ensuring they are safely disposed of as hazardous waste or recycled.

USEPA has historically encouraged waste handlers to manage LIBs under the universal waste battery classification, but these regulations were written before LIBs became commonplace. Therefore, they are not specifically tailored to the management of LIBs with their high energy density and unique chemistry. While LIBs are not a listed waste, they commonly exhibit the characteristic of ignitability due to flammable electrolyte. Some LIBs also exhibit reactivity characteristics which would include them in a hazardous waste category. Additionally, LIBs with cobalt-containing cathodes would be considered hazardous wastes. Since some LIBs possess characteristics of HW, this means that some LIBs are HW. In Hawai‘i, lithium ion batteries can be managed as universal waste under chapter 11-273.1, HAR.

In the near future, it will probably be necessary to develop dedicated LIB disposal and recycling programs and regulations. Recycling of LIBs could alleviate HW problems by diverting batteries that would otherwise be disposed. As noted in earlier sections, there is a growing demand for electric vehicles and energy storage systems (both utility-scale and behind-the-meter). While this is a new phenomenon, there will be a significant need for either disposal or recycling options by the end of this decade.

Recycling could be economically beneficial by decreasing the amount of raw natural resources needed for LIB production, decreasing both the amount of ore that must be extracted from the earth and the amount of greenhouse gases emitted in the process [39]. Since raw materials account for over half of the production costs of LIBs [40], increasing recycling rates could also drive down battery costs.

On the collection side, Call2Recycle, an organization that supports the collection of LIBs and other batteries for recycling, saw a 36% year-over-year increase in their LIB collection volume in 2019 [27].

The ideal end location of a LIB would be a dedicated battery recycler: a facility that is designed to receive LIBs and separate components for recycling into new batteries. In many LIBs, the concentrations of cobalt, nickel, lithium, and manganese exceed the concentrations in natural ores, making spent batteries akin to highly enriched ore [40]. Thus, waste batteries are a valuable resource, and specialty recyclers provide the opportunity to recover these materials. Battery facilities mainly recycle LIBs through mechanical or physical separation, pyrometallurgy, or hydrometallurgy. Some facilities use multiple methods to maximize material recovery. The industry is still growing, so new recycling methods are being developed.

Pyrometallurgy (e.g., smelting) is a process that heats material in a high temperature furnace to extract metals. Units run as high as 1,500 °C and the process can recover cobalt, nickel, and copper, but not lithium or aluminum, which end up in a waste residue called slag [40]. The high heat required causes this process to be energy intensive. An alloy of cobalt, nickel, and copper is the final product, along with residual gases and slag [41]. The resulting alloy requires more processing to extract individual minerals to be used as components in the battery supply chain.

Hydrometallurgy is a chemical leaching process for extracting and separating cathode metals. It generally has lower capital costs than pyrometallurgy. The process can run below 100 °C, requires less energy than pyrometallurgy, and recovers lithium in addition to the other metals recovered by pyrometallurgy [40]. The process uses a liquid bath to extract the metal from batteries, which can be composed of caustic reagents such as hydrochloric, nitric, or sulfuric acids [40]. Different facilities have different processes; for example, one facility crushes batteries under a liquid solution to produce metal solids (known as “black mass”), metal enriched liquid, and plastic fluff [42]. Materials are then sent to metal refiners for purification and sold back into the market to be made into new batteries and other products.

HNEI analysts have held initial discussions with two Nevada recycling start-up companies. As these are new endeavors, processes for recycling are closely held. However, it is known that one plans to focus on hydrometallurgy and one will focus on pyrometallurgy.

3.0. Solar hot water systems

3.1. Solar hot water panels

In Hawaiʻi, solar thermal panels are excluded from the definition of solar (PV) panels under the universal waste (UW) rules - the definition of solar panel does not include solar thermal panels that do not contain photovoltaic cells. Disposal of solar water heater panels can be executed through processes for white goods. Recyclable metals (e.g. copper, aluminum) can be stripped and the remainder sent to recyclers.

3.2. Solar hot water ancillary components

Ancillary components to solar water heaters are processed as white goods. The volumes, overall, are small compared to the material streams of home appliances, instrumentation, cars, and general construction trash (glass, plastic, wood…).

CONSIDERATION OF FEE FOR DISPOSAL OR RECYCLING

1.0 Photovoltaics.

Current costs of landfilling on the mainland are estimated at US$ 1.38 per module and the average recycling cost is US$ 28 per panel [43]. In Europe, by contrast, the price is currently 75¢ for a 250 W panel of 10 kg mass. The significantly lower cost in Europe is attributed to higher volumes and the learning effect [43]. A recent study applied this observation to suggest a subsidy system for the United States starting in 2021 [43]. The authors assumed an installation of 25 GW in 2021, a 25:1 ratio of newly installed to recycled panels, an average panel rating 350 W per pane, and a recycle cost of $18 per panel. Considering 25 new panels per panel being recycled, spreading the cost across 25 GW results in a "fee" of 0.2 cents per watt or approximately $0.78 per 350-Watt panel and just over 1$ per commercial scale panel. The authors further postulated that such a fee system would increase the cost of 7kW residential project by $15, a commercial scale project by a few hundred to a few thousand dollars, and a utility scale project between tens of thousands to a million dollars for a gigawatt scale facility [43]. Finally, the authors point out that although the ratio of new panels per panel being recycled will decrease with time, the cost of recycling panels in the US should significantly fall and offset the greater number of panels being recycled. Shipping PV panels from Hawaiʻi to mainland recyclers will add costs that includes packaging, shipping, and processing.

2.0 Battery systems

Mainland recyclers are beginning to emerge but current disposal/recycling of lithium ion batteries does not pay for itself. This is due in part to the fact that the recycling process is complex - recycling of lithium ion batteries through mechanical or physical separation, pyrometallurgy, or hydrometallurgy. Shipment from Hawaiʻi to mainland recyclers will also incur higher than average shipping costs. That being said, prospects for reduced costs or even profit from recovery of materials is possible. In many lithium ion batteries, for example, the concentrations of cobalt, nickel, lithium, and manganese exceed the concentrations in natural ores, making spent batteries akin to highly enriched ore [40]. Thus, waste batteries are potentially a valuable resource from which specialty recyclers can profitably recover these materials. The industry is still growing, so new recycling methods are being developed.

3.0 Solar hot water systems

Solar water heaters are processed by recyclers who first recover recyclable metals before processing the remaining waste as white goods. The current market price of recyclable metals covers the cost of disposal.

OTHER ISSUES TO CONSIDER FOR MANAGEMENT, RECYCLING, AND DISPOSAL

To date the working group of HNEI, the Department of Health and the HSEO have developed the following draft list of potential key issues to address. These will be covered more fully in the final report.

1.0 Power Purchase Agreements

For utility scale solar + storage, it should be explicitly written into the PPA that the IPP must remove and dispose of the materials – or there should be a fee attached to the PPA that will provide funding for the disposal of these materials. This is similar to the decommissioning fee that all nuclear reactors pay.

6.2. Policy Options to Promote End-of-Life Recycling

6.2.1 Manufacturer agreements

An EPR (Extended Producer Responsibility) or similar model, whereby the manufacturer, reseller, installer, is responsible for the management of the PV panels, electronic items, and batteries, should be considered. In most instances, these energy systems will be installed by contractors working with distributors and manufacturers. Collection of waste at this level appears to be most efficient.

6.2.2 Landfill ban

While Universal Waste and Hazardous Waste regulation will already prohibit the disposal of universal waste PV panels, electronic items and batteries into local municipal solid waste landfills (the State of Hawai’i does not have any hazardous waste landfills), those PV panels or electronic items that do not meet the definition of hazardous waste may be disposed into local landfills. A landfill ban would prohibit the disposal of non-hazardous waste PV panels or electronic items into the landfill and would promote the recycling of these materials as they most economical option next to landfill disposal on the mainland. This option may be feasible if cost-effective recycling options are available.

6.2.3 Pay forward deposit system

Fee charged at purchase) to support a buyback program for green materials that do not carry sufficient recycle payback to pay for their disposal).

6.3. Shipping costs

How to address. Can/should this cost be incorporated into any planned recycling program; not necessarily an individual action/program. For example, incorporated into the fee for recycling/disposal

6.4. Designated recycle packing centers

Are they needed and how should they be designed?

6.5. On island recycling infrastructure

Is it worth investing in upgrading on island ability to treat and recover metals (including toxic) and other recyclables for shipment to mainland recycling centers to reduce costs and to build up local business).

REFERENCES

1. Pellow, M.A., H. Ambrose, D. Mulvaney, R. Betita, and S. Shaw, *Research gaps in environmental life cycle assessments of lithium ion batteries for grid-scale stationary energy storage systems: End-of-life options and other issues.* Sustainable Materials and Technologies, 2020. **23**: p. e00120.
2. Pagnanelli, F., E. Moscardini, A. Atia, and L. Toro, *Photovoltaic panel recycling: from type-selective processes to flexible apparatus for simultaneous treatment of different types.* Mineral Processing and Extractive Metallurgy (Trans. Inst. Min. Metall. C), 2016. **125**(4): p. 221-227.
3. Alajlani, Y., A. Alaswadk, F. Placido, D. Gibson, and A. Diyaf, *Inorganic thin film materials for solar cell applications*. Module in Materials Science and Materials Engineering. 2018: Elsevier B.V.
4. Flavia, C.S.M., P. Altimari, and F. Pagnanelli, *Recycling of end of life photovoltaic panels: A chemical perspective on process development.* Solar Energy, 2019. **177**: p. 746 - 761.
5. Krebs-Moberg, M., M. Pitz, T.L. Dorsette, and S.H. Gheewala, *Third generation of photovoltaic panels: A life cycle assessment.* Renewable Energy, 2021. **164**: p. 556 - 565.
6. Dias, P.R., M.G. Benevit, and H.M. Veit, *Photovoltaic solar panels of crystalline silicon: Characterization and separation.* Waste Management & Research, 2016. **34**(3): p. 235–245.
7. Majewski, P., W. Al-shammari, M. Dudley, J. Jit, S.-H. Lee, K. Myoung-Kug, and K. Sung-Jim, *Recycling of solar PV panels- product stewardship and regulatory approaches.* Energy Policy, 2021. **149**: p. 112062.
8. Choi, J.-K. and V. Fthenakis, *Crystalline silicon photovoltaic recycling planning: macro and micro perspectives.* Journal of Cleaner Production, 2014. **66**: p. 443-449.
9. Xue, Y., K.C. Divya, G. Griepentrog, M. Liviu, S. Suresh, and M. Manjrekar, *Towards next generation photovoltaic inverters.* EEE Energy Conversion Congress and Exposition, 2011: p. 2467-2474.
10. Filho, F., Y. Cao, and L.M. Tolbert. *11-level cascaded H-bridge grid-tied inverter interface with solar panels*. 2010. IEEEAPEC.
11. Domínguez, A. and R. Geyer, *Photovoltaic waste assessment of major photovoltaic installations in the United States of America.* Renewable Energy, 2019. **133**: p. 1188 - 1200.
12. Dominguez, A. and R. Geyer, *Photovoltaic waste assessment in Mexico.* Resources, Conversation & Recycling, 2017. **127**: p. 29-41.
13. Gautam, A., R. Shankar, and P. Vrat, *End-of-life solar photovoltaic e-waste assessment in India: a step towards a circular economy.* Sustainable Production and Consumption, 2021. **26**: p. 65–77.

14. Manimekalai, P., R. Harikumar, and S. Raghavan, *An Overview of Batteries for Photovoltaic (PV) Systems.* International Journal of Computer Applications. **82**(12): p. 28-32.
15. Zubi, G., R. Dufo-Lópeza, M. Carvalho, and G. Pasaoglu, *The lithium-ion battery: State of the art and future perspectives.* Renewable and Sustainable Energy Reviews, 2018. **89**: p. 292–308.
16. Sun, L., C. Wei, D. Guo, J. Liu, Z. Zhao, Z. Zheng, and Y. Jin, *Comparative Study on Thermal Runaway Characteristics of Lithium Iron Phosphate Battery Modules Under Different Overcharge Conditions.* Fire Technology, 2020. **56**: p. 1555–1574.
17. Wang, L., H. Wu, Y. Hu, Y. Yu, and H. Hunag, *Environmental Sustainability Assessment of Typical Cathode Materials of Lithium-Ion Battery Based on Three LCA Approaches.* Processes, 2019. **7**(2): p. 83.
18. Kallitsis, E., A. Korre, G. Kelsall, M. Kupfersberger, and Z. Nie, *Environmental life cycle assessment of the production in China of lithium-ion batteries with nickel-cobalt-manganese cathodes utilizing novel electrode chemistries.* Journal of Cleaner Production, 2020. **254**: p. 120067.
19. Oliveira, L., M. Messagie, S. Rangaraju, J. Sanfelix, M. Hernandez Rivas, and J. Van Mierlo, *Key issues of lithium-ion batteries – from resource depletion to environmental performance indicators.* Journal of Cleaner Production, 2015. **108, Part A**: p. 354-362
20. Hesse, H.C., M. Schimpe, D. Kucevic, and A. Jossen, *Lithium-Ion Battery Storage for the Grid—A Review of Stationary Battery Storage System Design Tailored for Applications in Modern Power Grids.* energies, 2107. **10**.
21. Diekmann, J., C. Hanisch, L. Frobose, G. Schalicke, T. Loellhoeffel, A.-S. Folster, and A. Kwadea, *Ecological Recycling of Lithium-Ion Batteries from Electric Vehicles with Focus on Mechanical Processes.* Journal of The Electrochemical Society,, 2017. **164**(1): p. A6184 - A6191.
22. IRENA, *Renwable Capacity Statistics 2020.* . 2020, International Renewable Energy Agency (IRENA): Abu Dhabi, UAE.
23. Yang, C.-J., *Reconsidering solar grid parity.* Energy Policy, 2010. **38**: p. 3270–3273.
24. Baldwin, S.F., *Quradrenial Technology Review: as Assessment of Energy Technologies and Research Opportunities*. 2015, Department of Energy, USA.
25. Gao, D., Y. Zhou, T. Wang, and Y. Wang, *A method for predicting the remaining useful life of lithium-ion batteries based on particle filter using kendall rank correlation coefficient.* Energies, 2020. **13**(6): p. 4183.
26. Yu, D., Z. Huang, B. Makuza, X. Guo, and Q. Tian, *Pretreatment options for the recycling of spent lithium-ion batteries: A comprehensive review.* Minerals Engineering, 2021. **173**: p. 107218.
27. Call2Recycle. *2020 – A Milestone Year: 8.4 Million Pounds of Batteries Recycled* Call2Recycle, Inc. 11/11/2021. Available from: https://www.call2recycle.org/2020collectionmilestone/.

28. Dias, P., S. Javimczik, M. Benevit, H. Velt, and A.M. Bernardes, *Recycling WEEE: Extraction and concentration of sliver from waste crystalline silicon photovoltaic modules.* Waste Managment, 2016. **57**: p. 220 - 225.
29. Tokoro, C., M. Nishi, and Y. Tsunazawa, *Selective grinding of glass to remove resin for silicon-based photovoltaic panel recycling.* Advanced Powder Technology, 2021. **32**: p. 841 - 849.
30. Latunussa, C.E.L., F. Ardente, G.A. Blengini, and L. Mancini, *Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels.* Solar Enegy Materials & Solar Cells, 2016. **156**: p. 101-111.
31. Tao, J. and S. Yu, *Review on feasible recycling pathways and technologies of solar photovoltaic modules.* Solar Energy Materials & Solar Cells, 2015. **141**: p. 108 - 124.
32. Corcelli, F., M. Ripaa, E. Leccisi, V. Cigolotti, V. Fiandra, G. Graditi, L. Sannino, M. Tammaro, and S. Ulgiati, *Sustainable urban electricity supply chain – Indicators of material recovery and energy savings from crystalline silicon photovoltaic panels end-of-life.* Ecological Indicators, 2018. **94**: p. 37–51.
33. Granata, G., F. Pagnanelli, E. Moscardini, T. Havlik, and L. Toro, *Recycling of photovoltaic panels by physical operations.* Solar Enegy Materials & Solar Cells, 2014. **123**: p. 239 - 248.
34. Klugmann-Radziemska, E., *Current trends in recycling of photovoltaic solar cells and module waste.* Chemistry-Didactics-Ecology-Metrology, 2010. **17**(1-2): p. 89-95.
35. Fthenakis, V., *End-of-life management and recycling of PV modules.* Energy Policy, 2000. **28**(14): p. 1051-1058.
36. Zeng, D.W., M. Born, and K. Wambach, *Pyrolysis of EVA and its application in recycling of photovoltaic modules.* Journal of Environmental Science, 2004. **16**(6): p. 889 - 893.
37. Jung, B., J. Park, D. Seo, and N. Park, *Sustainable system for raw-metal recovery from crystalline silicon solar panels: from noble-metal extraction to lead removal.* Sustainable Chemistry Engineering, 2016. **4**: p. 4079 - 4083.
38. Weckend, S., A. Wade, and G. Heath, *End-Of-Life Management: Solar Photovoltaic Panels*. 2016, International Renewable Energy Agency. p. 41.
39. Dewulf, J., G. Van der Vorst, K. Denturck, H. Van Langenhove, W. Ghyoot, J. Tytgat, and K. Vandeputte, *Recycling rechargeable lithium ion batteries: Critical analysis of natural resource savings.* Resources, Conservation and Recycling, 2010. **54**(4): p. 229 - 234.
40. Jacoby, M., *It's Time to Recycle Lithium-Ion Batteries.* Chemical & Engineering News, 2019. **97**(28): p. 28-32.
41. Harper, G., R. Sommerville, E. Kendrick, L. Driscoll, P. Slater, R. Stolkin, A. Walton, P. Christensen, O. Heidrich, S. Lambert, A. Abbott, K. Ryder, L. Gaines, and P. Anderson, *Recycling lithium-ion batteries from electric vehicles.* Nature, 2019. **575**: p. 75-86.
42. Chen, M., X. Ma, B. Chen, R. Arsenault, P. Karlson, N. Simon, and Y. Wang, *Recycling End-of-Life Electric Vehicle Lithium-Ion Batteries.* Joule, 2019. **3**: p. 2622–2646.

43. Walzberg, J., A. Carpenter, and G.A. Heath, *Role of the social factors in success of solar photovoltaic reuse and recycle programmes.* Nature Energy, 2021. **6**: p. 913-924.

APPENDIX A:

Hawaiian Electric
Renewable Project Status Board

Stage 2 RFP Final Award Group Projects Awaiting Regulatory Approval

Name	Island	Developer	Tech	Size	Estimated Completion	RPS % Points Contribution
Keahole Battery Energy Storage	Hawai‘i Island (Kailua-Kona)	Hawaiian Electric Company	BESS	12 MW, 12 MWh	4/2023	N/A
Barbers Point Solar	O‘ahu (Kapolei)	Innergex	Solar + BESS	15 MW, 60 MWh (BESS)	2023	0.4
Waena BESS	Maui (Kahului)	Hawaiian Electric Company	BESS	40 MW, 160 MWh	2023	0.2

APPROVED BY REGULATORS

Name	Island	Developer	Tech	Size	Estimated Completion	RPS % Points Contribution
AES Kuihelani	Maui (Central Maui)	AES Kuihelani Solar, LLC	Solar + BESS	60 MW 240 MWh (BESS)	10/2023	1.9
AES Waikoloa Solar, LLC	Hawai‘i Island (Waikoloa)	AES Waikoloa Solar, LLC	Solar + BESS	30 MW 120 MWh (BESS)	11/2022	0.8
AES West Oahu Solar, LLC	O‘ahu (West O‘ahu)	AES West Oahu Solar, LLC	Solar + BESS	12.5 MW 50 MWh (BESS)	9/2022	0.4
Hale Kuawehi Solar LLC	Hawai‘i Island (Waimea)	Hale Kuawehi Solar LLC (Innergex)	Solar + BESS	30 MW 120 MWh (BESS)	12/2022	0.8
Ho‘ohana Solar 1, LLC	O‘ahu (Kunia)	Hanwha Energy USA Holdings Corp (174 Power Global)	Solar + BESS	52 MW 208 MWh (BESS)	8/2023	1.4
Kahana Solar	Maui (Napili - Honokowai)	Innergex	Solar + BESS	20 MW, 80 MWh (BESS)	2023	0.7
Kamaole Solar	Maui (Kihei)	Potentia Renewable Developments LLC and Peg Gen Holdings LLC	Solar + BESS	40 MW, 160 MWh (BESS)	2023	1.4
Kapolei Energy Storage	O‘ahu (Barbers Point Harbor)	Energy Storage Resources LLC	BESS	185 MW, 565 MWh	2022	0.1
Kupehau Solar	O‘ahu (Kunia)	Hanwha Energy USA Holdings Corp. (174 Power Global)	Solar + BESS	60 MW, 240 MWh (BESS)	7/2023	1.3

APPROVED BY REGULATORS (Cont’d)

Name	Island	Developer	Tech	Size	Estimated Completion	RPS % Points Contribution
Mahi Solar	O‘ahu (Kunia)	Longroad Development Company, LLC	Solar + BESS	120 MW, 480 MWh (BESS)	2023	3.1
Mililani I Solar, LLC	O‘ahu (Mililani)	Mililani I Solar, LLC (Clearway)	Solar + BESS	39 MW 156 MWh (BESS)	7/2022	1.2
Mountain View Solar	O‘ahu (Wai‘anae)	AES Distributed Energy Inc.	Solar + BESS	7 MW, 35 MWh (BESS)	2023	0.3
Paeahu Solar LLC	Maui (Wailea)	Paeahu Solar LLC (Innergex)	Solar + BESS	15 MW 60 MWh (BESS)	4/2023	0.5
Pulehu Solar	Maui (Pulehu)	Longroad Development Company, LLC	Solar + BESS	40 MW, 160 MWh (BESS)	2023	1.2
Waiawa Phase 2 Solar	O‘ahu (Waiawa)	AES Distributed Energy Inc.	Solar + BESS	30 MW, 240 MWh (BESS)	2023	1.2
Waiawa Solar Power LLC	O‘ahu (Waiawa)	Waiawa Solar Power LLC (Clearway)	Solar + BESS	36 MW 144 MWh (BESS)	9/2022	1.2
Mahi Solar	O‘ahu (Kunia)	Longroad Development Company, LLC	Solar + BESS	120 MW, 480 MWh (BESS)	2023	3.1
Mililani I Solar, LLC	O‘ahu (Mililani)	Mililani I Solar, LLC (Clearway)	Solar + BESS	39 MW 156 MWh (BESS)	7/2022	1.2

BESS = Battery Energy Storage System

PROPOSED, AWAITING APPROVALS

Name	Island	Developer	Tech	Size	Estimated Completion	RPS % Points Contribution
Honua Ola (Hu Honua)	Hawai‘i Island (Pepe‘ekeo)	Hu Honua	Biomass	21.5 MW	TBD	1.6
Puna Geothermal Venture	Hawai‘i Island (Puna)	Ormat Technologies Inc.	Geothermal	46 MW	2022	~4.0

OUT OF SERVICE

Name	Island	Owner	Tech	Size	Estimated Return to Service
Waiau Hydro	**Hawai‘i Island (Hilo)**	**Hawaiian Electric**	**Hydo**	**1 MW**	**TBD**

BESS = Battery Energy Storage System