Characterising Material Stocks for PV Systems and Estimating Material Recovery Potential

Institute for Sustainable Futures

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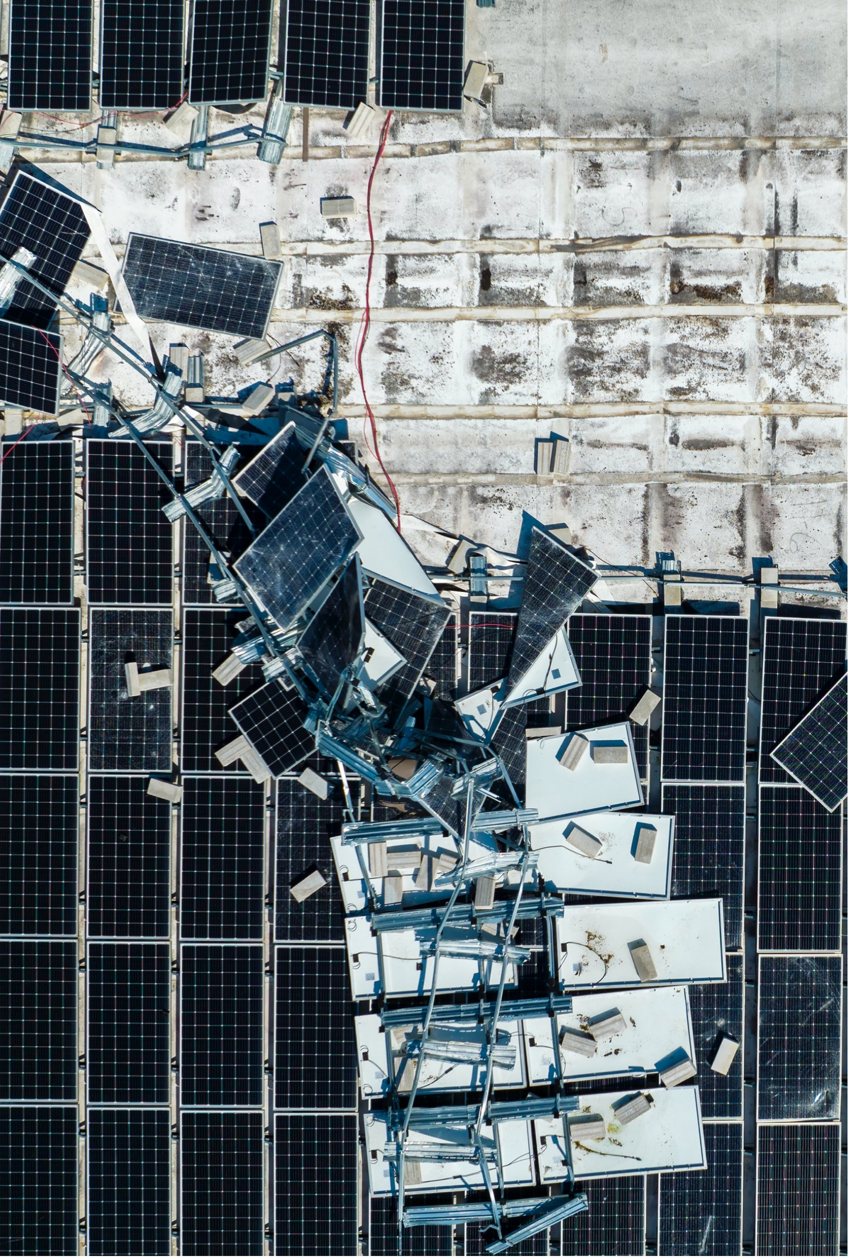
UTS Institute for Sustainable Futures



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This research is part of a broader project led by PV Industries Pty Ltd.

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Summary of Key Findings

Installed **PV and battery capacity** in Australia **expected to significantly increase from 2020 to 2042**, driven by increasing uptake of large-scale systems

Glass, aluminium, copper and plastics make up the majority of **materials in-use** for installed PV systems

EoL material arisings expected to increase from **17,000 tonnes of material in 2020 to 205,000 tonnes in 2042**

68,000 tonnes of potentially recoverable materials from EoL PV systems are **expected in 2030**; mainly glass, aluminium and copper

Queensland, New South Wales and Victoria have the **greatest potential** in terms of **recoverable EoL systems**. Metropolitan areas will see greater opportunity from small-scale system recovery

Advancements in recovery technologies and **expansions in EoL PV systems collection** (e.g., through improved stewardship) **may see an increase in potential recovery of EoL PV systems in the future**

Introduction

This research aimed to investigate the potential of materials recovery from EoL PV system arisings in Australia, from 2020 to 2042. Key aims of this work were:

- Estimate projections of installed capacity of PV systems (PV panels, inverters and batteries) across Australia
- Characterise the in-use material stock of installed systems
- Estimate the EoL arisings and material composition of PV systems
- Assess the quantities of materials potentially recovered from EoL systems

The Institute for Sustainable Futures UTS was commissioned to undertake this research as part of a broader project that aims to investigate the feasibility of a whole-of-supply chain solution for managing EoL PV panels and energy storage batteries in Australia. The project is funded by the NSW Environment Protection Authority through the Circular Solar Grants Program.

Findings from this work and the broader research project support the transition to a circular economy for PV systems in Australia.

Contents

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Methodology

Characterising the material stocks of PV systems, and estimating potential recovery of materials to 2042

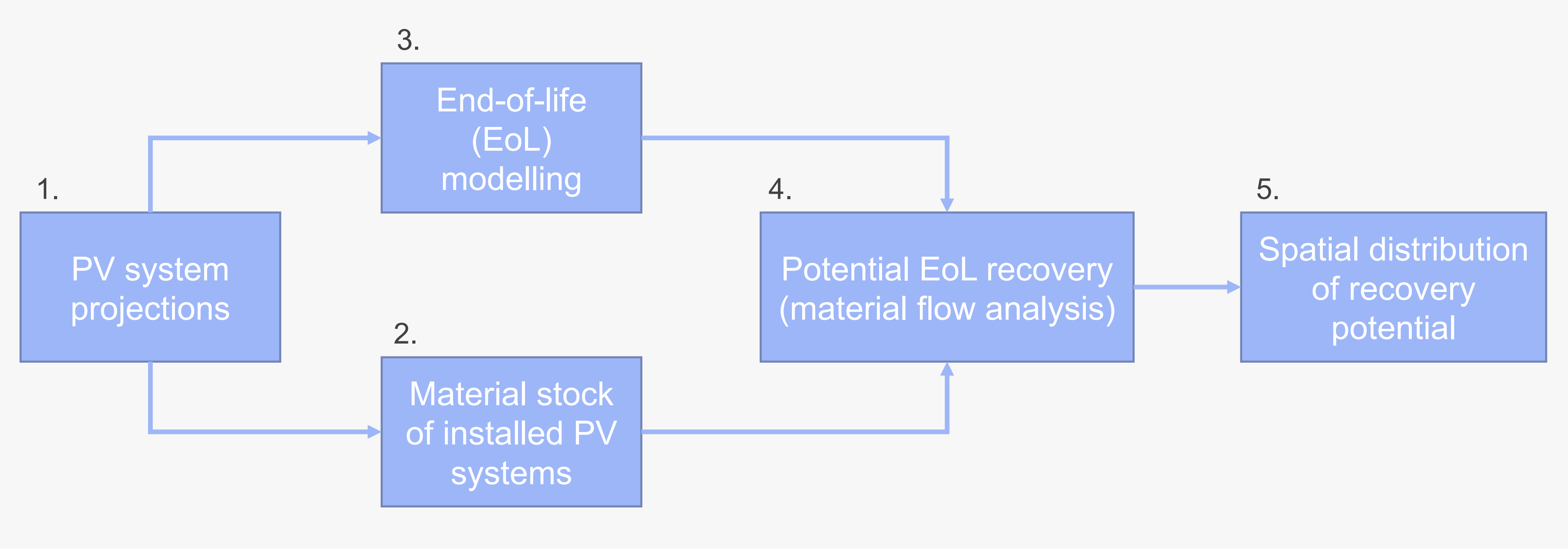
This study investigates the potential for material recovery of EoL PV systems in Australia to 2042

This analysis builds on previous work performed by ISF on end-of-life (EoL) PV and battery systems in New South Wales[1]. This work extends the previous analysis to include all Australian states and territories, as well as inverter installations.

The aims of our study are to: i) estimate the material stocks of PV system installations from 2006 to 2042; ii) estimate the material arisings from EoL PV systems; and iii) estimate the material recovery potential of EoL systems, including the spatial distribution of potential recoverable materials

The geographical scope of our analysis is Australia-wide, with estimates differentiated by sate and territory. The temporal scope is the 2006 to 2042 period for material stocks of installed systems, and 2021 to 2042 for EoL arisings.

The diagram below gives a simplified overview of our analysis, which is explained in further detail throughout this report



[1] ISF (2020). Scoping study for solar panels and battery system reuse and recycling in NSW. Prepared for NSW Department of Planning, Industry and Environment by UTS Institute for Sustainable Futures and Equilibrium, Feb 2020

The scope of study includes PV systems installed between 2006 and 2042

Our study is focused on PV systems, which for the purposes of the analysis, includes PV panels, inverters, and battery storage installations. We also differentiate small (less than 100kW) and large (above 100kW)[1] scale PV and inverters, as well as behind-the-meter (BTM) and virtual power plant (VPP) battery systems. The table below gives an overview of the PV systems in scope of our analysis.

PV system scope	
PV panels installed capacity [MW]	Small (<100kW)[1] systems: e.g., residential rooftop solar, small-medium commercial rooftop solar
	Large (>100kW) systems: e.g., large commercial rooftop solar, solar farm
Inverters installed capacity [MW]	Small systems: assume single inverter installation per 5kW of PV panel installation[2], sized at 1.15 PV capacity[3]
	Large systems: string inverter, number of total inverters based on 1.15 sizing ratio and 500kW string inverter[3]
Batteries installed capacity [MW]	Behind-the-meter (BTM): standalone distributed battery systems (small and large scale)[4]
	Virtual power plant (VPP): network of connected distributed battery systems[5]

[1] System size determined by CER (https://www.cleanenergyregulator.gov.au/RET/Scheme-participants-and-industry/Agents-and-installers/Small-scale-systems-eligible-for-certificates). i.e., small systems are those eligible for small generation unit (SGU) certificates
[2] Ikkurti & Saha (2015). A comprehensive techno-economic review of microinverters for building integrated photovoltaics (BIPV). *Renewable and Sustainable Energy Reviews*, 47, 997-1006
[3] Dominguez & Geyer (2019). Photovoltaic waste assessment of major photovoltaic installations in the United States of America. *Renewable Energy*, 133, 1188-1200
[4] ISF (2020). Scoping study for solar panels and battery system reuse and recycling in NSW. Prepared for NSW Department of Planning, Industry and Environment by UTS Institute for Sustainable Futures and Equilibrium, Feb 2020
[4] AEMO (2022). Australian Energy Market Operator, Integrated System Plan

Material composition of PV systems installed and reaching EoL are considered in our study, to identify potentially recoverable materials

The material scope for our analysis is shown in the table below, with cells coloured dark blue indicating materials that are considered for each PV system component. This material breakdown is based on PV panel, inverter and battery system material composition found from the literature[1,2,3,4]. A more detailed breakdown of proportional system composition is described later in this report.

	PV panels	Inverters	Batteries
Silver (Ag)	■	■	
Aluminium (Al)	■	■	■
Copper (Cu)	■	■	■
Glass	■		
Lithium, cobalt, nickel compounds			■
Lead (Pb)	■	■	
Plastic	■	■	
Silicon (Si)	■		
Steel		■	■
Other metals (e.g., …)	■	■	■

[1]Gautam, Shankar, Vrat (2021). End-of-life solar photovoltaic e-waste assessment in India: a step towards a circular economy. *Sustainable production and Consumption*, 26, 65-77
[2]Dominguez & Geyer (2019). Photovoltaic waste assessment of major photovoltaic installations in the United States of America. *Renewable Energy*, 133, 1188-1200
[3]ISF (2020). Scoping study for solar panels and battery system reuse and recycling in NSW. Prepared for NSW Department of Planning, Industry and Environment by UTS Institute for Sustainable Futures and Equilibrium, Feb 2020
[4]Velazquez-Martinez, Valio, Santasalo-Aarnio, Reuter, Serna-Guerro (2019). A critical review of lithium-ion battery recycling processes from a circular economy perspective. *Batteries*, 5, 68

02

Installed PV system capacity in Australia

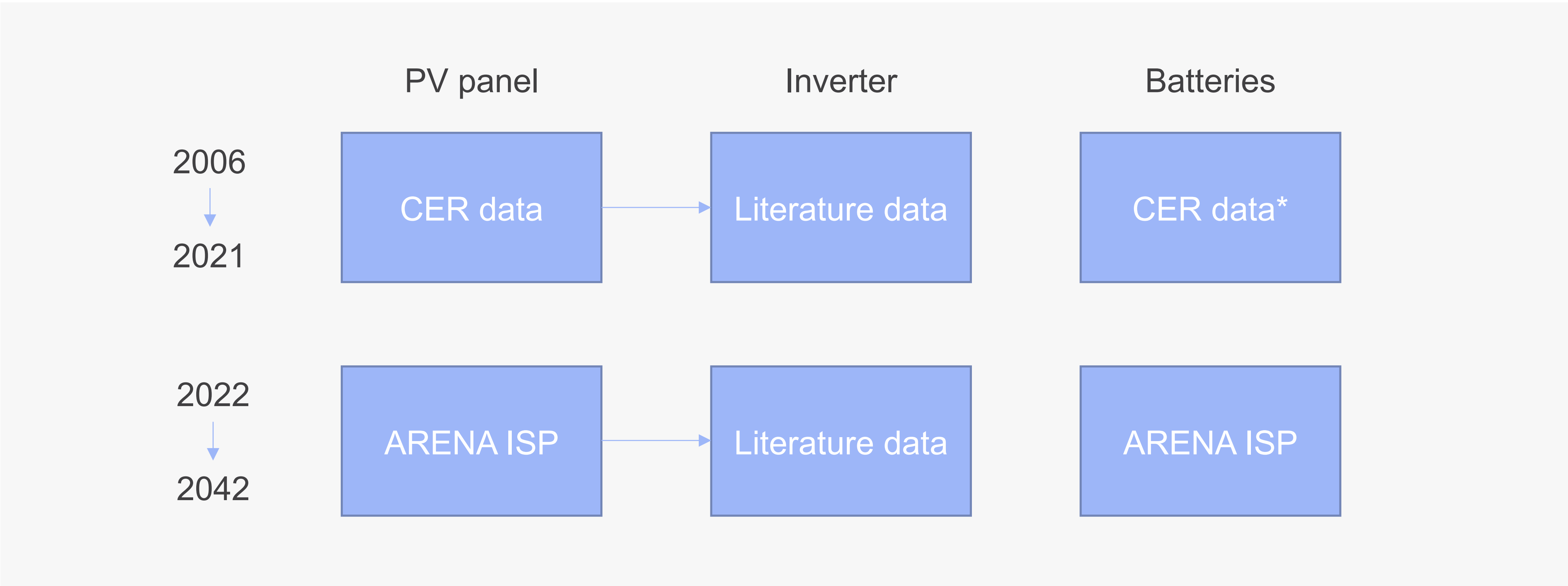
Summary of 2021 data and projections to 2042

Installed PV system capacity is estimated over the 2006 to 2042 period, to estimate EoL arisings, and to identify changes in the material stock over time

Installed PV system capacities over the 2006 to 2042 period were calculated for each Australian state and territory using CER data on PV panel and battery installations from 2006 to 2021, and AEMO ISP data on cumulative installed capacity for 2022 to 2042. For WA and NT which are outside the National Energy Market (NEM) and not included in the ARENA ISP projections, installed capacity from 2022 to 2042 was estimated assuming a linear, year-on-year increase in capacity.

Installed inverter capacity was based on installed PV panel capacity due to limited data, following the method in Gautum et al. (2021), which applies an inverter sizing ratio to the installed PV panel capacity to estimate inverter capacity.

The figure below illustrates which data is used in establishing timeseries of installed capacities by system type



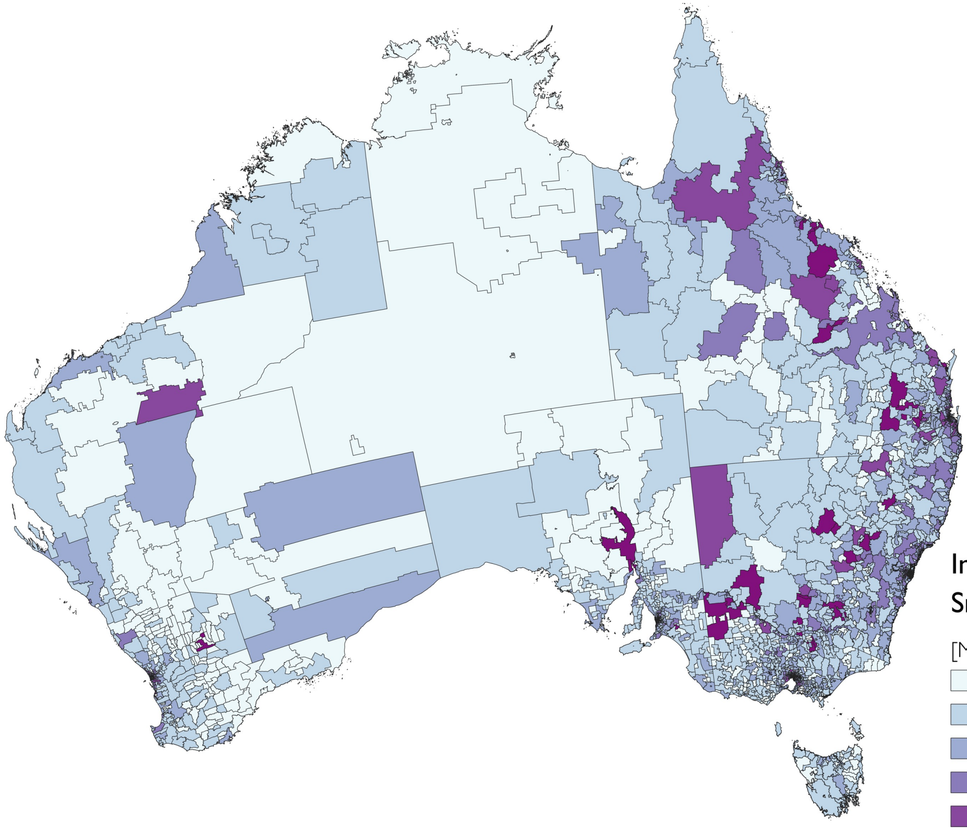
*The CER (2022b) data reports only the number of battery installations by year. An average kW storage capacity per system assumption of 4.316 kW/system, taken from the previous ISF scoping study (ISF, 2020) was used to estimate installed capacity for battery systems

Existing installed capacity of PV systems across Australia in 2021

The table below shows the total installed capacities for small and large PV systems and inverters, as well as VPP and BTM battery systems across Australia in 2021. Data in the table is summarised based the CER data and AEMO ISP projections, which includes data on 2021 installed capacity for BTM and VPP systems. The figure shows the spatial distribution at the postcode level of installed capacity for PV panels only in 2021, from the CER data, which was also utilised to estimate the spatial distribution of end-of-life PV systems on Pages 40 to 42. Note that the CER postcode data does not include data on inverter installations or battery installations at the postcode level.

Installed PV system capacity in 2021 is mainly centred on the east coast and around population centres, with large scale PV systems distributed more regionally.

Juris-diction	Small-scale PV (MW)	Large-scale PV (MW)	Small-scale invert. (MW)	Large-scale invert. (MW)	BTM batt. (MW)	VPP batt. (MW)
NSW & ACT	4,487	2,127	5,220	2,447	50	197
QLD	4,422	2,241	5,086	2,576	31	123
VIC	3,165	1,299	3,640	1,495	32	195
SA	1,858	509	2,137	586	40	300
TAS	213	0	245	0	2	16
WA	1,962	238	2,257	274	12	38
NT	190	59	18	68	2	9
National	16,297	6,473	18,601	7,445	170	878



Installed PV capacity, 2021
Small + large scale

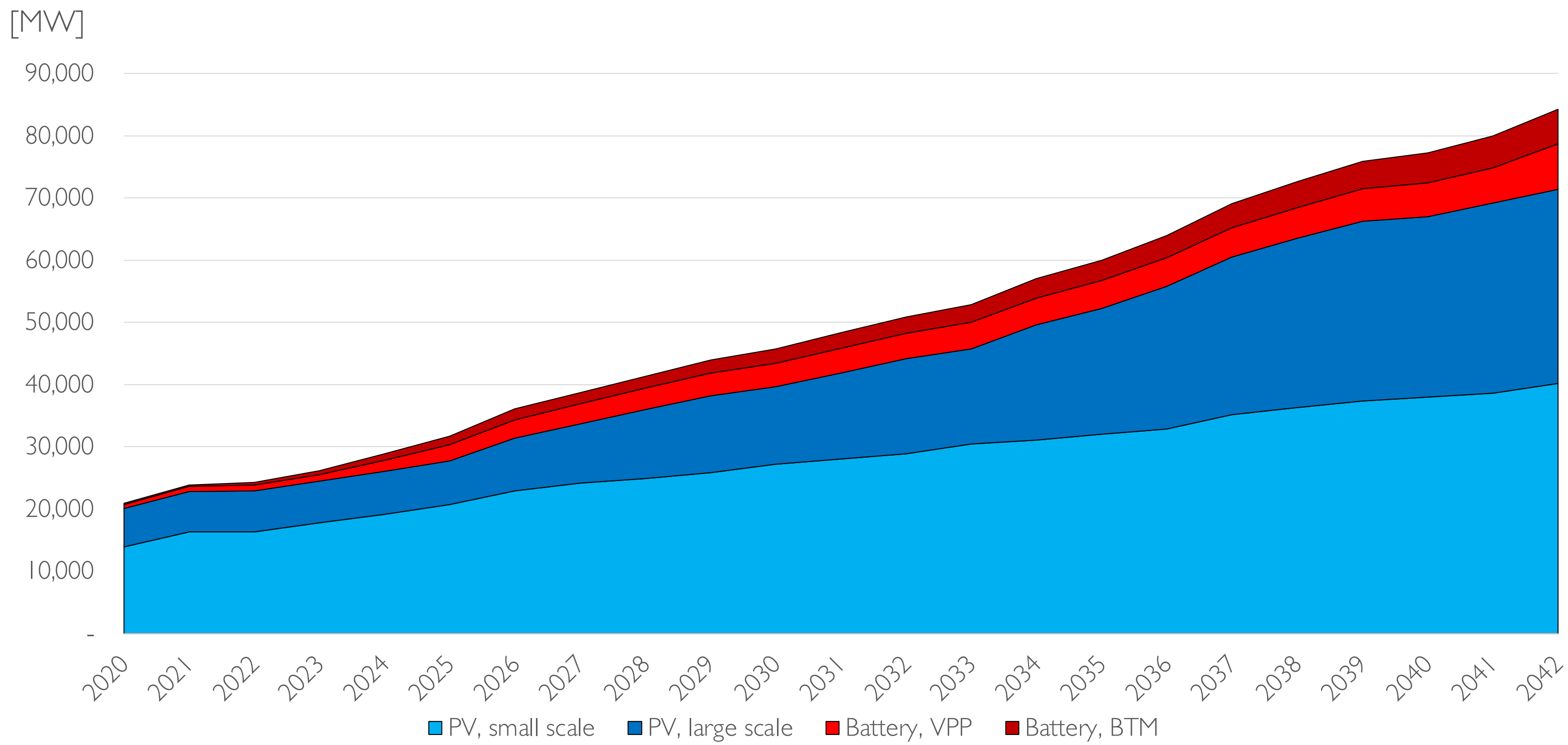
[MW]
- 0 - 0.5
- 0.5 - 5
- 5 - 20
- 20 - 50
- 50 - 100
- 100+

PV system capacity is expected to increase significantly over the 2021 to 2042 period, with battery installations seeing they largest increase in installed capacity

The figure below shows the estimated installed capacity projections for PV systems nation-wide to 2042, based on CER and ARENA data. Installed large scale PV panel capacity is expected to be 31,244 MW in 2042, an increase of 383% compared to 2021 capacity. Small scale PV capacity will also increase significantly to 40,136 MW of capacity—an increase of 189%.

Uptake of battery storage systems will increase significantly by 2042, from 690 MW of installed capacity for VPP systems in 2021, to 7,349 MW in 2042—an increase of 964%. BTM systems will see an even greater increase of approximately 4000% over 2021 capacity, increasing from 135 MW in 2021 to 5,543 MW in 2042.

National installed capacity projections (PV and batteries)

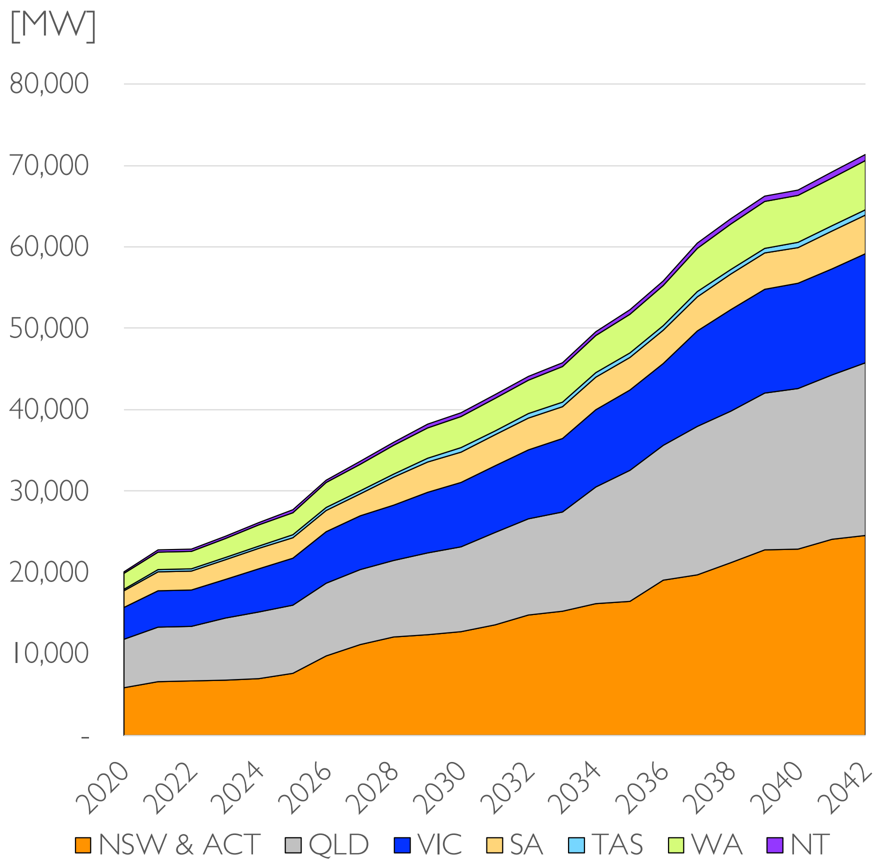


All Australian states will see growth in PV system installed capacities over time, with NSW and Queensland expected to see the largest growth

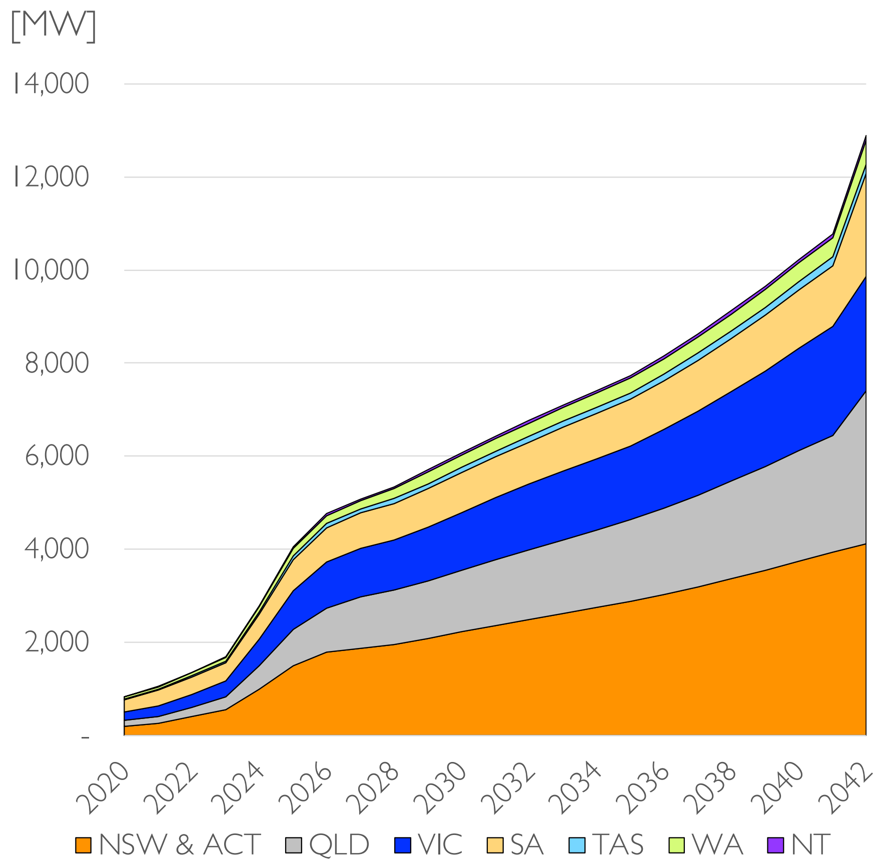
The figures below show projected installed capacity by state for PV panels (left figure) and batteries (right panel). Growth in PV system uptake is relatively consistent across the states and territories, with installed PV capacities projected to increase between approximately 200%±20%. The exceptions to this are NSW, which will see the greatest increase in PV installed capacity of 271% compared to 2021; and South Australia, with a projected increase of only 102%.

For battery systems, increases by state and jurisdiction were more varied. Queensland is expected to see the largest increase in battery capacity, increasing by 2,038% compared to 2021. SA again will see the smallest increase in capacity, with installed battery capacity increasing by 547%. Installed capacities by state/territory are tabulated on the following page

National Installed capacity (PV panels)



National installed capacity (batteries)



Installed capacities by state and jurisdiction—2020, 2030 and 2042

PV panels (small + large)

	NSW & ACT [MW]	QLD [MW]	VIC [MW]	SA [MW]	TAS [MW]	WA [MW]	NT [MW]
2020	5,797	5,992	3,864	2,090	188	1,916	208
2030	12,727	10,380	7,917	3,779	513	3,852	438
2042	24,549	21,193	13,417	4,780	631	6,073	736

Battery (BTM and VPP)

	NSW & ACT [MW]	QLD [MW]	VIC [MW]	SA [MW]	TAS [MW]	WA [MW]	NT [MW]
2020	196	124	177	267	14	38	8
2030	2,224	1,324	1,241	859	111	259	50
2042	4,110	3,291	2,469	2,202	203	517	99

Concluding points on national PV system installed capacity and projections

- Installed PV system capacity is expected to significantly increase Australia-wide over the 2020 to 2042 period
- Battery storage systems will see the largest increases in capacity, expected given that total installed storage capacity was only 825 MW in 2020
- NSW is expected to see the greatest increases in PV system uptake over the 2020 to 2042 period, driven primarily by large-scale solar installations
- Queensland is expected to see the largest increase in battery storage system uptake over the period, driven by increases in BTM systems

03

PV system materials in use in Australia

Material stocks now, and to 2042

In-use material stocks are calculated by estimating the total mass of installed PV systems, and applying assumed system material composition breakdowns

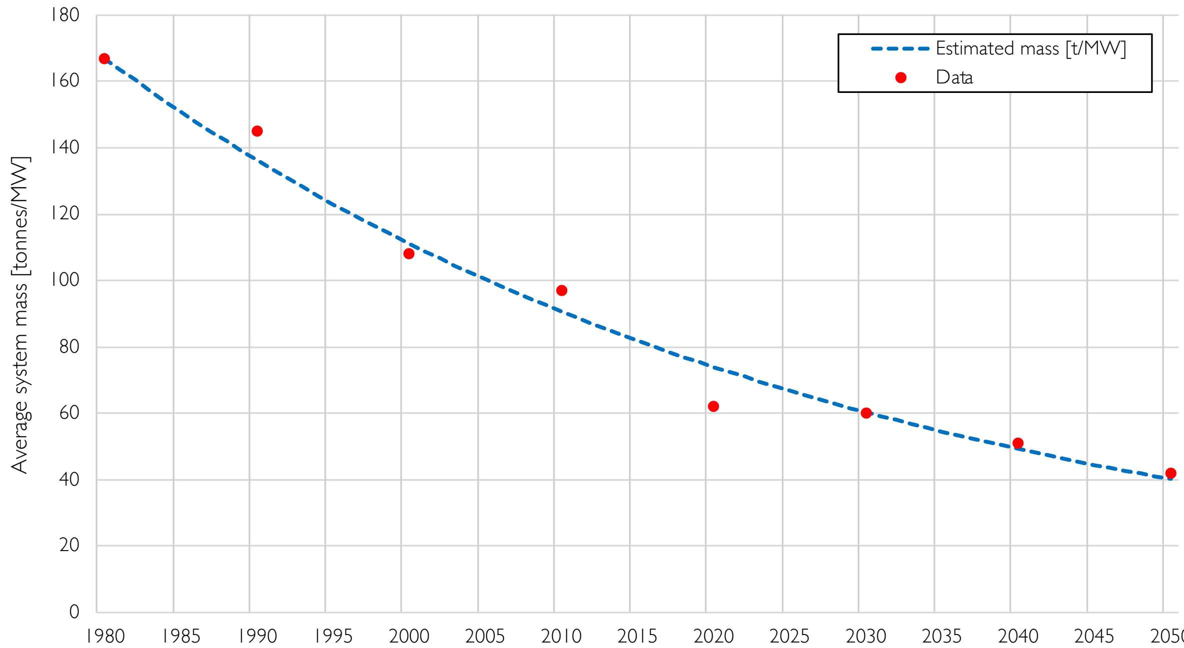
In our study, the 'in-use material stock' is defined as the total mass of installed capacity for PV systems in each year.

PV panel system size, represented as t/MW, was estimated using a negative exponential model, fit to data on system mass[1]. This gives a timeseries of PV panel system size shown in the figure below, reflecting an anticipated decrease in system size through technology development. The modelled PV size was applied to each year's estimated newly installed capacity to estimate installed PV panel material stock in tonnes for each year, e.g., in-use material stock(year T) = [PV mass(year T) * newly installed capacity(year T)] + in-use material stock(year T-1), where *T* is a given year.

Data on system size for inverters and batteries were only available as a static estimates[2,3,4]. These are shown in the table below, and are applied in the same manner as used to estimate the in-use PV material stock

System type	Average system mass [t/MW]
Inverter (small)[2]	7.26
Inverter (large)[3]	3.82
Battery (VPP)[4]	26.1
Battery (BTM)[4]	26.1

PV system size (mass) over time

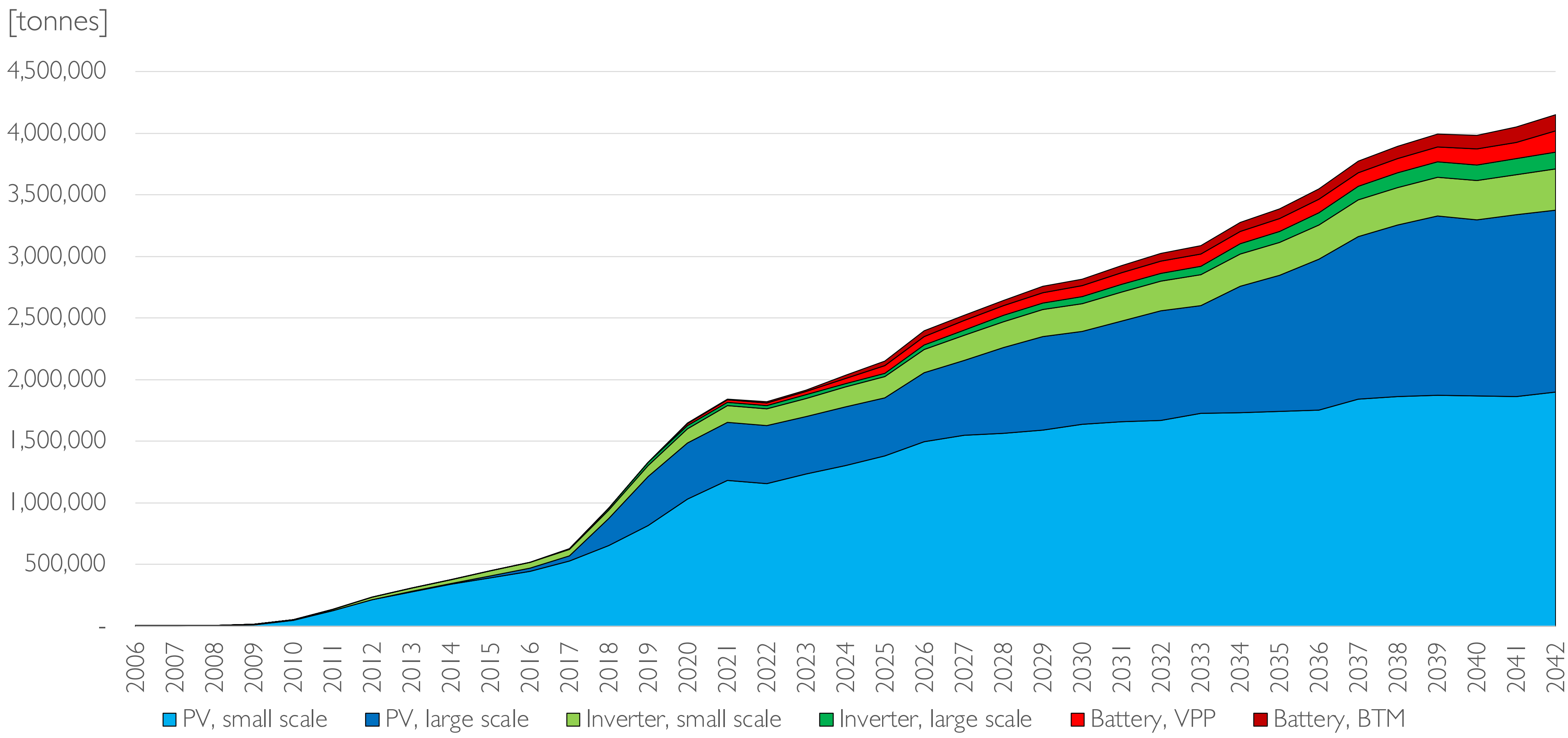


[1]IRENA & IEA-PVPS (2016). *End-of-life Management: Solar Photovoltaic Panels*. International Renewable Energy Agency and International Energy Agency Photovoltaic Power Systems
[2]Ikkurti & Saha (2015). A comprehensive techno-economic review of microinverters for building integrated photovoltaics (BIPV). *Renewable and Sustainable Energy Reviews*, 47, 997-1006
[3]Dominguez & Geyer (2019). Photovoltaic waste assessment of major photovoltaic installations in the United States of America. *Renewable Energy*, 133, 1188-1200
[4]ISF (2020). Scoping study for solar panels and battery system reuse and recycling in NSW. Prepared for NSW Department of Planning, Industry and Environment by UTS Institute for Sustainable Futures and Equilibrium, Feb 2020

Overall, in-use material stock is projected to increase to over 4 million tonnes of material in 2042, mainly consisting of small- and large-scale PV panels

The figure below shows the in-use material stock for PV systems nationally from 2006 to 2042. In-use material stock increases significantly over time, driven by the uptake of PV systems.

National in-use material stock over time by system type



In-use material stock composition

Once estimated, the in-use material stock can be broken down by in scope materials (shown on Page 9) by applying assumed material compositions per system. These compositions are shown in the table below, representing the proportion of total system mass. Data in the below table is derived from a number of literature sources[1,2,3,4]

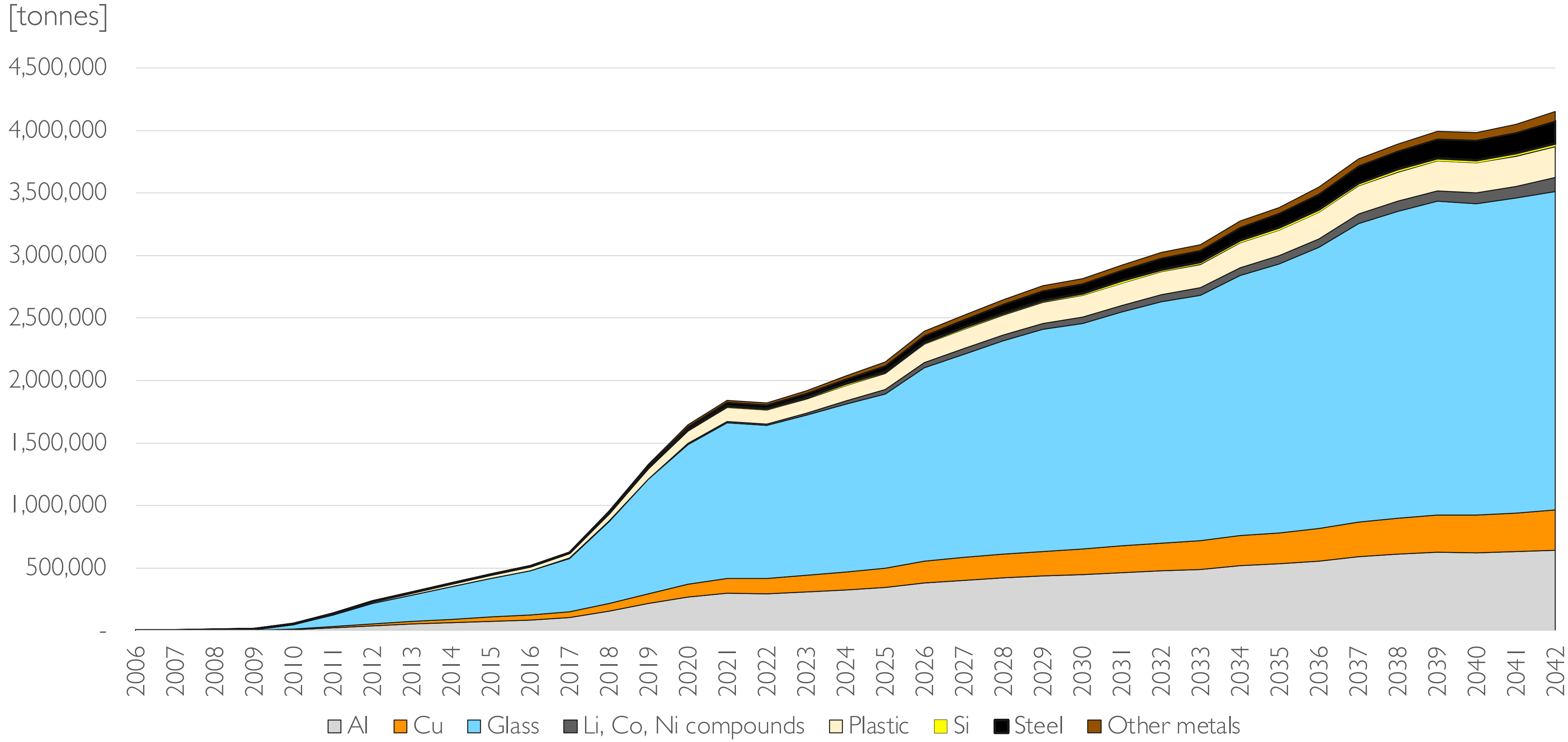
Material	PV, small	PV, large	Inverter, small	Inverter, large	Battery, BTM	Battery, VPP
Aluminium	15.59%	15.59%	27.68%	6.85%	5.42%	5.42%
Copper	0.97%	0.97%	71.62%	17.74%	7.58%	7.58%
Glass	75.44%	75.44%	0%	0%	0%	0%
Lithium compounds	0%	0%	0%	0%	37%	37%
Plastics	6.64%	6.64%	0%	0%	8%	8%
Silicon	0.74%	0.74%	0%	0%	0%	0%
Steel	0%	0%	0%	75.24%	25%	25%
Other metals	0.62%	0.62%	0.7%	0.17%	17%	17%

[1]Gautam, Shankar, Vrat (2021). End-of-life solar photovoltaic e-waste assessment in India: a step towards a circular economy. *Sustainable production and Consumption*, 26, 65-77
[2]Dominguez & Geyer (2019). Photovoltaic waste assessment of major photovoltaic installations in the United States of America. *Renewable Energy*, 133, 1188-1200
[3]ISF (2020). Scoping study for solar panels and battery system reuse and recycling in NSW. Prepared for NSW Department of Planning, Industry and Environment by UTS Institute for Sustainable Futures and Equilibrium, Feb 2020
[4]Velazquez-Martinez, Valio, Santasalo-Aarnio, Reuter, Serna-Guerro (2019). A critical review of lithium-ion battery recycling processes from a circular economy perspective. *Batteries*, 5, 68

Glass makes up 60-70% of the overall in-use PV system material stock, followed by aluminium (~16%) and copper (~7%)

The figure below shows the in-use material stock over time, broken down by major material categories in scope of the analysis. Glass is a significant proportion of the total in-use stock over the time period, expected given that PV panels account for the majority of installed capacity. In-use material stock is further examined on the following page.

National in-use material stock over time by material



In-use material stock for 2021 and 2042

The tables below show the estimated in-use material stock by material category and system for 2021, and 2042. The proportion of in-use stock that is PV panels (large and small) was approximately 89% in 2021, and falls to 80% by 2042 on account of projected growth in battery capacity. This projected growth in battery installations can also be seen in the proportions of battery-specific materials (e.g., lithium compounds, graphite and steel) increasing significantly from a combined 3% of total in-use material stock in 2021, to 9% in 2042.

Plastic is also a significant material type, accounting for approximately 6% of the in-use material stock (248,200 tonnes in 2042). Quantities of steel will also increase over time as new battery capacity and large scale inverters are installed, accounting for approximately 4% of the in-use stock in 2042.

2021 - National in-use material stock by system

[tonnes]	Material											
System	Ag	Al	Cu	Glass	Li, Co, Ni compounds	Pb	Plastic	Si	Steel	Other metals	System total	System share of total
PV, small scale	532	160,140	9,997	775,095	-	47	68,219	7,594	-	5,773	1,027,398	62.41%
PV, large scale	236	71,065	4,436	343,964	-	21	30,274	3,370	-	2,562	455,928	27.70%
Inverter, small scale	91	32,189	83,298	-	-	442	-	-	-	286	116,306	7.07%
Inverter, large scale	5	1,858	4,807	-	-	26	-	-	20,391	16	27,103	1.65%
Battery, VPP	-	879	1,231	-	6,004	-	1,298	-	4,057	2,759	16,227	0.99%
Battery, BTM	-	171	240	-	1,170	-	253	-	790	537	3,161	0.19%
Total	**864**	**266,302**	**104,008**	**1,119,058**	**7,174**	**536**	**100,044**	**10,964**	**25,238**	**11,934**	1,646,123	
Material share of total	0.05%	16.18%	6.32%	67.98%	0.44%	0.03%	6.08%	0.67%	1.53%	0.72%		

2042 - National in-use material stock by system

[tonnes]	Material											
System	Ag	Al	Cu	Glass	Li	Pb	Plastic	Si	Steel	Other metals	System total	System share of total
PV, small scale	982	295,683	18,459	1,431,138	-	87	125,960	14,022	-	10,660	1,896,992	45.72%
PV, large scale	764	230,175	14,369	1,114,069	-	68	98,054	10,915	-	8,298	1,476,712	35.59%
Inverter, small scale	263	92,889	240,376	-	-	1,276	-	-	-	826	335,630	8.09%
Inverter, large scale	27	9,414	24,362	-	-	129	-	-	103,339	83	137,354	3.31%
Battery, VPP	-	9,351	13,091	-	63,873	-	13,810	-	43,157	29,347	172,628	4.16%
Battery, BTM	-	7,052	9,873	-	48,173	-	10,416	-	32,549	22,133	130,196	3.14%
Total	**2,036**	**644,564**	**320,530**	**2,545,207**	**112,045**	**1,561**	**248,240**	**24,937**	**179,045**	**71,348**	4,149,514	
Material share of total	0.05%	15.53%	7.72%	61.34%	2.70%	0.04%	5.98%	0.60%	4.31%	1.72%		

10th Percentile Median 90th Percentile

Concluding points on national in-use material stock

- PV panels account for between 80 to 90% of the total in-use material stock over the 2020 to 2042 period

- PV panel weight (tonnes per MW capacity) is expected to decline over time, from an average of ~70 tonnes per MW in 2020 to ~45 tonnes per MW in 2042

- Glass accounts for the majority of in-use materials, accounting for around 60 to 70% of in-use materials—expected given PV panels account for the majority of in-use materials

- Aluminium, copper, plastic and steel are also significant materials in-use, and are components of PV panels, inverters and battery storage systems

- The in-use material stock composition will likely change over time, on account of changing system mass, and possibly also as advanced technology utilising alternative materials become available

04

End-of-life arisings of PV systems in Australia

Results from lifetime distribution model

EoL arisings of PV systems are modelled following a lifetime modelling approach

The approach used in this study follows that used in the previous ISF study and others in the literature, using a Weibull probability distribution to model when PV systems and batteries reach their EoL based on key parameters, which characterise average EoL periods (the *scale* parameter), and the rate in which installed units reach EoL (the *shape* parameter).

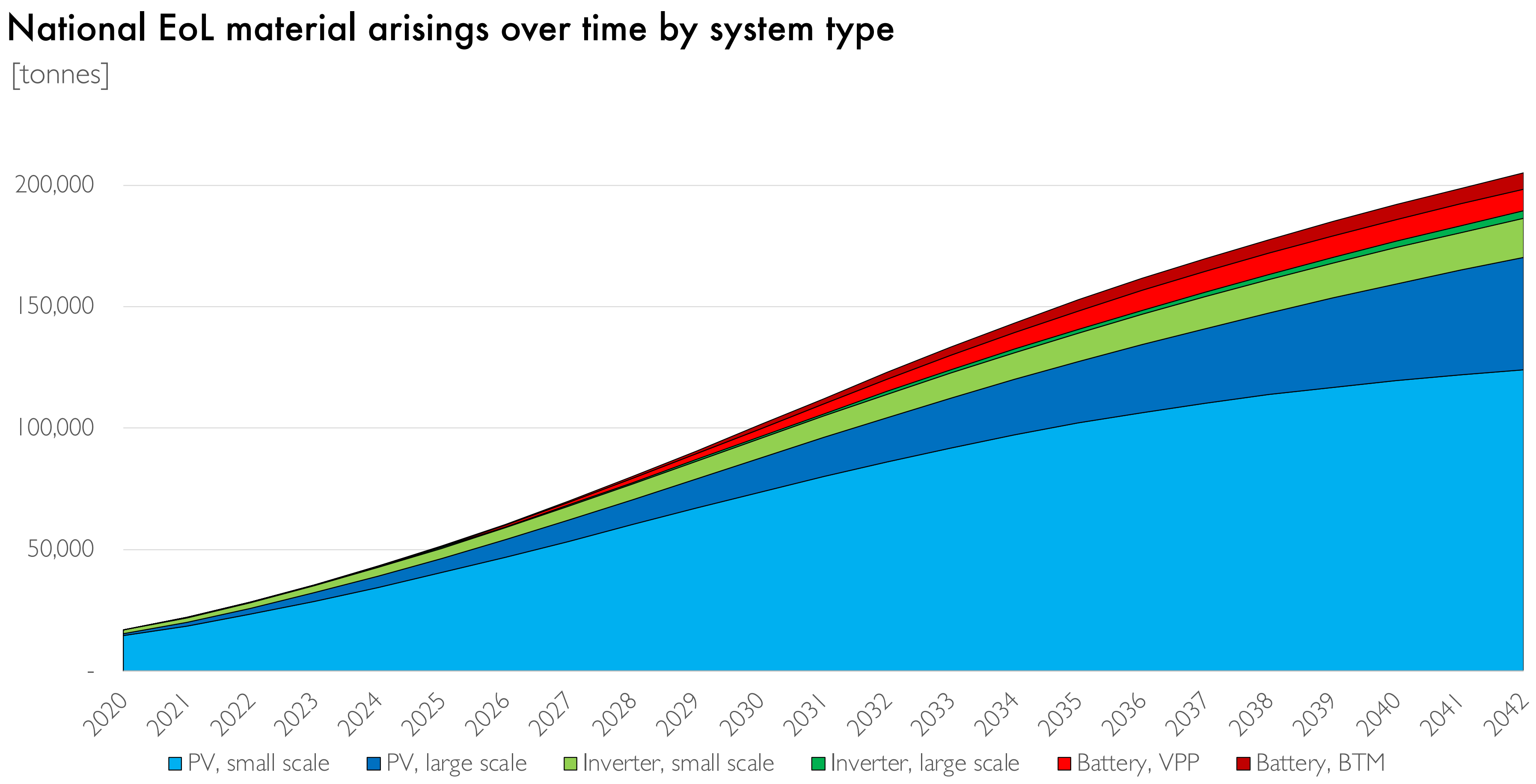
Scale and shape parameters used in the study for each PV system component are shown in the below table, and are based on parameters from the literature, which are highly varied. For PV panels, parameters were taken from Tan et al. (2022)[1], whereby small-scale EoL is influenced by economic motivations; and large-scale EoL is influenced by decrease in power output from panels over time. Parameters for battery end-of-life were taken from the previous ISF study, and represent a conservative EoL rate in the absence of data. Inverters were assumed to be replaced when PV panels reach their EoL.

System	Parameter values
PV, small-scale	Scale parameter: 17 Shape parameter: 2.4928
PV, large-scale	Scale parameter: 23 Shape parameter: 2.4928
Batteries (VPP and BTM)	Scale parameter: 12 Shape parameter: 3.5

[1]Tan, V., Dias, P.R., Chang, N., Deng, R. (2022). Estimating the lifetime of solar photovoltaic modules in Australia. *Sustainability,* 14, 5336

Estimated PV system EoL material arisings to 2042

The figure below shows the estimated EoL material arisings of the national in-use material stock of PV systems, shown in tonnes of equipment reaching end-of-life. Consistent with the national in-use stock breakdown on Page 19, PV panels make up the bulk of EoL arisings throughout the study period. The proportion of arisings attributed to small scale PV panels does decrease over time even though uptake increases. This is due to the assumption of declining PV panel mass as described on Page 18



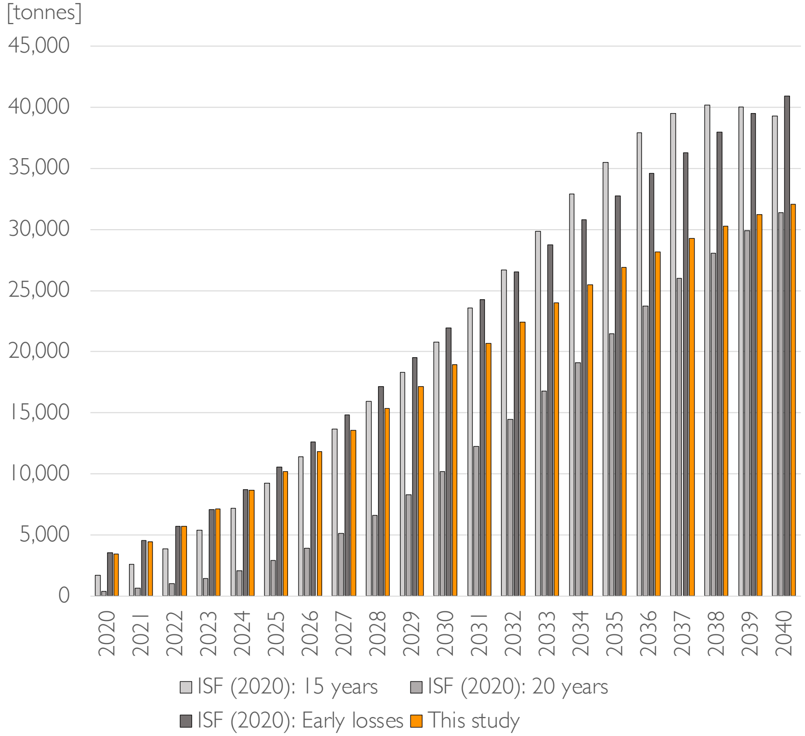
Estimated PV system EoL material arisings to 2042

Quantities of estimated EoL arisings are dependent on both underlying data and parameter selection. The figures below compare the estimated arisings for small-scale and large-scale systems from the ISF (2020) study, and this study. While both studies utilised Weibull lifetime modelling, this study utilised more up-to-date data on installed capacity, as well as updated AEMO projections, along with different parameters.

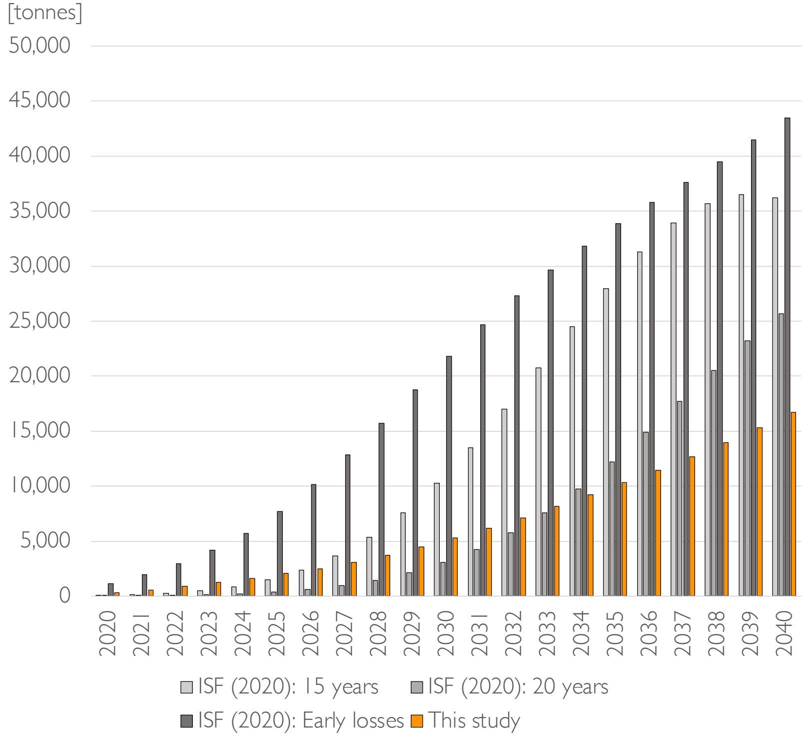
In the case of small-scale installations, this study's estimates fall roughly between the regular loss (15 & 20 years avg. lifetime) and the early loss models used in ISF (2020). For large-scale EoL, this study estimates a much slower rate of arisings. This is due to a longer average lifetime for large-scale panels of ~23 years, as well as a lower replacement rate power decrease being the primary motivation for panel replacement in Tan et al. (2022).

Parameters used here are based on the up-to-date, Australian specific Tan et al. study. However the range of EoL estimates especially w.r.t. large-scale EoL across both studies, illustrates the uncertainty surrounding parameter selection in lifetime modelling.

EoL model comparison (NSW small-scale PV)

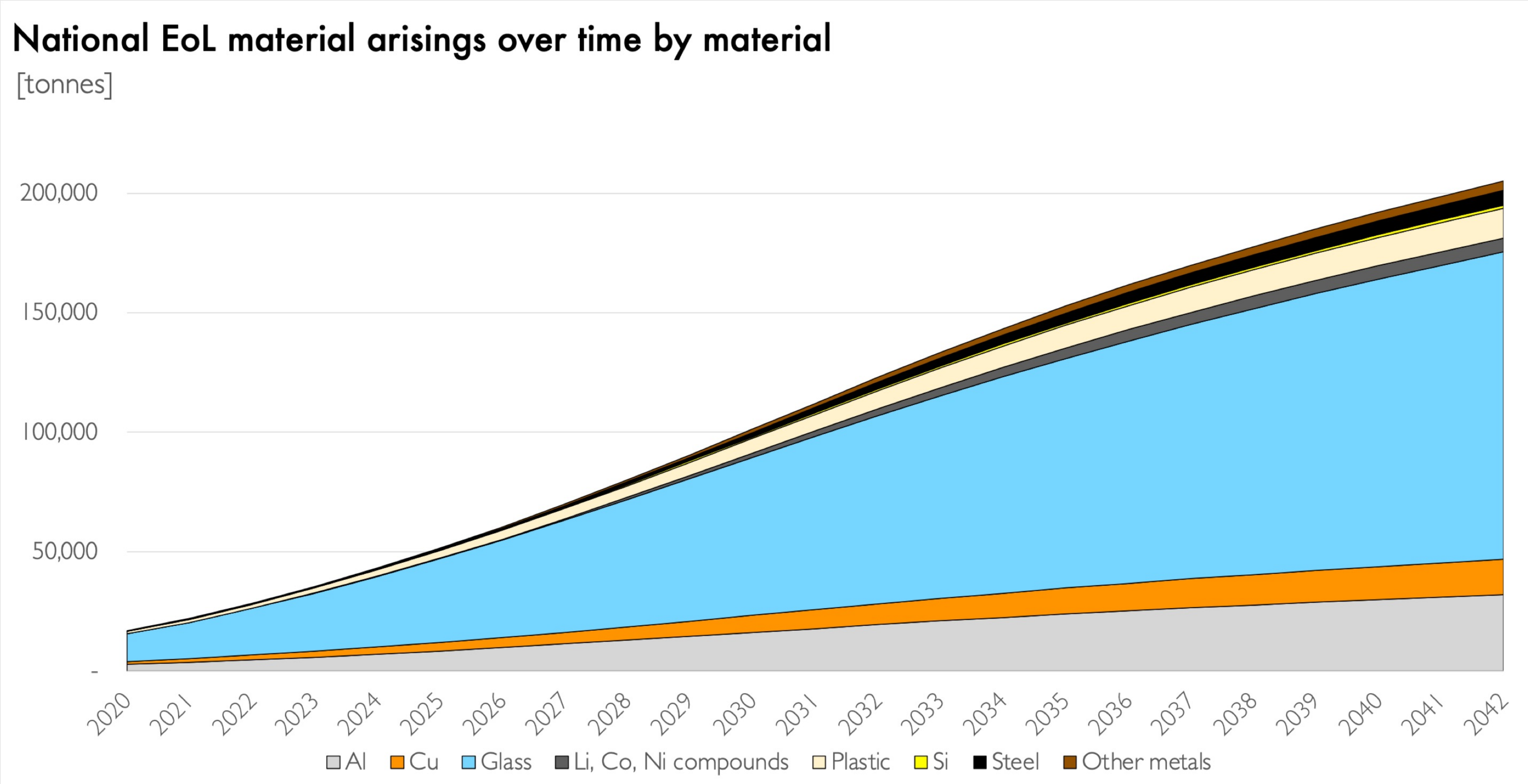


EoL model comparison (NSW large-scale PV)



Estimated PV system end-of-life material arisings to 2042

The figure below shows the EoL material arisings over time from the previous page, broken down by material type. The distribution of EoL materials approximately mirrors the distribution of in-use materials, with glass making up the bulk of EoL material arisings (60-70%). Aluminium, copper and plastic also make up a significant proportion of the EoL material stock (approximately 30%). EoL materials are described in further detail in the below.



Estimated PV system EoL material arisings to 2042

The tables below show estimated EoL arisings by material and system type for 2021 and 2042. Overall PV system arisings in 2021 were approximately 16,800 tonnes in 2021, projected to increase to approximately 205,200 in 2042, on account of the significant uptake of PV systems over the time period. The share of overall EoL material from large PV panels will increase significantly, from 5% of total material in 2021, to 23% of total material in 2042.

As noted previously, glass from EoL panels make up the majority of EoL materials, increasing from 11,600 tonnes in 2021 to 128,500 tonnes in 2042. EoL panels present a significant, growing opportunity for glass material recovery. Other significant opportunities include aluminium, copper and plastic, which all have significantly increasing volumes due to panel and inverter uptake. Lithium compounds and steel will also see a significant increase in proportion of total EoL material, both increasing from <1% in 2021 to 3% on 2042 on account of VPP and BTM battery uptake, as well as large scale inverters w.r.t. steel.

2021 - National EoL materials by system

[tonnes]	Material										
System	Ag	Al	Cu	Glass	Li	Pb	Plastic	Si	Steel	Other metals	System share of total
PV, small scale	7.5	2,264.6	141.4	10,961.0	-	0.7	964.7	107.4	-	81.64	86.15%
PV, large scale	0.4	132.0	8.2	639.1	-	0.0	56.3	6.3	-	4.76	5.02%
Inverter, small scale	1.1	396.1	1,025.0	-	-	5.4	-	-	-	3.52	8.49%
Inverter, large scale	0.0	3.2	8.3	-	-	0.0	-	-	35.2	0.03	0.28%
Battery, VPP	-	-	-	-	-	-	-	-	-	-	0.00%
Battery, BTM	-	0.6	0.8	-	3.8	-	0.8	-	2.6	1.73	0.06%
Total	**9.1**	**2,796.5**	**1,183.7**	**11,600.1**	**3.8**	**6.2**	**1,021.8**	**113.7**	**37.8**	**91.69**	
Material share of total	0.05%	16.58%	7.02%	68.79%	0.02%	0.04%	6.06%	0.67%	0.22%	0.54%	

2042 - National EoL materials by system

[tonnes]	Material										
System	Ag	Al	Cu	Glass	Li	Pb	Plastic	Si	Steel	Other metals	System share of total
PV, small scale	64.2	19,320.8	1,206.1	93,514.4	-	5.7	8,230.6	916.2	-	696.55	60.41%
PV, large scale	24.0	7,229.5	451.3	34,991.3	-	2.1	3,079.7	342.8	-	260.64	22.60%
Inverter, small scale	12.5	4,412.4	11,418.4	-	-	60.6	-	-	-	39.25	7.77%
Inverter, large scale	0.6	214.2	554.4	-	-	2.9	-	-	2,351.7	1.90	1.52%
Battery, VPP	-	485.4	679.6	-	3,315.8	-	716.9	-	2,240.4	1,523.49	4.37%
Battery, BTM	-	369.4	517.2	-	2,523.5	-	545.6	-	1,705.0	1,159.43	3.32%
Total	**101.3**	**32,031.7**	**14,827.0**	**128,505.7**	**5,839.3**	**71.4**	**12,572.9**	**1,259.1**	**6,297.1**	**3,681.25**	
Material share of total	0.05%	15.61%	7.23%	62.63%	2.85%	0.03%	6.13%	0.61%	3.07%	1.79%	

90th Percentile

Median

10th Percentile

Concluding points on PV system EoL arisings

- EoL material arisings are expected to significantly increase over the 2020 to 2042 period—from approximately 17,000 tonnes in 2020 to 205,000 tonnes in 2042
- Small-scale PV systems are expected to make up the majority of EoL material arisings, accounting for 60 to 86% of total EoL arisings over the 2020 to 2042 period. Contribution to EoL arisings from large-scale PV systems will increase towards the end of the 2020-2042 timeframe.
- Glass from EoL PV panels is expected to account for 63 to 69% of total EoL materials—confirming the significant potential opportunity for glass recovery from the management of EoL PV panels.
- There is much uncertainty on average system lifetimes and losses in the literature, owing to limited comprehensive data on EoL arisings of PV panels, inverters and battery systems

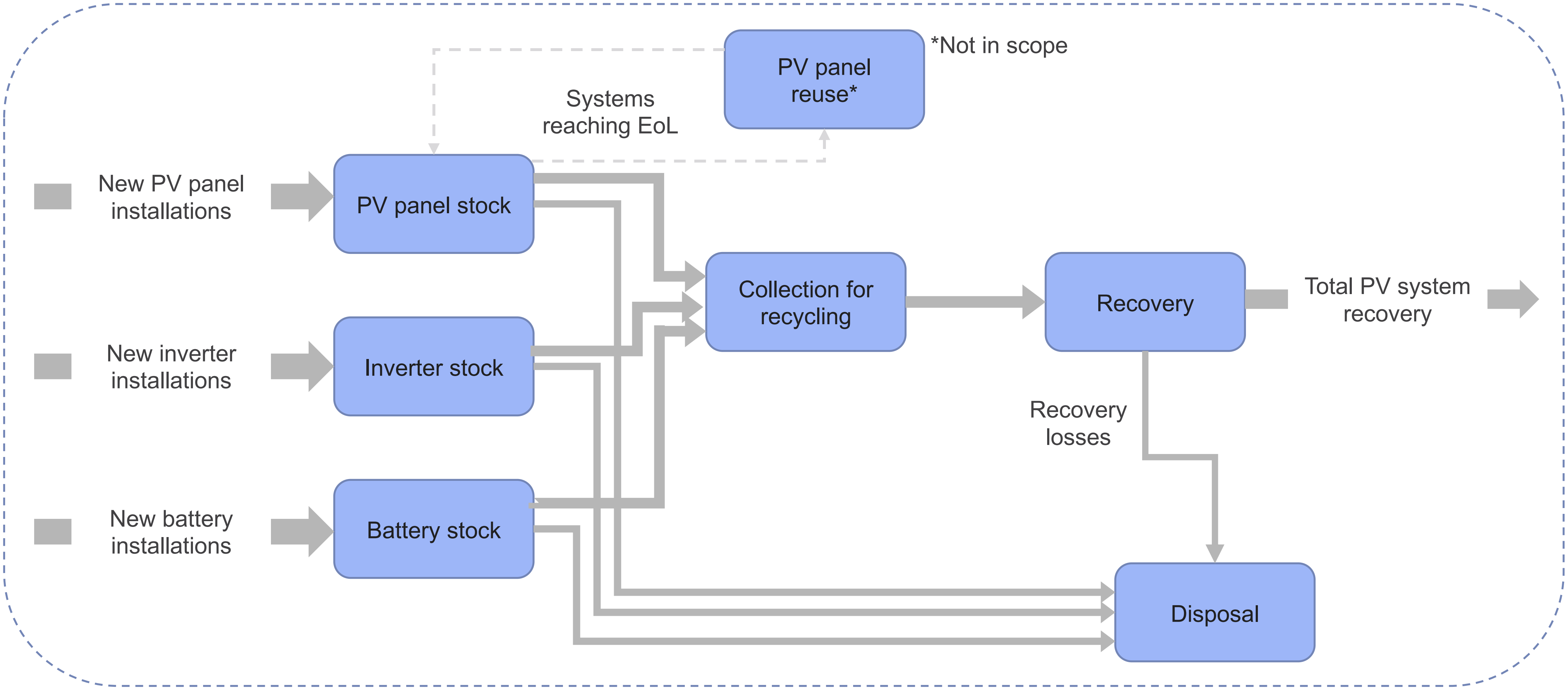
05

Potential PV system material recoveries in 2030

Results of the material flow analysis

Material flow analysis is used to estimate quantities of potentially recoverable materials from EoL PV systems across Australia to 2042

Material flow analysis (MFA) is a quantitative approach used for estimating the flows of material through a system of processes (e.g., collection and recovery systems). The figure below shows the assumed system diagram used to estimate flows of EoL material, from the point of installation to recovery and disposal. Each arrow in the diagram represents flows that are quantified through our analysis, which allows us to estimate quantities of PV systems reaching their end-of-life, and tracing their fates (recovery or disposal) through the system.



PV system EoL collection and recovery system assumptions

The tables below show the assumed collection rates and recovery rates by material and system type. For our analysis, collection rates are taken from the previous ISF study, and assume a product stewardship scheme is in place to incentivise the collection of EoL PV systems. Material recovery rates are taken from the previous ISF study, and the literature on EoL PV panels and inverter recoveries (i.e., Gautam et al. (2021), Dominguez & Geyer (2017, 2019)).

The assumed recovery process for PV systems reflect recovery pathways that are currently mature in Australia (ISF, 2020). For EoL PV panels and inverters, recovery includes manual dismantling and shredding/crushing to recover valuable materials. In the case of batteries, recovery involves disassembly and shredding/crushing to produce a mixed metal dust (‘black mass’), consisting of lithium, cobalt and nickel compounds (ISF, 2020).

	PV panel / inverter, small	PV panel / inverter, large	Batteries – VPP and BTM
EoL collection rate	80%	95%	80%

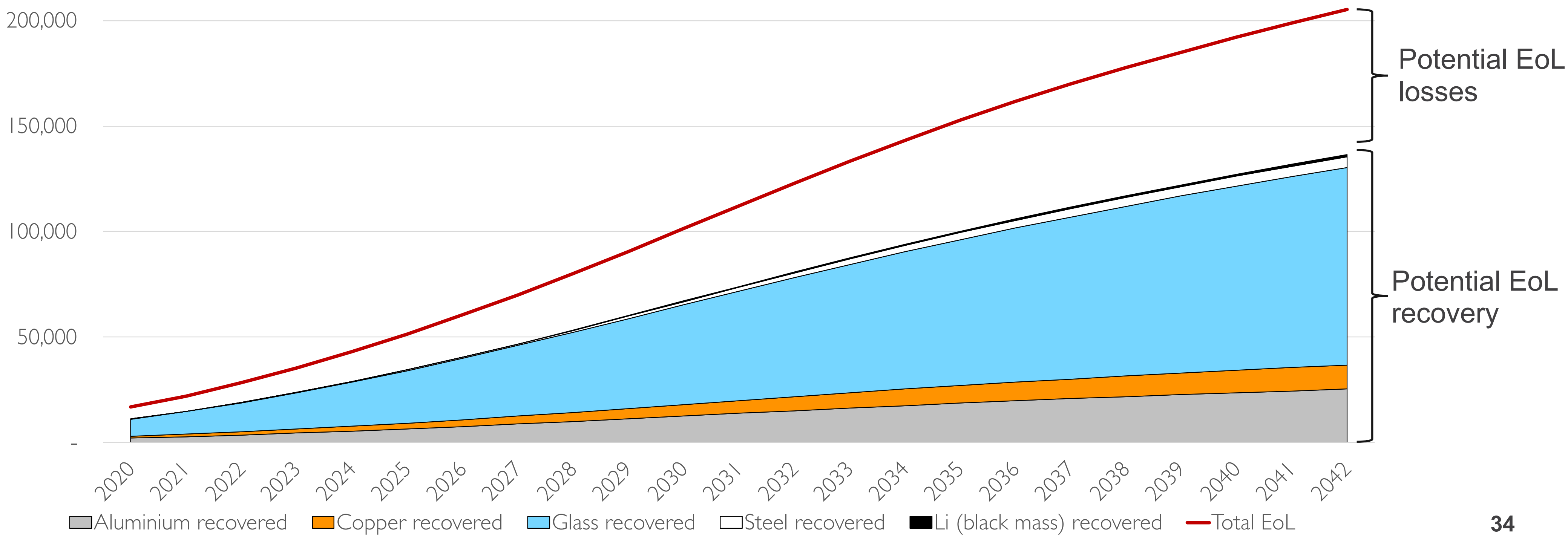
Material	PV panel recovery rate	Inverter recovery rate	Battery recovery rate
Aluminium	95%	95%	92%
Copper	95%	95%	92%
Glass	87%	NA	NA
Steel	NA	90%	96%
Lithium (as black mass)	NA	NA	21%

Potential EoL PV system recovery over time

Using the parameters shown in the previous page, national total recovery potential can be calculated from the EoL estimates. The figure below compares total quantities of end-of-life systems over time with potentially recoverable materials. The proportion of EoL material recovered is consistently around 66% over the study time frame, with total EoL material recovery for 2042 estimated at approximately 136,500 tonnes, compared to an estimated 14,700 potential recovery in 2021. This is a conservative estimate, and the analysis does not consider improvements over time in collection rates or recycling technological capabilities. Reflecting the EoL material composition shown previously, glass accounts for approximately 70% of overall material recovery over the time period.

National EoL material recovery over time by material

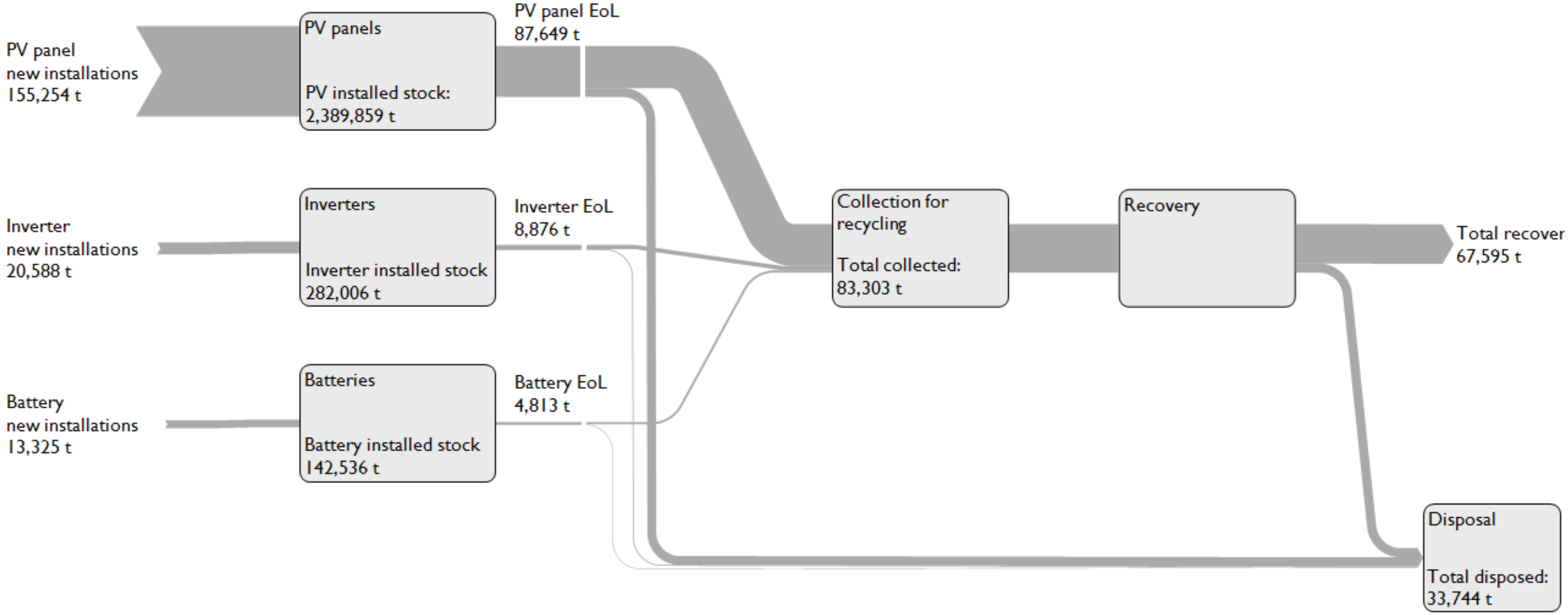
[tonnes]



Potential EoL collection and recovery system—snapshot of 2030 performance: system material flows

The below figure shows quantified material flows for the system diagram on Page 32, showing quantities (tonnes) of new PV systems installed, installed stock, and EoL arisings for national PV systems. The figure is a static view of estimated material flows for 2030, and shows a greater level of detail of the system losses highlighted on the previous page, for a time period relevant for short-term collection and recovery system planning.

Overall recovery of material from EoL PV systems was approximately 67,600 tonnes, equivalent to a recovery rate of 67% of total EoL arisings. Losses from points of collection (e.g., disposed incorrectly, or not collected for recycling), and from residual losses from recovery processes, are approximately even at 53% and 47% of total losses respectively. Potentially recoverable materials in 2030 are explored in greater detail on the next page.



Potential EoL collection and recovery system—snapshot of 2030 performance: material recovery details

The below table shows the quantities of potentially recoverable materials from EoL systems nationally in 2030. Recovery of EoL small-scale PV panels account for 71% of total PV system recovery, with large-scale panels accounting for 16% of total recovery. Recovered glass accounts for 70% of all recovered materials, with 38,500 tonnes recovered. Aluminium and copper also represent a significant proportion of recovered EoL materials, accounting for a combined 27% of overall recovery, primarily from small and large scale PV panels, and small scale inverters.

The table below also shows the expected EoL recovery rate for each system (that is, the proportion of overall EoL arisings in 2030 that are recovered). Large scale PV panels and inverters have the highest estimated recovery rates, on account of higher assumed collection rates for large-scale systems (see Page 33). Battery system recovery rates were poorest, on account of low assumed recovery rates for cathode materials as black mass.

The results in the table highlight the significant potential for recovery of high-valued materials from used PV systems with an effective product stewardship scheme in place.

2030 - National EoL materials recovery by system

[tonnes]	Material							
System	Al	Cu	Glass	Steel	Black mass	Total system recovery	System share of recovery	System end-of-life recovery rate
PV, small scale	8,718.1	544.3	38,514.5	-	-	47,776.9	70.7%	64.9%
PV, large scale	1,977.0	123.4	8,734.0	-	-	10,834.4	16.0%	77.1%
Inverter, small scale	1,693.5	4,382.5	-	-	-	6,076.0	9.0%	75.5%
Inverter, large scale	51.0	132.1	-	530.7	-	713.7	1.1%	86.5%
Battery, VPP	127.5	178.5	-	611.9	534.8	1,452.7	2.1%	45.6%
Battery, BTM	65.1	91.1	-	312.2	272.9	741.3	1.1%	45.6%
Total	12,632.2	5,451.7	47,248.5	1,454.8	807.8	67,595.0		
Material share of total	18.7%	8.1%	69.9%	2.2%	1.2%			

90th Percentile

Median

10th Percentile

Potential end-of-life collection and recovery system—snapshot of 2030 performance: state and territory breakdown

The table below shows potentially recoverable materials from EoL systems by state and territory in 2030. Queensland, NSW/ACT and Victoria will see the largest quantities of EoL materials recovered, accounting for over 75% of total potential recovery. This highlights that these jurisdictions should be prioritised for any expansion in recovery and collection systems, and product stewardship schemes.

The spatial distribution of potential recovery of EoL systems is examined in greater detail on the following pages, with a particular focus on New South Wales in 2030.

	Al	Cu	Glass	Steel	Li compounds (black mass)	Total recovered	Recovery rate (% total EoL recovered)
NSW & ACT	3,518	1,470	13,079	514	271	18,852	66.6%
QLD	3,674	1,535	13,826	341	148	19,524	67.1%
VIC	2,492	1,105	9,310	278	167	13,352	66.6%
SA	1,309	590	4,842	233	166	7,140	65.6%
TAS	154	75	572	18	15	834	65.8%
WA	1,349	614	5,106	60	33	7,162	67.1%
NT	137	61	513	12	7	730	66.8%
Total	12,632	5,451	47,248	1,455	808	67,594	66.7%

Comments on potential recovery of EoL materials

- Approximately 68,000 tonnes of EoL PV system material can be potentially recovered in 2030, with small-scale PV panel recovery accounting for more than 70% of overall recovery

- Recovery of glass is most significant, at 47,000 tonnes potentially recovered and accounting for 70% of all materials recovered

- Large-scale PV panels and inverter systems had the highest system-level recovery rates, at ~80% of EoL systems recovered

- Queensland and New South Wales will have the highest potential recoveries in 2030, with around 19,000 tonnes of EoL systems recovered in each state

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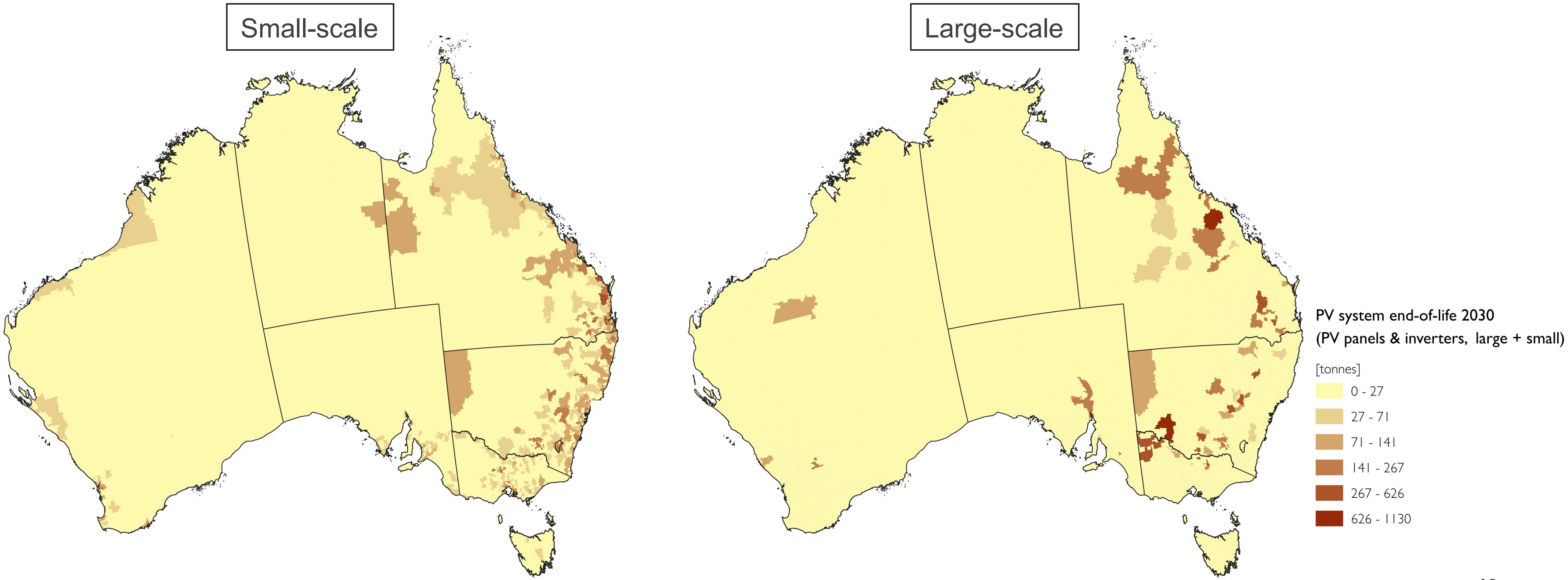
Spatial distribution of end-of-life PV system recovery

Snapshot of NSW in 2030

Spatial distribution of EoL arisings in 2030

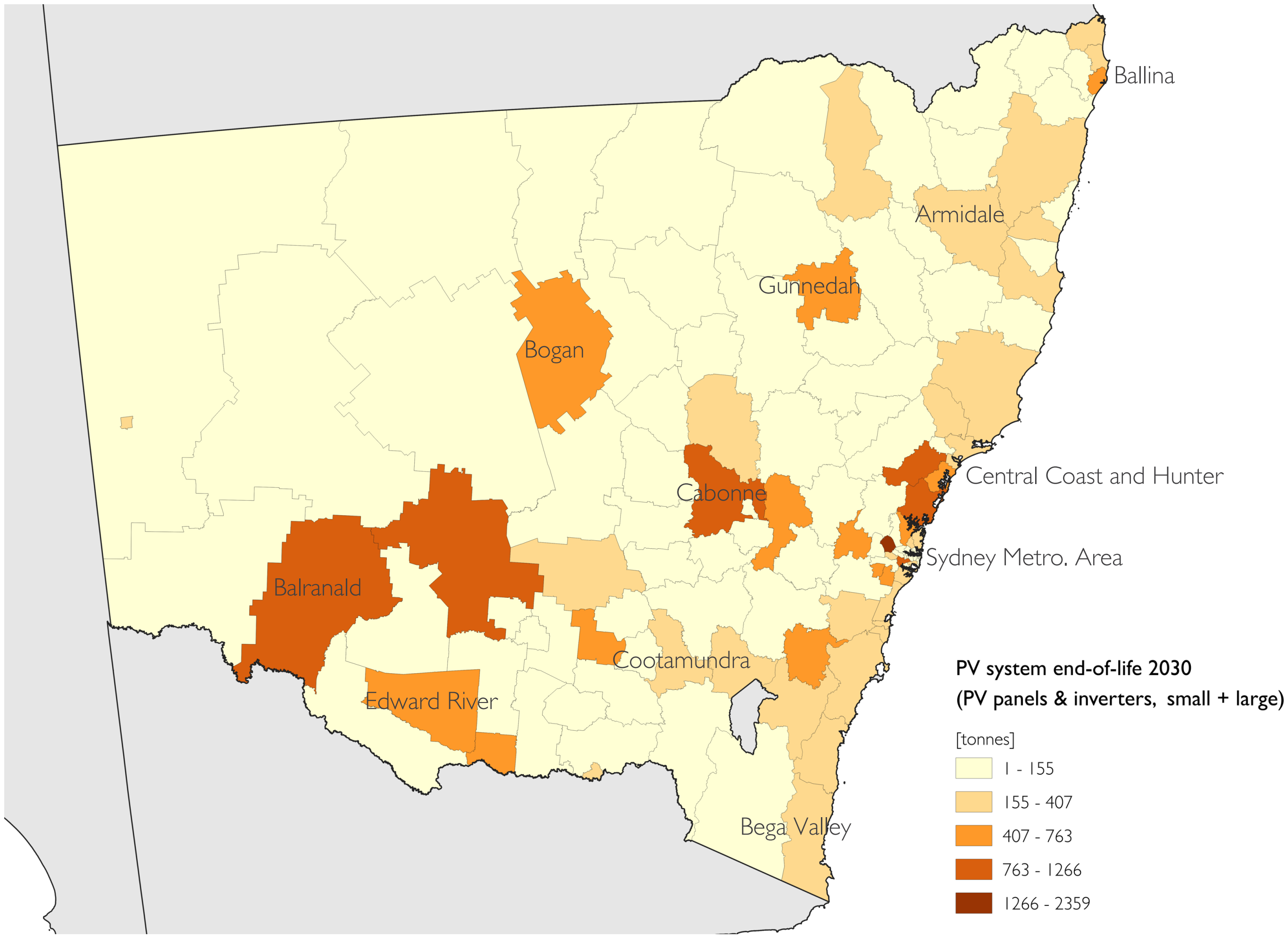
The figure below shows the spatial distribution at the postcode level of estimated EoL arisings of small and large scale PV panels and inverters for 2030. The spatial distribution for 2030 is modelled assuming the distribution of installed capacity in 2021 (i.e., Page 12) is the same in 2030,which we consider to be reasonable given the short time horizon. EoL arisings are then modelled for each postcode. Note that batteries are not included in this spatial analysis, as data on battery storage installations were not available at the postcode level.

The figures below highlight areas where EoL arisings are expected to be greatest, indicating that areas along the east coast and near population centres will see high levels of small-scale EoL arisings in 2030, and more regional locations seeing higher levels of large-scale end-of-life arisings.



EoL arisings aggregated to local government areas can help identify where to target for expanded PV system collection and recovery services

The figure below shows estimated PV system EoL arisings at the postcode-level from the previous page, aggregated to local government areas (LGAs) in NSW for 2030. This was done as an illustration, to show how high resolution data on the distribution of EoL arisings can help to identify areas for prioritisation for PV panel collection and recovery processes. The spatial distribution of projected end-of-life PV system arisings are explored in further detail on the next page



Analysis has identified the top 10 local government areas with the greatest opportunity for future EoL PV system recovery—a mix of metro, suburban and rural locales

The table below shows the top 10 NSW LGAs in terms of EoL quantities in 2030, based on data shown on the previous page. There is a mix of different LGA classifications[1] in the table. Expected volumes of EoL materials in metropolitan and metro-fringe areas are significantly higher than other locales, with the exception of large regional towns with high numbers of detached dwellings, and specific rural jurisdictions hosting solar farms (e.g., the large-scale Sunraysia Solar Farm is located in Balranald).

Top 10 LGAs based on total EoL 2030				Potential material recovery in 2030				
LGA	LGA classification	Projected small scale PV and inverter EoL [tonnes]	Projected large scale PV and inverter EoL [tonnes]	Al [tonnes]	Cu [tonnes]	Glass [tonnes]	Steel [tonnes]	Total PV panel and inverter recovery [tonnes]
Blacktown	Metropolitan	2,306.2	53.0	301.3	140.1	1,119.0	1.9	1,562.3
Cabonne	Rural	380.6	885.8	169.3	38.2	699.5	31.6	938.6
Central Coast	Metro-fringe	1,172.3	24.2	152.8	71.2	567.2	0.9	792.0
Balranald	Rural	71.2	1,125.1	162.4	23.6	694.0	40.1	920.2
Cessnock	Regional town	901.1	22.0	117.9	54.7	437.9	0.8	611.4
Canterbury-Bankstown	Metropolitan	877.4	14.7	113.9	53.2	422.5	0.5	590.2
Carrathool	Rural	173.8	691.1	116.4	22.4	487.6	24.6	651.0
Camden	Metro-fringe	757.9	5.2	97.3	45.8	360.5	0.2	503.9
Hornsby	Metro-fringe	672.7	3.2	86.2	40.6	319.2	0.1	446.1
Blue Mountains	Metro-fringe	659.4	2.0	84.4	39.8	312.2	0.1	436.5

1 https://www.yourcouncil.nsw.gov.au/wp-content/uploads/2020/05/Australian-Classification-of-Local-Government-and-OLG-group-numbers.pdf

Conclusions on spatial distribution of potential EoL material recovery

- Distribution of installed capacity and EoL arisings mostly centred around population centres and the eastern states
- Analysis focused on NSW, showing the top 10 LGA in terms of end-of-life arisings in 2030; indicating that metropolitan and metro-fringe locales have the greatest potential for recovery based on small-scale system EoL arisings
- Specific regional locations hosting large-scale installations (e.g., Balranald, Cabonne and Carrathool) also identified as significant sources of EoL arisings for recovery in 2030

07

Conclusions

Study conclusions

- PV and battery system capacity is projected to increase substantially over the 2020 to 2042 period, led by significant increase in large-scale PV and battery system uptake

- PV panels account for 80-90% of in-use materials by mass over 2020-2042, with glass accounting for the majority of this material

- EoL arisings to increase from 17,000 tonnes in 2020 to 205,000 tonnes in 2042. Small-scale PV panels expected to make up the majority of arisings, however large-scale PV will make larger contribution towards 2042

- Approximately 68,000 tonnes of EoL materials will be potentially recoverable in 2030, mostly consisting of glass (70%), aluminium (19%) and copper (8%) from EoL systems mainly in Queensland, New South Wales and Victoria

- Advancement of recovery technology and improved EoL collection systems (e.g., through expanded stewardship) would increase the scale of potentially recoverable materials

Remarks on data sources

These data sources are listed in the table below, along with a description of what each data set includes, and how it is utilised in our analysis.

Data source	Remarks
Clean energy regulator data on small-scale installations by postcode, 2006-2021 (CER, 2022a)	Installations in kW of small scale PV installations Australia wide, from 2006 to 2021 at the postcode level for all of Australia. This data is used to calculate existing installed capacity of small scale PV, and used to estimate the spatial distribution of installed capacity and end-of-life arisings
Australian PV Institute data on large-scale and utility-scale installations (APVI, 2022)	Data on installations of large scale (above 100kW) installations Australia wide, from 2006 to 2021. This data is used to calculate existing installed capacity of large-scale PV
Clean energy regulator data on battery installations by state, 2006-2021 (CER, 2022b)	Data on the number of distributed battery installations for small scale installations (<100kW) from 2006 to 2021, by Australian state and territory. This data is used to estimate the installed capacity of existing battery storage
Australian Energy Market Operator, Integrated System Plan (AEMO, 2022)	The AEMO ISP is a system roadmap for the National Energy Market for the next 20 years and beyond. The ISP was used to estimate future projections of small-scale and large-scale PV and battery storage capacity to 2024, following the 'Step Change' Scenario utilised in the previous ISF scoping study
Scoping study for solar panels and battery system reuse and recycling fund, report prepared for NSW DPIE (ISF, 2020)	This scoping study, prepared by ISF and Equilibrium in 2020, aimed to provide an evidence-base to inform the future development of PV system recovery systems in NSW. Assumptions from this report were used in our analysis, and are stated throughout this report
Gautam et al. (2021)	A study evaluating the recovery potential of EoL PV panels and inverters. This study provided data on the material composition of PV panels and inverters, and potential recycling rates
Dominguez and Geyer (2017, 2019)	These two studies evaluated the end-of-life recovery potential of PV systems in the USA and Mexico. These studies provided data on the material composition and recycling yields of PV panel and inverter materials, and inverter sizing ratios
End-of-life management: Solar photovoltaic panels, report by IRENA and IEA-PVPS (IRENA. 2016)	Data on the historical and projected weight of PV panels, which were used to calibrate a negative exponential model to estimate PV panel weight (in tonnes per MW) over time
Tan et al. (2022)	A study on estimating the lifetime of solar PV modules in Australia, based on a meta-analysis of lifetime model parameters in the literature. This study was used to calibrate our own lifetime model for end-of-life arisings of PV systems over time