End-of-Life Management of Solar PV Panels

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Disclaimer

Project Team

The project team comprised Dr Deepika Mathur (Northern Institute, Charles Darwin University), Dr Robin Gregory (Regional Development Australia NT) and Mr Tristan Simons (Intyalheme Centre for Future Energy, Desert Knowledge Australia). Collectively the team brings together expertise and a good understanding of current issues in waste management, regional development and renewable energy.

It should be noted that this project was conceived by and initially arose out of discussions between Dr Deepika Mathur (Charles Darwin University), Ms Sarah Johnston (DKA) and Dr Robin Gregory (Regional Development Australia NT). The Team would like to acknowledge Ms Johnston's contribution towards developing the project proposal. The project team would also like to acknowledge and thank Dr Eleanor Hogan for her work on the literature review, initial database generation and preliminary analysis.

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All photos shown in this report are courtesy of Intyalheme Centre for Future Energy

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Abbreviations

CEC	Clean Energy Council
CdTe	Cadmium telluride
CER	Clean Energy Regulator
CfAT	Centre for Appropriate Technology
c-Si	Crystalline silicon
CIGS	Copper indium gallium (di)selenide
C2C	Cradle-to-cradle
DKASC	Desert Knowledge Australia Solar Centre
EOL	End of life
EARC	East Arnhem Regional Council
EU	European Union
FRELP	Full Recovery End-of-Life Photovoltaic
GW	Gigawatt
IEA-PVPS	International Energy Agency Photovoltaic Power Systems Program
IRENA	International Renewable Energy Agency
ITRPV	International Technology Roadmap for Renewables
LSI	Large-scale installation
LCA	Life cycle assessment
LGA	Local Government Areas
LRRF	Landfill and Resource Recovery Facilities
MW	Megawatt
Mt	Metric Megaton
NEDO	New Energy and Industrial Technology Development Organization
NTCRS	National Television and Computer Recycling Scheme
NT	Northern Territory
NTG	Northern Territory Government
PV	Photovoltaic
PWC	Power and Water Corporation
RWMF	Regional Waste Management Facility
RRC	Resource Recovery Centres
SETuP	Power and Water's Solar Energy Transformation Program
SSI	Small-scale installations
t	Metric tonne
WEEE	Waste Electrical and Electronic Equipment
WMF	Waste management facility

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Executive Summary

The purpose of this study was to quantify the nature and extent of the Northern Territory's solar photovoltaic (PV) waste and to explore how end-of-life (EOL) management planning could be used to mitigate both the environmental threats posed by solar waste as well as offset the potential costs of managing this waste in the future. As the first study of its kind in the Northern Territory (NT) (and first of its kind to focus on Outer Regional, Remote and Very Remote areas of Australia), this project sought to provide insights into the current policy environment and practices and the barriers and challenges associated with managing solar PV waste, as well as generate a robust evidence base regarding the current and future solar waste trajectories in the NT. The study also aimed to identify potential options for managing this waste including opportunities for regional and remote communities.

In order to address these aims, there were two key data collection activities: gathering data on solar PV panel installations from Clean Energy Regulator (CER), Power and Water Corporation (PWC) and Ekistica, in order to create a robust solar panel database, and conducting a series of stakeholder interviews regarding current policy and practice, barriers and challenges and preferred solutions for managing solar PV waste.

In order to contextualise the study findings and inform on their interpretation the report includes a review of literature from Australia and overseas that relates to EOL management of solar PV waste. This review revealed a substantial body of research and development on PV recycling and material recovery processes yet found very few commercial facilities worldwide that fully recycle the modules, none of which are located in Australia. It also revealed that transport and logistics issues pose significant challenges for the economic recycling of PV panels, even in more densely populated parts of the world. Potential solutions such as decentralised recycling plants, mobile recycling plants and collaborative collection schemes have not been subject to detailed evaluation in different geographic and demographic settings. An overarching theme from the literature review that became apparent was that considerations of PV waste issues have rarely occurred within regional or remote settings and the majority of potential solutions require economies of scale.

Previous research and our data indicate that in the NT there are multiple solar PV waste flows and stakeholders involved in this sector. Rather than consider solar waste management issues through the lens of a straightforward supply chain, it should be conceived of as an interconnected system, with responsibility for managing this waste shared amongst governments, industry and consumers. It follows that solutions need to involve a range of stakeholders and a collaborative approach.

Using the volumes and trajectories presented in this report as a rough guide, findings suggest that economies of scale with regard to panel discards will be difficult to achieve until at least the mid-2040s. This is in part because waste trajectories vary across the regions and local government areas (LGAs); not all of the latter experience a surge or peak of solar PV waste at the same time. Given that the potential economic returns from recycling c-Si panels also appear to remain relatively modest up until the mid-2040s, the capacity to offset some of the economic costs of managing the NT's solar PV waste through recycling appears limited.

The data gathered from this study suggests that solar PV panels are often removed prematurely (i.e. before reaching end of working life) and for reasons other than technical failures or adverse weather impacts. Data also suggests that there is a real need for policy development and regulatory reform regarding solar PV waste management. Clear directions are required on 'what to do next' once the panels are removed. Additionally, there is a policy gap between Northern Territory Government (NTG) policies, such as the renewables policies, waste policies and public housing improvement policies.

Currently, solar PV waste management practices in the Territory are occurring within a policy vacuum. There is a clear disconnect between the current push to encourage renewables (and uptake of solar PV systems) and absence of any clear policy regarding the management of solar PV waste. Furthermore, Schedule 2 of the *NT Waste Management and Pollution Control (Administration) Regulations*, includes some materials which may be found in solar panels such as cadmium, lead, selenium, tellurium, and encapsulated, chemically fixed, solidified or polymerised wastes, as listed wastes. It is recommended that solar PV panels should not be landfilled. It is further recommended that solar panels be listed as a class of waste under Schedule 2 of the Regulations. This would resolve the current ambiguity that exists in relation to whether or not solar panels are listed waste.

It is evident from our research that not only is clear and unambiguous policy required, but also clear regulations regarding the collection, transport, stockpiling and disposal methods for solar PV panel waste. The data yielded strong evidence that various stakeholders are unclear what to do with solar PV panels once they have been removed. Further information regarding collecting, stockpiling, transporting and disposing of solar PV waste and clear guidelines on best practice in this regard is urgently required for local government and solar PV installers.

Decisions regarding the best way(s) to manage the Territory's solar PV waste both now and in the future should be underpinned by a good understanding of the nature and extent of that waste (i.e. a robust evidence base). The NT Waste Management Strategy identified the disparate data on waste flows and trends as one of several challenges for waste management in the Territory and this is certainly the case regarding removed solar PV panels. Our research has demonstrated a clear need for the creation of a readily accessible, centralised fit-for-purpose database that captures all panel installations and removals, as well as details regarding panel types and brands, aggregated to local government area level. We suggest that as the databases held by CER are likely the most comprehensive, changes to the way that data is collected and presented may to be the most cost-effective approach.

In the absence of any centralised fit-for-purpose database, our estimates of the nature and extent of the Territory's solar PV waste, both now and in future trajectories, can only be read in terms of magnitudes of impact. In order to more accurately gauge the nature and extent of this waste, we recommend that ground-truthing be undertaken in small pilot areas to capture existing roof-mounted panels, ground-mounted arrays and stockpiles of panels held by installers and at existing waste management facilities. This would provide researchers, decision-makers and potential investors with a better idea as to how closely or otherwise existing databases reflect the magnitude of the Territory's solar PV waste.

Key amongst our research findings was that in the Territory, solar PV panels are being removed for a range of reasons and some are being removed prematurely i.e. before they reach regular EOL. It is possible therefore that the Territory's solar PV waste burden may begin to surge as early as 2025, rather than 2040. A range of measures are therefore required to reduce the potential waste burden in the future, including public and other stakeholder information and life extension through repair and reuse.

Our research revealed that changing consumer attitudes and behaviour towards solar panels was a contributing factor to their premature removal; specifically, that solar PV installations are viewed as consumer items which can be frequently upgraded at relatively little cost. A public awareness program is required that explains to consumers that solar panels are not like mobile phones and do not need replacing every few years and that there are significant environmental consequences to consider regarding their disposal, regardless of whether they have reached the end of their warranty period or not.

An unintended consequence of current Government legislation and programs aimed at encouraging solar PV panel uptake, is that they appear to be encouraging the premature removal of solar PV panels before the panels have reached their regular EOL. All Government legislation and programs relating to solar PV panel uptake and usage should be reviewed and amended where appropriate to ensure that premature removal of solar PV panels is not encouraged.

An increasing number of solar PV installations are occurring on government buildings. Participants in this study identified the need for government works tenders/contracts to include clear directions regarding the treatment of existing panels and, if panels are being replaced, clear directions around the disposal of those panels. Additional measures to extend the life of solar PV panels installed on government buildings might include the use of remote monitoring devices to warn of early defects (which may be able to be repaired) before they require major interventions (panel or entire system replacement).

Achieving economies of scale (volumes) and overcoming transport logistics will be challenging. Our research suggests that at the present time, a least-cost option(s) should be pursued. In the current circumstances, collection and stockpiling, with some limited dismantling, appears to be the best approach until such time that economies of scale (or scope) can be achieved and/or future developments in recycling technology make regional and remote processing feasible. Given the issues relating to economies of scale, we suggest that effort is invested in identifying to what extent economies of scope may help offset the costs of managing solar PV panel waste.

Collection and transport costs emerged as a key issue in both the literature and during the stakeholder interviews. One potential mechanism to mitigate these costs may be a form of decentralised collection points in towns and major communities. Reverse logistics (opportunistic backloading) should be encouraged wherever possible to further reduce transport costs.

We believe that collection and stockpiling (with initial dismantling), establishment of testing centres, creation of outlets for used panels sales (and/or parts) and greater emphasis on 'retain and repair', all represent potential business and/or employment opportunities for the Territory. These opportunities should be explored in greater detail, including pilot trials, ahead of the main waste surge expected in the NT.

The literature review revealed that there is considerable research and development work focussed on solar PV recycling and materials recovery processes and techniques. Regardless of the process used, solar PV panels are not made to be unmade, which adds to the costs and complexity associated with recycling. There is a clear need to invest in research in panel design and specifically 'design for disassembly'. Not only would this facilitate module recycling generally, it would also facilitate greater repair and reuse of panel components.

Product stewardship has been proposed as a potential solution for managing solar PV waste. It is vital that any model of product stewardship consider how regional and remote areas will be effectively serviced by that model prior to implementation.

INTRODUCTION AND REPORT STRUCTURE

'Despite the growth in solar PV and its bright future, the sun sets on even the best panels.' (IRENA 2019:50)

The purpose of this study was to quantify the nature and extent of the Northern Territory's solar photovoltaic (PV) waste and to explore how end-of-life (EOL) management planning could be used to mitigate both the environmental threats posed by solar waste as well as offset the potential costs of managing this waste in the future. As the first study of its kind in the Northern Territory (NT), this project sought to provide insights into the current policy environment and the practices, barriers and challenges associated with managing solar PV waste, as well as generate a robust evidence base regarding the current and future solar waste trajectories in the NT. The study also aimed to identify potential options for managing this waste including opportunities for regional and remote communities.

It must be stated at the outset that this report is not intended to be a definitive 'blue-print' for dealing with solar waste in the Territory. Rather, we hope that the information provided here will assist a range of stakeholders working together to address this issue and will provide a starting point for further discussions, deliberations and investigations.

Part 1 of this report provides a background to the project, beginning with Section 1, which offers an overview of the research project and context, including a description of the Northern Territory. Section 2 presents a literature review of relevant academic, government and industry reports and sources relating to the management of PV waste. This includes current policy and strategies. Section 3 describes the study design and methodology, including the broad approach, ethical conduct of the study, datasets as well as the data analysis process.

Part 2 of the report presents the findings from the datasets. Section 4 quantifies the nature and extent of the Territory's solar panel waste. This is presented in terms of potential future trajectories as well as quantifying potential volumes of recoverable and hazardous materials. It includes a hypothetical exploration of the possible economic returns from recycling PV modules and recovery of different materials that comprise solar panels. Section 5 presents the results of the stakeholder interviews. This section describes the current EOL practices in the Northern Territory and identifies the challenges and barriers to managing solar waste in the region, as well as a range of potential solutions suggested by participants.

Part 3 contains the discussion, implications and recommendations arising from this study. It draws the key findings from Part 1, Section 2 and Part 2 into a discussion in which several key themes emerge regarding policy reform, reusing and recycling PV panels, PV panel collection and management models, as well as identifying the potential regional development opportunities. This was also informed by stakeholder feedback from two information sessions. A summary and series of recommendations regarding EOL management, including how to address key challenges and barriers for the NT, is presented in Section 7.

PART 1: BACKGROUND

In this part of the report we detail the need for the current study, including the growth of the solar PV market globally, nationally and in the Northern Territory. This is followed by a description of key socio-economic and geographic features of the NT as well as the current policy environment relevant to managing solar PV waste.

The literature review describes international approaches towards addressing this issue and summarises the kinds of research that has been undertaken to date. Finally, we describe our own approach towards investigating the Territory's solar PV waste.

Section 1: Setting the Scene

1.1. Growth in the solar PV sector and need for the project

Globally, there has been significant growth in the PV sector. In 2016 global-installed solar power reached 310 GW, and is expected to reach 700 GW by mid-2020, and potentially 4,500 GW by 2050 [1, p2934]. Australia has also seen substantial growth in this sector; the rooftop solar market alone doubled capacity in four years, from 5.1 GW installed by end of 2014, to the same amount added by end of 2018 [2, p. 5].

However, as the number of solar installations has increased, so too has the number of solar panels that have reached their EOL. At the end of 2016, cumulative PV waste reached 250,000 t worldwide. As more PV panels reach the end of their life span, PV waste streams are expected to rise by 2030, with the highest volumes projected for Asia (3.5 Mt), followed by Europe (3 Mt) and the United States (1 Mt). A further waste volume surge is predicted between 2030 and 2050, with global PV waste estimated to increase to over 60-78 Mt by 2050 [3, pp. 20,35].

According to Salim et al [4, p. 2], the cumulative installed capacity of solar PV systems in Australia has increased dramatically between 2007 (25.3 MW) and 2017 (77,078 MW). As a result of this growth, Australia is predicted to have 30,000–145,000 t of PV waste by 2030, with more than one million solar panels requiring disposal from 2010 to 2034 [5 , 6]. Reclaim PV Recycling directors Clive Fleming and David Galloway claim that approximately 300,000 PV modules will need to be disposed of annually up to 2030, rapidly increasing to 5 million per annum by 2035 as legacy modules reach the end of their life span. Additionally, an estimated 8–10% of the 11-plus million modules installed in Australia since 2009 are failing due to 'manufacturing faults and untested, environmentally deficient components' [7]. Future EOL management of PV waste will be critical for the sector to be sustainable. The International Renewable Energy Agency (IRENA) and IEA Photovoltaic Power Systems Programme (IEA-PVPS) have identified that 'growing PV panel waste presents a new environmental challenge, but also unprecedented opportunities to create value and pursue new economic avenues'. [3]

At the time this project proposal was developed, in late 2018, early 2019, it was clear that in the Northern Territory an increasing number of panels had reached their end of life. Anecdotally we had heard of large numbers of panels being removed from remote communities, in one instance up to 800 from a single community. Meanwhile, we were aware that in 2012 the European Union (EU) had introduced a comprehensive regulatory framework to address solar panel waste. In contrast, Australia was just beginning to consider issues associated with solar panel waste with lead agency Sustainability Victoria commencing an assessment of a national product stewardship approach to solar panels. Given that solar panels contain heavy metals (such as lead (Pb) and cadmium (Cd)), which are hazardous, can pollute the environment and pose a threat to human health, we were interested in the fate(s) of those panels reaching their end of life in the NT. However, as solar panels also contain materials that are valuable for reuse (such as precious and scarce materials silicon (Si), silver (Ag), gallium (Ga), indium (In) and germanium (Ge), in addition to aluminium (Al) and glass, which can be recycled) [8]), we were also interested in the extent to which recycling existing panels could be employed to offset the environmental threats and economic costs of end-of-life management in a region facing particular geographic and demographic challenges, unlike those in Europe, and in the potential opportunities this might create for regional and remote communities in the NT.

The need for this project, and its timeliness, was reinforced by several developments which all drew attention to Australia's waste generally, including:

- The announcement by China of a new set of import restrictions for 24 streams of recyclable

material[1] [9] and announcements by Vietnam, Thailand and Malaysia regarding new restrictions and future plans to stop imports of certain waste categories [10];

- The announcement by Indonesia that it would return eight containers of contaminated household (recyclable) waste to Australia [11];
- The appointment of an Assistant Minister with specific responsibility for waste reduction and environmental management in the Commonwealth Ministry in May 2019;
- The September 2019 release by the ABS of a new experimental account on waste, the first under the common national approach to environmental-economic accounting in Australia [12];
- and more specifically,
- An increasing number of researchers and media articles calling attention to the barriers and challenges associated with managing solar waste in Australia [13, 14 , 11 , 15 , 16 , 17]. However, little (if any) of the academic literature has considered the issue from a regional and/or remote perspective.

Within the NT, the release of the NT Government's draft *Climate Change Response [18]*, the proposed Sun Cable development in the Barkly [19 , 20] and consideration of the economic growth opportunities in the NT's waste sector by the NT Government, further highlighted the importance and timeliness of identifying potential EOL management options for solar waste, appropriate for the NT's particular circumstances. These circumstances are described in more detail in the section below.

However, it should be noted at the outset that this study reflects the Territory situation as it was in 2019–2020. It has not factored in future developments such as the proposed Sun Cable solar farm in the Barkly region because not enough information regarding the number and type of panels was available at the time of writing, although a figure of 22 million panels had been mooted in the media [20]. If the project does proceed, and the figure of 22 million panels is more or less correct, this would potentially create a significant PV waste issue for the Territory prior to 2030 simply through the early failure of a percentage of the panels installed. Assessing how this would impact PV recycling and materials recovery in the NT was beyond the scope of this study.

1.2. The Northern Territory context

1.2.1. Geographic and demographic characteristics

The Northern Territory of Australia (NT) comprises one-sixth of Australia's landmass but is home to less than 2% of the population; in 2018 the Territory's estimated resident population was 247,327[2]. This poses challenges for service delivery and regional development, when combined with the extremely long distances between settlements, smaller dispersed industries (apart from mining) that find it difficult to achieve economies of scale, lack of essential services, limited and poorly maintained infrastructure, extreme climatic weather and seasonal constraints and high transport costs, that characterise the NT's economic geography [21,p. 24, 22].

Most of the population (60.7%) lives in the Wider Darwin area, followed by Alice Springs (10.7%), Katherine (4.3%), Nhulunbuy (1.3%) and Tennant Creek (1.2%). Outside of these main centres, settlements take the form of major communities, minor communities, family outstations or homelands, mining settlements and pastoral homesteads. Family outstations or homelands usually comprise small communities of fewer than 50–100 people in permanent or semi-permanent residence with a water supply and permanent accommodation [23]. Altogether, approximately 10,000 Aboriginal Territorians are residents in 2,400 dwellings on more than 500 homelands across the Territory [24]. Much of the Territory is classified as 'Very Remote' or 'Remote' by the Australian Bureau of Statistics *Australian Statistical*

1 These restrictions set a maximum contamination threshold of 0.5% on paper and plastics, which is currently unachievable when processing household wastes. Australia's contamination rate of kerbside recycling averages between 6% and 10%.

2 Based on ABS ERP data for 2018. Accessed via https://profile.id.com.au/rda-northern-territory/population-estimate

Geography Standard – Remoteness Structure, with the urban areas of Darwin, Palmerston and surrounds categorised as 'Outer Regional' (Figure 1.1).

The predominant means of freight transport are by road and rail and transport costs are high. For example, transport infrastructure costs are two to three times higher in Very Remote areas compared to the rest of the country [25]. On average, over 30% of household expenditure in Very Remote communities is spent on transport compared to the national average of 16% [26, p. v]. Residents of nearly half of the Aboriginal communities in remote arid and savannah areas have to travel between one and four hours to reach services [Taylor and Prideaux 2006 cited in 27, p12]. This adds significantly to the cost of living and working in these areas, as well as impacting upon the productivity and competitiveness of businesses and other institutions [27, pp7-8]. It also impacts upon waste management and collection services and has implications for the cost of managing solar PV waste in the future.

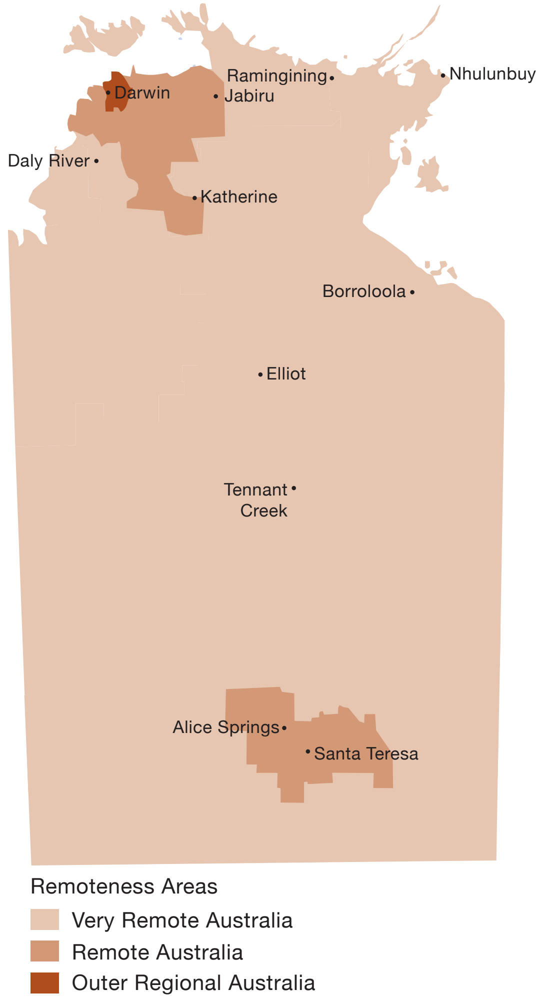

Figure 1.1 Remoteness structure of the Northern Territory Map Source: Commonwealth of Australia

1.2.2. Uptake of solar PV in the NT

For the Territory as a whole, domestic PV installations are relatively low (6%) compared to the national average (14%) and this has been attributed to the nature of household ownership in the Territory, which has a higher proportion of the population relying on public housing, high levels of population mobility and a smaller proportion of owner-occupiers compared with the rest of the country [28, p. 31]. In contrast, the NT has historically had the highest level of uptake of solar water heaters (close to 100% of households) and replacement of these units has taken precedence over solar PV [28, p. 82]. In 2018 the ABS found that nationally 24% of suitable private dwellings (separate houses, semi-detached or row houses) were equipped with a roof-top solar PV system, compared with 17% of suitable private dwellings in the NT [29].

Given the Territory's population and housing characteristics, it is therefore not surprising that uptake of domestic or small-scale installations (SSIs) is greatest in those LGAs which have higher levels of owner-occupiers and least in those LGAs that have a high proportion of public housing (Figure 1.2). This pattern is consistent with research by Best et al, who found that renting and apartment living were key constraints for solar panel uptake across Australia [30, p. 15]. Additionally, as a result of Power and Water's (PWC's) Solar Energy Transformation Program (SETuP), 70% of the 20 remote Indigenous communities that have been identified as major towns, are now powered either by hybrid power installations or solar PV systems alone, thereby negating the need for individual household solar PV systems in these locations. In view of this, it is not surprising that the majority of large-scale installations (LSIs) in the NT are situated in remote communities (61.11%), with most of the remaining LSIs being commercial installations situated in either the Darwin or Alice Springs LGAs. Most (59.25%) of the large-scale installations in the NT have been installed within the last five years.

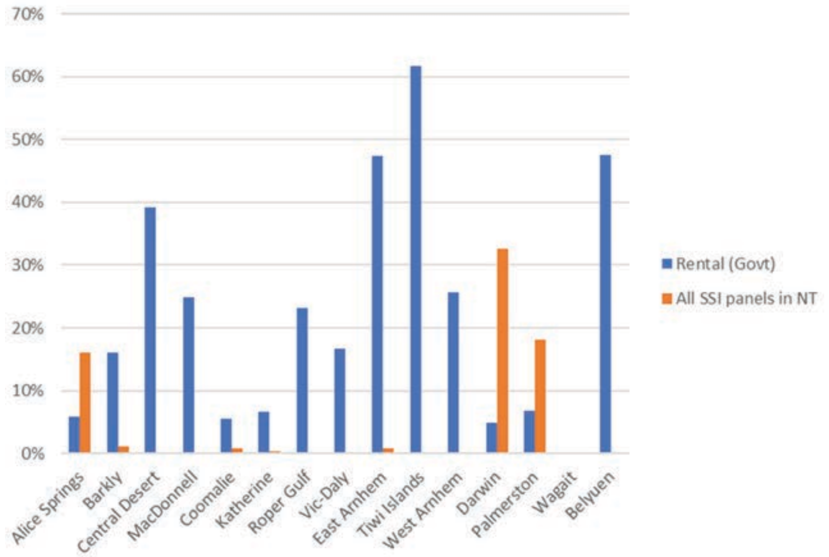

Figure 1.2 Frequency distribution of public housing and panels on SSI installations, by LGA, NT (Note: For the sake of clarity, LGAs with less than 100 panels and panels which occur in postcodes that overlap one or more LGAs are not shown here.)

The situation is more diverse regarding energy supply to smaller communities such as family outstations and homelands. For example, a 2015 survey of 401 of the 630 homelands/ outstations across the NT included observations on the nature and reliability of energy supplies to these settlements. Of these, 26% had access to a hybrid power supply[3], 23% used generators only, 22% had access to a grid (managed by PWC or another agency) and 14% relied on solar PV systems alone (these were single-house systems or community-wide systems such as Bushlight). The remaining 14% had no access to power at the time of the survey either because there was no energy infrastructure, or the supply was no longer functional [23, p. 33].

These geographic and demographic features of the NT have implications in relation to future uptake of solar PV. For example, in communities where there is a solar PV system powering the community, it is unlikely that there will be a significant increase in solar PV panels except to expand the capacity of the existing system if required; unlike major urban centres these remote communities are not expected to see any individual/domestic uptake of solar PV. In contrast, those homelands/outstations which currently have no energy supply, or those that rely on generators, may see the installation of hybrid or solar PV-only systems in the future although the rate at which this occurs will depend on various factors including future NT Government policy and funding priorities.

1.2.3. Value of the NT's Waste Management Sector

The NT's waste management sector is a growing industry. For example, in the five years between 2013–14 and 2018–19, the NT's waste collection, treatment and disposal services sector went from generating $25.8m in output, $20.4m in value add, and employing 403 people, to creating $90.8m in output, $28.5m in value add and employing 549 people [31]. The ratio of jobs to residents in 2018–2019 was 1.29, meaning that there were more jobs available than resident workers [31]. A total of 48 businesses registered in the NT are in the broader electricity, gas, water and waste services industry; this is likely an underestimate as some businesses operate in the Territory but are registered interstate, with the larger businesses usually employing upwards of 20 people.

Additionally, renewable energy was identified as a developing sector under the NT Government's *Economic*

3 Centre for Appropriate Technology Limited 2016 (p. 33) defined a hybrid power supply as 'A combination of solar power and generators are used for energy supply. It may be a fully integrated automatic hybrid for the whole community, or a solar system with one or more backup generators that are turned on manually when the solar system is not working'.

Development Framework [32]. In pursuing a target of 50% of electricity from renewable resources by 2030, the NT Government has recognised that development of this sector provides an opportunity for Territory businesses to integrate best-practice technologies in solar power generation, storage and management, and this expertise could be sold by Territory firms to earn income from outside the Northern Territory. This is part of the policy context described below.

At a broader level, it is relevant to note that the Australian Government's 'Developing the North' agenda aims to encourage greater investment, industry development and population of the northern regions of Western Australia, Queensland and all of the NT. As the latter develops into a major international gas hub and trade gateway to Asia,

> *Increased waste volumes and further new waste streams are likely to be generated into the future and will require suitably designed facilities with experienced operators. The emerging wastes include those generated through exploration, drilling and mining. Further development in the North must be accompanied by a growing capacity within the waste industry to predict and provide the necessary waste management infrastructure, services and enterprise. [33, p 14].*

These initiatives are all likely to result in further growth of the NT's waste management sector, as well as continued uptake of solar PV; this may present new economic opportunities for businesses and local employment.

1.2.4. NT policy and practice

In the Northern Territory, the Environment Protection Authority's (NTEPA) *Waste Management Strategy for the Northern Territory 2015–2022* provides a basis for the management of waste across the NT [33], whilst the NT Government's Response to the *Roadmap to Renewables Report* sets out the major actions it will take in order to achieve a target of 50% electricity from renewable sources by 2030 [34]. Among these latter actions are aligning policy objectives and government programs towards purchasing power from renewable sources; regulatory reform regarding the NT's three regulated electricity markets; future system planning for the power system; creating certainty for investors; and encouraging uptake of renewable power resources by households and business through greater community engagement [35]. These actions are all designed to encourage investment and uptake of renewable energy resources, including solar. Notably absent, however, are any measures to address EOL management and solar waste.

The *Waste Management Strategy for the Northern Territory 2015–2022* identified several broader challenges for waste management in the NT. Of particular relevance in the context of our study are: data on different waste flows and trends is collected and held by multiple agencies; there is limited waste infrastructure and access to markets for recyclables, particularly in remote locations; the high costs of establishing standard resource recovery facilities in smaller regional and remote centres; the vast distances and poor road conditions between settlements that limits the opportunity to separate and transport recyclable and hazardous wastes to appropriate facilities; and that

> *Across the Territory the total number of accessible, practical and specialised waste processing or recycling facilities is limited in comparison to other Australian states. As a result many wastes need to be transported interstate for recycling, treatment or disposal, and operators face high transportation costs combined with lost economic opportunity to process wastes locally. [33, p. 6]*
> *Nevertheless, the waste management strategy also recognised that the provision of local facilities can 'stimulate economic opportunity and reduce the additional environmental risks introduced by transporting waste over distances by road and rail [33, p. 7].*

To address these issues it proposed a number of management actions around engagement and education, including facilitation and promotion of

product stewardship programs for recycling and treating nationally significant waste streams, including tyres, batteries, e-waste, paint and oil; improvement of waste management, including through the promotion of waste reduction and resource recovery; improvement of data collection and analysis; and improvement of the regulatory framework [33, p. 11].

The waste management strategy also discussed ‘problem wastes’, defined as wastes that are difficult to dispose of owing to their hazardous properties, or lack of options for disposal. While what constitutes problem wastes may vary across the NT according to the location, volumes and access to infrastructure for storage and disposal, there are several common problem wastes across the Territory: liquid wastes, asbestos, medical waste, batteries, paints and solvents. Many of these are also listed wastes under the *Waste Management and Pollution Control Act* and landfills are not permitted to accept these wastes without an Environment Protection Licence under the Act [33, p. 13]. Instead, listed wastes are those that pose public or environmental risk and must be dealt with in accordance with the Act and associated Regulations. In remote community environments this requires the separation and storage of these wastes until safe disposal can be economically arranged. Notably, solar panel waste is not included as a hazardous or listed waste under Schedule 2 of the *Waste Management and Pollution Control (Administration) Regulations* although some materials which may be found in solar panels, such as cadmium and cadmium compounds, lead and lead compounds, copper compounds, selenium and selenium compounds, tellurium and tellurium compounds, zinc compounds and encapsulated, chemically fixed, solidified or polymerised wastes, are included as listed wastes.

1.2.5. Role of local government

As is the case elsewhere in Australia, local governments are responsible for the collection and management of the majority of waste including Waste Electrical and Electronic Equipment (WEEE) and, importantly, are the first point of contact for residents with waste management queries [36, p. 220]. They also play a central role in the implementation of national waste collection schemes such as the *National Television and Computer Recycling Scheme* (NTCRS) [36, p. 220].

Across the Territory there are 17 local government areas (LGAs), as well several areas of unincorporated land (Figure 1.3). A number of these local governments have come together to form waste management groups: for example, MacDonnell, Central Desert and Barkly

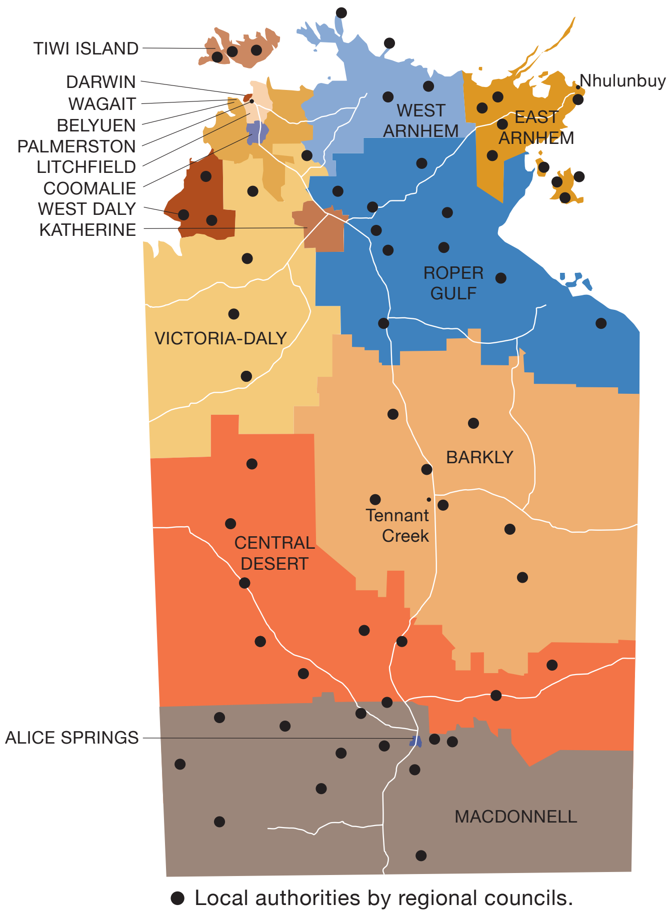

Figure 1.3 Local Government Areas (LGAs) in the Northern Territory
Map source: https://www.lgant.asn.au/councils-2/

Regional Councils are part of the Central Australian Waste Management group, whilst the Big Rivers Waste Management group includes Roper Gulf, Victoria-Daly, Katherine, West Daly Councils as well as representatives from the Local Government Association of the NT (LGANT), NT Dept of Health, Dept of Housing and Community Development, NT Environmental Protection Authority and NT Worksafe. These groups represent collaborative efforts to address common waste management issues across their communities including through resource sharing. Underpinning these groups is the notion that collaboration across wider regions helps to create economies of scale for waste and recycling.

Within the policy frameworks established by the Australian and NT Governments, local governments have developed their own waste management policies and priorities according to the needs of their individual communities. These deal with listed and hazardous wastes, including WEEE, in particular ways. For example, the *Central Australian Remote Landfill Operating Manual* which is used by communities in the MacDonnell, Central Desert and Barkly LGAs, specifies that landfill should be predominately for domestic (household) waste and should not be used for the disposal of, among other things, metals, chemicals/ paints, batteries, or e-waste [37, p. 19]. Rather, these items should have their own designated areas to prevent them from being incorporated into landfill. The manual notes that there is an emerging market for e-waste so these items (currently limited to TVs, DVD players, radios, computers) should be collected and stored for potential transport to a regional centre [37, p. 40]. Scrap metal is also stored separately for up to five years, with non-ferrous metals (copper, brass, aluminium) that have a high scrap value, in a secure area to prevent theft [37, p. 38]. Some other local government waste management guidelines are similar in that they provide for the separation of listed wastes (which includes some WEEE) from landfill (e.g. *Waste Management Guidelines for MacDonnell Regional Council Working Towards Best Practice 2019–2022*), while others accept only limited types of commercial hazardous waste which are disposed of in accordance with Land Use Contaminants Guidelines [38].

East Arnhem Regional Council (EARC) provides a free pick-up service for e-waste (computers, laptops, flat screen TVs, cables) with the Council office acting as a collection point for mobile phones and small batteries [39]. EARC's *Waste Management Strategy 2015–2025* includes a target of 50% of waste recycled by 2025 and the creation of Resource Recovery Centres (RRCs) at selected communities in addition to the existing Landfill and Resource Recovery Facilities (LRRFs).

As part of its recycling activities, the Katherine Waste Management Facility also participates in the Tech Collect (e-waste) free national recycling service for televisions, computers and associated accessories; Mobile Muster, by providing a drop-off point for mobile phones, batteries, chargers and accessories as well as smartwatches; and other national recycling schemes such as Drum Muster (the national program for collecting and recycling of empty, cleaned, non-returnable crop protection and animal health chemical containers) and Tyre Stewardship Australia (which promotes the development of viable markets for end-of-life tyres to increase the recycling and resource recovery of tyres and minimise environmental health and safety impacts) [40]. As for other local governments in the Territory, there is no specific reference to managing solar panel waste in the publicly available waste management policy or strategy documents.

In the NT it is apparent that despite solar panels containing materials that are listed as wastes, solar panels have not been identified as a specific waste category, nor are they considered to comprise e-waste. The ways in which other countries have addressed the management of large PV waste volumes, as well as elsewhere in Australia, is explored in the following literature review.

Section 2: Literature Review

Within the last decade, a growing body of scientific literature has emerged in response to a looming environmental crisis – the need to address EOL management of global PV waste. In this section we review relevant academic sources as well as government and industry reports relating to the management of solar PV waste. We begin by examining the international policy context and summarise current PV waste management practices overseas. Much of the existing research has focussed on four key areas: reporting on the development of particular methods and techniques for the physical recycling and recovery of materials from PV panels; assessing the economic feasibility of PV waste recycling; assessing the economic and environmental impacts through life cycle assessments (LCAs); and transportation costs. In contrast, an area which is pertinent to the current study, but which appears to have received relatively little attention, is the role of the secondary or 'used panel' market. We then move on to describe the current policy context in Australia, followed by a brief overview of key research and developments in PV waste management and planning at the national level.

2.1. International EOL management policy context

In 2012 the EU became the first jurisdiction worldwide to adopt a comprehensive regulatory framework to address PV waste under the Waste Electrical and Electronic Equipment (WEEE) Directive 2012/19/EU [1]. Under the WEEE Directive's extended producer responsibility principle, responsibility during the post-consumer stage of a PV product's life cycle is shifted (physically and/or economically; fully or partially) upstream towards the producers (manufacturers) and away from governments [2, p. 2]. The collection, transport and recycling of retired PV modules has been regulated in every EU country since February 2014. Notably, within Europe the export of waste is prohibited, which has served to promote research and development in ways in which solar PV components can be recovered and recycled [2, p. 2]. Within this context, the joint IRENA and IEA-PVPS Task 12 report, *End-of-Life Management Solar Photovoltaic Panels* [3], is a key policy publication communicating existing technological and regulatory knowledge and providing a framework – reduce, reuse, recycle – for EOL management of PV waste. Most academic research literature concerning EOL PV waste management also issues from Europe (particularly Italy), reflecting this policy and regulatory environment.

Outside Europe, other nations (including those with expanding PV markets such as Japan, China, India, Australia and the United States [3, pp. 59-74]) treat PV waste within a general regulatory framework for hazardous and non-hazardous solid waste or WEEE and classify PV panels as general or industrial waste. In 2017 Japan published voluntary guidelines on how to properly dispose of EOL PV modules and invited producers, importers and distributors of PV modules to inform waste disposal companies about substances within their composition [4]. In the United States, California has developed legislation for classifying EOL PV waste as hazardous that extends beyond the federal *Resource Conservation and Recovery Act* that regulates hazardous and non-hazardous waste management [5].

Developing countries face increasing challenges concerning PV waste management, with major schemes planned to alleviate energy poverty through the large-scale installations of grid-connected PV systems [3, pp. 72-3]. An unregulated informal sector also operates in some countries (Philippines, India and Africa), re-conditioning PV and other electrical waste, often in 'backyard' smelter outfits, involving exposure to hazardous chemicals [6].

2.2. International PV waste management: processing and planning

2.2.1. Processing PV waste

A significant portion of the literature focuses on the environmental impacts of PV waste – its toxicity in soil and water – through exposure to hazardous material either released from damaged panels [7 , 8] or through processing PV waste, for example, through leaching toxic materials [9 , 10], or pollution from transportation [11].

Currently, the options available for EOL management of PV waste are: landfill disposal, incineration, reuse and recycling (mechanical, thermal and chemical processes). In the absence of regulations mandating recycling, most PV waste is disposed of in landfill because it is the cheapest option. The methods of processing waste solar panels involve either: component repair – repair of components within the junction box; module separation – mechanical separation of panel materials, or the removal and recycling of silicon and other rare metal elements from components, using mechanical, thermal and/or chemical recycling processes [12][4]. Sica et al [13, p. 2939] and Chowdhury et al [2, p. 7] both noted that although there are many methods which have been subject to research, there are currently only two commercially available treatments that recycle PV modules: First Solar (operational in the US, Germany and Malaysia) applies both mechanical and chemical treatments to thin film CdTe solar panels; and Deutsche Solar, who recycle crystalline silicon (c-Si) modules. It should be noted that in 2018 Veolia and PV Cycle opened what they claimed to be Europe's first dedicated c-Si PV recycling facility in France [14] and processed 1,800 t of material however they have yet to scale up to achieve their stated goal of 4,000 t of waste recycled per annum with a 95% recovery rate [15].

To date, most PV waste recycling is undertaken in glass and metal recycling facilities, referred to as 'first-generation' facilities [14], although the Full Recovery End-of-Life Photovoltaic (FRELP) recycling project is conducting research into technologies for 'second-generation' PV-specific recycling facilities [16 , 17]. The Japanese Government has funded the New Energy and Industrial Technology Development Organization (NEDO) to undertake a pilot project using pyrolysis to recycle c-Si. Loser Chemie has also developed a mechanical and chemical process for recycling material from c-Si, CdTe, CIGS and GaAs systems, from panels collected within Europe [4, pp. 19-20][5].

2.2.2. Panel types and composition

Panel type and composition necessarily directs investigation of suitable recycling technologies: much of current research focuses on recycling first-generation silicon (c-Si) PV modules (mainly poly or multi crystalline), which are estimated to comprise 85–95% of panels installed since the early 1990s and, in some countries, the early 1980s [18, p. 41, 3 , 10 , 7 , 2]. Up until recently, CIGS and CdTe panels made up 2% and 5% respectively of the market share of solar panel sales worldwide [3, p. 38]. Table 2.1 gives an overview of the three generations of PV panels referred

Table 2.1 Types of photovoltaic panels

Generation	Role(s) in managing the PV panel lifecycle
1st generation	Crystalline Silicon (c-Si) • Monocrystalline • Multi crystalline (most common type)
2nd generation	Thin film • Amorphous silicon (a-Si) • Cadmium telluride (CdTe) • Copper indium diselenide (CIS) • Copper indium gallium selenide (CIGS)
3rd generation	Concentrator photovoltaics (CPV) and emerging technologies • CPV – silicon or III-V compounds • Dye-sensitised solar cells • Organic solar cells • Tandem/Hybrid cells (organic and inorganic semi-conductors) • Silicon – PERC (passive emitter and rear cell/contact)

4 See also Chowdhury et al's 2020 Tables 1 and 2 for a summary of the currently available solar panel recycling technologies
5 See also IRENA 2016 for an overview of these processes, their advantages and disadvantages

to in the literature. It is anticipated that in the future this market share will change, with first-generation c-Si PV panels expected to decrease from 92% to 44.8% by 2030, and third-generation panels predicted to reach 44.1% (from a base of 1% in 2014) by this time [2, p. 4].

Table 2.2 summarises the compositional breakdown of first- and second-generation PV modules according to different sources. It is apparent that within the literature there is a lack of consistent data available regarding the material composition of PV panels, complicated by the fact that different brands use different materials and different quantities of materials over time. Additionally, it is expected that the quantities of some components such as silver, silicon and aluminium will decline over time as new technologies develop [3, p. 42]. Since the third generation of PV modules is yet to be produced on a mass commercial basis, it is harder to quantify their composition and therefore to predict potential environmental and economic gains, deficits and risks [19 , 20 , 21]. Accordingly, most of the research literature focuses on recycling first- and second-generation PV modules.

Table 2.2 Material composition of 1st and 2nd generation panels (by percentage of panel mass/weight)

Material	Source and panel type											
	Monier and Hestin 2011:10			IRENA 2016:41-42			PV Cycle 2007			Sica et al 2018:2938		
	c-Si	CdTe	CIS/ CIGS	c-Si	CdTe	CIGS/ CIS	c-Si	CdTe	CIS	c-Si	CdTe	CIS/ CIGS
Glass	74	95	84	76	97	89	74	95	85	65.8	96.80	96.80
Aluminium	10*	<1	12	8*		7	10	0.01	12	17.5	-	-
Silicon				5			c.3	-	-	2.9	-	-
Polymer/ plastic		4^^	4+	10	3	4	c.6.5	3.5	6	12.8	3	3
Copper	16^			1		0.1	0.6	1	0.85	1	0.03	0.01
Zinc							0.12	0.01	0.12			0.04
Tin									-	-	0.02	-
Silver				<0.1++			<0.0006	0.01				
Indium						0.28	-	-	0.02	-	-	0.01
Gallium						0.1	-	-	-	-	-	0.01
Selenium						0.52	-	-	0.03	-	-	0.01
Molyb-denum							-	-		-	-	0.012
Cadmium							-	0.07		-	0.08	-
Tellurium							-	0.07		-	0.07	-
Lead							<0.1	<0.01	<0.1			

*represents the frame which is primarily aluminium

^ includes all other components such as silicon, rare metals, EVA, adhesives and lead

^^ includes all other components such as rare metals, EVA and cadmium

+ includes all other components such as rare metals, EVA and heavy metals

++ IRENA states that silver and other metals (mostly tin and lead) comprise <0.1%

Some studies have addressed the potential high volume yield of common materials, such as glass and aluminium, from recycling c-Si modules [4 , 22 , 23 , 24 , 13] and have noted that the recoverable percentage of glass (97%) and aluminium (100%) is particularly high, and significant for copper and telluride (around 80%). Others highlight the potential benefits of separating and recycling rare valuable minerals [25 , 26 , 27 , 28 , 24 , 29]. Further studies discuss the challenges of dealing with increasing volumes of hazardous waste from PV modules, particularly the disposal of lead (c-Si panels) and cadmium (CdTe & CIGS panels) [9 , 28 , 13 , 8].

2.2.3. Economic feasibility

In the absence of regulatory levers, economic feasibility and potential financial incentives to encourage PV waste recycling emerge as significant considerations within the research literature. At present, recycling processes for c-Si panels, the most prevalent modules nearing the end of their life span, are unprofitable [2, p. 9, 27 , 30]. Current low waste volumes present economical obstacles for the development of recycling processes, but if more recycling of PV waste occurs, the volume of recoverable material and precious minerals will also increase. IRENA estimates that:

> *The raw materials technically recoverable from PV panels could cumulatively yield a value of up to USD 450 million (in 2016 terms) by 2030. By 2050, the recoverable value could cumulatively exceed USD 15 billion, equivalent to 2 billion panels, or 630 GW. [3, p. 87].*

The costs of recycling and who bears responsibility for these costs are important considerations when considering the economic feasibility of recycling. Lefkowitz [31] notes that there are many points in the recycling process which may incur costs: removal of the panels, fixing the roof, transporting the panels to the recycling centre, extraction of salvageable parts, transport of reclaimed parts and transport of the remains to landfill.

D'Adamo et al [11] raise pertinent questions about what volume of waste and after what period of time PV module recycling becomes viable. Chowdhury et al [2, p. 9] suggest that a strategy for recycling and recovery will be required by 2040. Domínguez & Geyer [26] offer projections of the high volume and value of minerals that could be extracted from PV waste in Mexico by 2050. Kang et al [21] predict that by 2032 in Australia, module recycling will be an industry valued in the order of $100m. However, these and other studies note that price volatility affects projected value of metals [14 , 21].

2.2.4. Life cycle assessment

Other studies implement a life cycle assessment (LCA) to assess the economic and environmental impacts of PV modules over their life spans to consider whether upstream and/or downstream interventions might enhance their recyclability. Contreras-Lisperguer et al [32] investigates a cradle-to-cradle (C2C) manufacturing approach that seeks to address economic and environmental impacts of the c-Si PV life cycle ('eco-efficiency') by reusing materials recycled from retired panels in the production of new ones. Following the 'Closing the loop' EU action plan to encourage a holistic PV panel life cycle and a circular economy, Sica et al [13] suggest research and development to improve the recyclability of PV panels upstream and more extensive recycling of panels downstream. Similarly, Dominguez and Geyer [33] and Malandrino et al [10] propose development of comprehensive waste management planning.

2.2.5. Transportation costs

Transport costs feature in LCA and eco-efficiency models in determining the economic feasibility and potential environmental impacts of PV EOL recycling and merit special note in view of the significant distances to be factored within PV waste management planning in Australia.

In comparing landfill, incineration, reuse and recycling as approaches to managing EOL c-Si PV waste, Lunardi et al [27] find that transportation (distance and type) increased the environmental impacts of all forms of recycling. D'Adamo et al [11] emphasise that the FRELP model of PV-waste recycling dedicated plants has

advantages in reducing recycling costs but potentially increases environmental impacts through pollution from transportation flows. In their LCA of the environmental impacts of an innovative FRELP pilot project in Italy for recycling c-Si modules, Latunussa et al [16] find that most impacts relate to the transport of PV waste to the site, the plastic incineration processes and the further treatments (including sieving, acid leaching, electrolysis and neutralization) for the recovery of metals from the bottom ash. The impact of transportation ranges from about 10% (freshwater eutrophication) up to 80% (Abiotic Depletion Potential minerals). Consequently, they propose exploring the creation of decentralized recycling plants for treatment of some PV waste.

In comparing the environmental impacts of landfilling EOL c-Si panels with two recycling methods (LGRF and FRELP) in Thailand, Faircloth et al [14] propose locating a recycling plant within a province that is central to current PV installations (average distance 250 km) and a reasonable distance from the incinerator in Bangkok. In their techno-economic review of PV recycling approaches, Deng et al [34] advocate addressing transportation costs through a collaborative economical collection scheme. Fthenakis [35] suggests small-scale decentralized recycling facilities. Lunardi et al [27, p. 12] observe that:

> *For the distance of 100 km, the recycling processes are still better environmental options compared with some other choices. However, these results seem to show that it will important to develop either portable recycling plants or distributed recycling plants that can be located reasonably close to the places where modules reach EOL.*

IRENA [18, p. 51] has noted that future management of PV waste will largely depend on the type and size of PV systems. Specifically, they distinguish between the small, highly dispersed nature of rooftop systems that can add significantly to the costs of dismantling, collection and transport of expired panels, and large-scale utility PV systems which are logistically easier to manage.

2.2.6. Secondary or 'used panel' markets

In contrast to the plethora of research regarding recycling of solar PV panels, relatively little attention appears to have been paid to the used panel market, or secondary market and its contribution to the management of PV waste.

Secondary or used panel markets generally operate outside of the traditional supply chain. In the US, buyers and sellers connect through exchange markets, such as *EnergyBin*, a members-only web platform for solar companies, solar equipment brokers, resellers and suppliers, recycling and refurbishment firms, insurance companies and third party warranty companies, to seek and/or list components for sale [36]. These transactions are based on need rather than company category and a company can be both a buyer and seller. For example, an installer may sell excess equipment to another installer while a distributor may purchase a replacement part from another supplier. Decommissioned panels are also often sold to DIYers, farmers and installers in countries that have a high proportion of the population living off-grid [37]. Solar equipment brokers may represent a range of clients, including DIY homeowners, bargain shoppers, non-profit organisations, savvy commercial property owners, operations and maintenance companies and repairers [38].

The secondary market generates opportunities for the development of new services to support a sustainable solar sector, particularly repair and recycling services working in tandem to refurbish what can be reused and recycle what has reached its actual EOL [37]. Schmidt [37 , 38] has also noted that the secondary market fulfills a critical role regarding sourcing legacy equipment, which is important in an industry which has seen many manufacturers come and go. Additionally, the secondary market provides an outlet for surplus, clearance and excess stock as well as product from liquidations. It plays a key role when demand outstrips supply, for example when there are surges in PV growth following the introduction of new subsidies or other monetary incentives [38].

2.3. Australian EOL management policy settings

There are several key pieces of legislation relevant to note in the context of this study: the *National Waste Policy*, 2009 (revised in 2018); the *Product Stewardship Act 2011*; the *Product Stewardship (Televisions and Computers) Regulations 2011*; and the *National Television and Computer Recycling Scheme 2011*. Together these pieces of legislation constitute Australia's WEEE management [39, p. 218]. The *Product Stewardship Act 2011* is designed to reduce the amount of hazardous waste going to landfill as well as increase recycling and recovery of valuable materials. Under the Act, the Minister for the Environment publishes a list of additional product classes to be considered every year. For 2016–17 the product list included a class covering PV cells, inverter equipment and system accessories, such as batteries, for domestic, commercial and industrial applications in recognition that 'the volume of photovoltaic system equipment reaching end-of-life is expected to sharply increase in coming years to become Australia's largest electronic waste growth stream.' [40]. However, despite this legislation, Australia is among a number of developed countries that export the majority of its WEEE to developing countries. This this is illegal under the Basel Convention, since these countries have little or no measures to protect workers using recycling techniques, such as burning and acid dips. [39, pp. 219-20].

At a state level, in 2012 South Australia was the first government to ban e-waste from landfill, alongside investing in recycling infrastructure. However, their definitions of e-waste are designed to support the *National Television and Computer Recycling Scheme* (NTCRS), so PV components are exempted from the ban to date; this may change if the Commonwealth legislation is updated.

In 2014 the Victorian Government committed to a ban on e-waste going to landfill, with regulatory measures to be in place by June 2019. In the Eight Meeting of Environment Ministers, it was agreed that the state of Victoria would lead innovative programs that seek to reduce the environmental impacts caused throughout the life cycle of photovoltaic systems. In 2018 the Victorian Government provided $15m of e-waste infrastructure grants to increase local governments' capacity to collect and store the increasing volumes of e-waste safely in Victoria. These grants will establish the basis of a significant e-waste collection network.

In 2018 Sustainability Victoria engaged Equilibrium and Ernst Young in a research project surveying relevant stakeholders to assess product stewardship over the life cycle of PV panels, using the *Product Stewardship Act 2011* as a framework. The key aim of this assessment was to identify options for a nationally coordinated approach to product stewardship of photovoltaic systems and to implement a national system of shared responsibility for end-of-life PV products. Within the working group there were seven broad stakeholder groups, including local, state and federal government members. Notably, government stakeholders identified that high levels of PV use in rural and regional areas are an important consideration for any product stewardship approach. Broadly, the lack of obvious industry leaders in addition to the rapid turnover of industry participants (i.e. solar manufacturers and installers) are considered major challenges to a mandatory or co-regulatory product stewardship model. Other issues identified included the need for clarity regarding stakeholders' roles, the provision of reasonable access (i.e. collection points), recycling and material recovery targets and auditing and compliance measures. In this respect, these findings echo those of an earlier review of the effectiveness of Australia's WEEE management including the *National Television and Computer Recycling Scheme* [39]. Of particular note is that in the submissions for the review of the NTCRS, many stakeholders raised concerns regarding the limited number of services and collection points in regional and remote locations [39, p. 228]. Morris and Metternicht [39, p. 229] suggested three measures to help overcome deficiencies in Australia's WEEE management generally: increasing the scope of WEEE, utilising existing transport logistics of industry and, with the support of local government, greater engagement and education of the public.

In their report, Equilibrium [41, p. 4] made an interesting comparison between panels and inverters and the ease

with which they can each be recycled. E-waste recyclers reported that they can and do already recycle inverters because the equipment is similar to other electronic equipment and contains high value components. Similarly, used energy storage batteries are generally well managed due to the recognised value of constituent materials and existing policies for recycling. In contrast, PV panels are more difficult because they do not readily fit into existing recycling programs. However, a previous investigation identified PV panels as the most rapidly growing e-waste stream due to the rapid increase in their use over the last decade (especially with government subsidies for installation) [41].

A key finding in the context of the current study was that:

> *Multiple key stakeholders operating in Australia noted they currently send PV panels overseas to be recycled, commonly to the country of original manufacturer. Where is it being sent, who is providing these services and what volumes are currently unknown. [41]*

Meanwhile, at the time of writing, other States are yet to announce plans to ban e-waste, including PV, from their landfills [40]. The Equilibrium report noted that current (2019) EOL management across Australia is ad hoc, with PV panels and systems being stockpiled and landfilled owing to limited recycling and processing capacity nationally [41, p. 8]. However, some new projects, such as a 60 MW (200,000 panel) solar farm in Narrabri South, NSW, are including EOL provisions in their contracts [42].

2.4. Australian PV waste management: processing and planning

It was noted above that research and modelling for PV recycling and EOL management has developed mainly within Europe in response to implementation of the WEEE directive. While d'Adamo et al [42, p. 5] suggest that 'a recovery centre treating several typologies of waste (multicore) could be the solution to these issues', this may be more suited to Europe than Australia. Australia's large, sparsely populated land area, high freight costs and vast distances need to be taken into account in any consideration of adapting European modelling, such as FRELP pilot projects, to the Australian context.

Kang et al [21] discuss adapting the European PV Cycle model to Australia, suggesting that while fewer recycling centres and collection points may be needed, the logistics of transporting material will cost more. Regarding the economic feasibility of recycling EOL solar panels, they hypothesise that, in Australia, much less quantity of waste may be processed before 2030 but with higher financial return for recycling per unit c-Si PV. The situation may be opposite after 2030 if increasing numbers of second- and third-generation PV panels are installed. Also, lead-free solar panels have been considered in many PV industries due to the concerns of environmental issues caused by lead release. Increasing landfill levies may make recycling a more attractive option. Kang et al suggest that if lead free solar cells are widely used, landfilling PV waste may be economically comparable if the cost of landfill disposal is lower than the recycling expense.

Deng et al [34] suggest addressing transportation costs through a collaborative economical collection scheme in which PV manufacturers provide recycling services so that there is an off-taker for the products of recycling and also a steady flow of recycling volume both from manufacturing scrap and end-of-life modules, such as First Solar's recycling program.

Best et al [43] sought to understand the economic, social and environmental determinants of solar PV uptake across Australian households, finding that higher net wealth was generally associated with a higher likelihood to install. Environmental preferences and related behaviours, space constraints and property tenure were associated with both actual uptake and intention to install [43]. They subsequently investigated the effectiveness of Australia's small-scale Renewable Energy Scheme for rooftop solar and its role in contributing to the considerable variation in small-scale solar uptake across different Australian postcodes [44]. Such studies are useful when considering the drivers of solar panel installation and, consequently, future panel waste trajectories.

At the other end of the panel life cycle, Salim et al's [45]

stakeholder survey identified a list of drivers, barriers and enablers to EOL management of PV panels and battery energy storage systems, based on 57 responses from key stakeholders across government, academics, distributors/installers and non-government organisations. While most of these respondents were based in NSW and Victoria (and none were from the NT), the study nevertheless provided useful insights into policy and economic barriers as perceived at a national level. Notably, these included a lack of profitability in recycling, lack of regulations, lack of incentives for collection and recycling and lack of incentives for installers to participate in a product stewardship scheme [45, p6]. Among the measures suggested by Salim et al [45, p10] are that circular business models (i.e. lease, deposit-, trade-in etc.) could help ensure a greater return rate and reduce collection costs.

Currently, a small informal voluntary market exists for consumers to recycle solar panels (online via Gumtree, eBay, etc), often for use in off-grid systems such as recreational vehicles. However, as for used panel markets overseas, it appears that to date this part of the PV industry has received relatively little attention from researchers or policy-makers.

During 2017 upgrades to Nyrstar's smelter and refinery in Port Pirie, South Australia, commenced, including an expansion of the range of e-waste it can process, reported to include PV cells [46 , 40]. Despite this, as noted earlier in this chapter, Australia exports much of its WEEE overseas for reprocessing. In their review of the NTCRS, Morris and Metternicht observed that although the material recovery target of 90% for WEEE was one of the highest in the world, without any enforcement the target was meaningless. They found that the majority of recyclers lacked the capacity to recover 90% of WEEE materials, 'resulting in the separated materials [being] sent overseas for reprocessing or locally landfilled' [39, p. 220]. The current lack of on-shore capacity to recycle was also recognised by governments that participated in Salim et al's [45] survey as a major barrier for EOL, along with the geographic dispersion of PV systems in Australia, which will 'make collection and recovery activities more challenging and costly' [45, p9].

2.5. Concluding remarks

From our literature review we made a number of key observations. Firstly, the general view that, despite the environmental hazards posed by solar PV waste, there are genuine potential economic opportunities arising from the need to manage such waste, was common throughout many of the papers. Secondly, although a substantial body of the literature is devoted to describing research and development work on PV recycling, materials recovery processes and techniques worldwide, there are currently very few facilities operating that include the recovery of the various metal components, that is, that fully recycle the modules. Thirdly, transport/logistics issues (principally costs) associated with panel collection and transportation to recycling facilities pose a significant challenge for economic recycling and materials recovery, even in more densely populated parts of the world. Decentralised recycling plants, mobile recycling plants and collaborative collection schemes have been proposed as potential mechanisms to manage PV waste but have not been subject to detailed evaluation at different geographic scales. Fourthly, in Australia, panel waste flows vary with some panels sent for recycling while others enter a largely unregulated used panel market and yet others end up at landfills. Given that currently there are no facilities in Australia which undertake full metals recovery, it seems that existing recycling programs and infrastructure is limited to the initial breakdown and separation of the major components (frame, glass, junction box and cabling) and some treatment of the glass (e.g. crushing). Finally, there is the absence of a clearly defined EOL policy at the national level. While product stewardship is being explored as a potential model to address EOL management, it is currently unclear to what extent this would apply to existing panels. Furthermore, in undertaking this study, it appears that little consideration has been given to the efficacy of this model outside the major metropolitan areas. This latter point has emerged as an overarching theme: the consideration of PV waste issues has rarely been examined in regional or remote settings and the majority of the potential solutions require economies of scale, in other words, large volumes of PV panels derived from small catchment areas. This is likely to prove challenging for the NT.

Section 3: Research Design and Methodology

In this Section we describe our overarching approach, several key concepts which informed our data analysis and interpretation and the ethical conduct of the study. We then describe the datasets used to generate an evidence base and data analyses.

3.1. Approach

This study positioned the issue of solar PV waste firmly within the notion of a 'circular economy', consistent with recent research and policy developments in the waste sector more broadly, including the 2018 *National Waste Policy* [1]. From a waste perspective, a circular economy is one that seeks to minimise waste including through recycling, re-using/re-purposing, repairing and recovering valuable materials to the fullest extent possible.

We were nevertheless aware that much of the discussion regarding solar PV waste to date has been framed in terms of techno-economic solutions that have tended to treat solar PV waste as a single, apparently uniform category of waste, rather than recognising that when solar things break down, they do not follow a single trajectory into electronic waste flows [2]. Therefore, this study sought to uncover the varied fates of the Territory's solar PV waste, as reflected in current practices. At the same time, given that this was an initial study aimed at generating a baseline dataset and understanding current roles and responsibilities, we felt that there was some value in adopting a systems approach to the initial identification of stakeholders. Although these conceptualisations may not necessarily sit comfortably side by side, conceiving of the solar waste sector as a system with different interest groups as interacting elements within it, may be a more holistic approach that can accommodate such theoretical tensions with ease. It is also an approach more likely to yield useful insights regarding potential opportunities for regional and remote areas, as it allows for practitioners of economies of scope and scale; recognises the diverse range of materials components that comprise solar waste; and can also allow for less traditional players in this space as well as a diversity of afterlife users.

In developing this approach we also drew upon a number of theoretical frameworks regarding waste and human behaviour and, in particular, identified several key concepts from the works of Davies' *Geography and the matter of waste mobilities* (2011), Stern's *Theory of Environmentally Significant Behaviour* (2000), Strasser's *Waste and Want* (1999), Packard's The Waste Makers (1960) and Brand's *How Buildings Learn* (1994). These concepts were applied in conjunction with the overarching methodology and approach described above to interpret and discuss the study findings.

3.2. Key concepts

Strasser's work suggests obsolescence arising from technological developments and a growing consumer culture. She observed that, by the 1920s, obsolescence had become an ordinary concept in everyday life. People threw away kerosene lamps in favour of more advanced ones and later, because they had electricity [3, p. 191]. They did not necessarily throw away the kerosene lamps because they no longer worked. Building on this, Packard introduced the notion of 'functional obsolescence' whereby, as a result of new technology(ies), an 'existing product becomes outmoded when a product is introduced that performs the function better' [4, pp. 55,103]. This is consistent with Strasser's contention that in a consumer culture, 'major consumption decisions almost always involved technological improvements' [3, pp. 199-200].

The existence of variable 'after-lives' of objects and waste mobility flows has been explored by Davies [5]. She argues that once objects are labelled as 'waste', it does not mean that they 'cease to exist, rather it marks the beginning of relocation and dematerialisation processes which occurs at varying scales over different time periods and with varying degrees of human intervention and environmental impact'. Furthermore, the relocation and dematerialisation processes can be conceived of in terms of waste mobility flows which can be mapped and followed [5].

Stern's [6] work identified four casual factors that influence an individual's environmentally significant behaviour: attitudinal factors, such as norms, beliefs and values; contextual forces, such as legislative, financial, interpersonal and physical constraints; personal capacity, including skills and knowledge, time to act, financial and literacy capacity; and 'habit or routine'. With regard to the latter, Stern noted that behavioural change often required breaking old habits and the establishment of new ones [6, p. 11]. Frequently, a combination of these factors is a pre-requisite to bring about change.

The concept of 'design for disassembly' was considered in several publications [7 , 8 , 9]. One which is particularly useful is the discussion by Brand, using buildings as an example. He argues that buildings could be thought of and designed as different layers with different use-lives. These layers include, for example, the Structure (foundation, loading bearing elements), which could last anywhere from 30 to 300 years, the Skin (external surface), which changed every 20 years, and Services (plumbing, communication, electrical), that wore out or became obsolescent every seven to 15 years. A long-lasting building would be comprised of layers that were independent of one another and easily changeable and replaceable, thereby negating the need to demolish the entire building [7].

3.3. Ethics

This research was undertaken with approval from the Charles Darwin University Human Research Ethics Committee (Approval H19023, 5th April 2019). This Committee operates in accordance with the National Health and Medical Research Council's Statement on Ethical Conduct in Human Research. Following these guidelines, the team used an informed consent procedure for all data collection, including sector interviews. Where individual participants have been quoted in this report, participants were provided with a draft copy of the relevant text and consent obtained prior to preparation of the final report.

3.4. Creating a solar panel dataset

3.4.1. Data sources

As one of the aims of this study was to attempt to quantify future solar PV waste trajectories at both the NT and local government level, as well as the potential for recycling materials from solar panels, data about small and large installations was sourced from:

- the Clean Energy Regulator's Small-scale and Large-scale Renewable Energy Databases;
- Power and Water Corporation, NT; and
- Ekistica.

The Clean Energy Regulator's postcode data for small-scale installations (SSIs) and Large-scale Renewable Energy Target (LRET) database provided this survey's basic reference point for sourcing data to estimate the amount and geographic distribution of potential solar panel waste across the NT. CER is an independent statutory authority established under the *Clean Energy Regulator Act 2011* which is 'responsible for accelerating carbon abatement for Australia through the administration of the National Greenhouse and Energy Reporting scheme, Renewable Energy Target and the Emissions Reduction Fund' [10].

The postcode database for SSIs provided information in relation to solar units, typically used for domestic dwellings, with a capacity of less than 100 kilowatts. In contrast, large-scale installations (LSIs) refer to those with a capacity of more than 100 kilowatts, which includes large rooftop and ground-mounted PV systems (hundreds of kW), as well as utility (MW) scale PV systems.

Information about small-scale installations dating back to 2000–01 and aggregated by postcode areas in the NT is available through the public register on CER's website. As some of the postcode areas overlapped two or more local government areas and may have included places in South Australia, the project team sought further aggregated, de-identified data regarding small- and large-scale solar panel installations in the Northern Territory at the local government area level and, specifically, the timing of installations and panel numbers. The Clean Energy Regulator provided the

number of installations in each postcode in the NT and the quantity of panels associated with those installations broken down by install year. However, staff from the Clean Energy Regulator advised that they were unable to provide any further breakdown of this data as disclosure of granular data is prohibited by the *Clean Energy Regulator Act 2011* [11]. It is important to note that the *Clean Energy Regulator Act 2011* provides the circumstances under which data may be provided, as well as the nature and the extent to which that data can be provided to external parties. Given the processes in place regarding claiming small-scale technology certificates, CER may hold data regarding system types (panel brands and manufacturers) but this information may also be regarded as 'protected information' that cannot be released to external parties. The dataset from CER for SSIs was current at June 2019, although they advised that the 2019 and 2018 figures will continue to rise due to the 12-month creation period for registered persons to create certificates under the Renewable Energy Target legislation. It is also important to note that the CER SSI data only captures those installations where the owner has participated in the Small-Scale Renewable Energy Scheme either directly, through receiving a number of small-scale energy certificates which they may sell to recoup some of their installation costs, or indirectly by receiving an upfront discount from a registered agent such as a retailer, installer or trader of small-scale energy systems. In other words, the CER SSI database does not necessarily capture all small-scale installations.

Information about LSIs was available on CER's large-scale installation certificate register. However, the number of solar panels in each LSI was not specified on the public CER certificate register, so additional data was sought from the NT Power and Water Corporation (PWC) who provided a customised dataset in relation to their installations for the NT Solar Energy Transformation Program (SETuP). Information about panel numbers was sought from other sources such as the Global Energy Observatory [12] and the Desert Knowledge Australia Solar Centre (DKASC) [13], as well as reports, articles and media releases relating to specific installations [14 , 15 , 16 , 17 , 13 , 18 , 19]. Where no information about panel numbers was available, an estimate was derived from comparison between installations in the PWC dataset with a similar kW capacity and from the same time period. Detailed data regarding panel types was available for 30 of the 57 LSI installations. Given that these installations all consisted of c-Si panels, it was assumed that, with the exception of the 10 installations excluded from this study, the remaining 17 installations also consisted of c-Si panels. Of the 10 LSI installations (totalling an estimated 35,364 panels), three were excluded as there was no publicly accessible information regarding their capacity available; five were excluded because no information regarding panel composition or weights for that particular type/brand could be located; and two were excluded because they comprised third-generation solar panel types. Appendix 1 provides further details regarding those LSIs that were excluded.

Data regarding solar panel installations that occurred under the Centre for Appropriate Technology's (CfAT) renewable energy program, 'Bushlight' (which ran from 2002–2013) was sought from Ekistica, a subsidiary of CfAT, which now specialises in, among other things, renewable energy systems. While information regarding panel brands was not available, panel numbers, installation dates (including some historical installations from the mid–late 1990s), location and technical capacity data was captured within this database. Systems that did not have an installation date recorded (accounting for 2325 solar panels) were excluded from analysis. This database also included references to non-Bushlight renewable energy systems but because installation dates, panel numbers or capacity for these installations were not included, non-Bushlight renewable energy systems (with the exception of those captured by the PWC database) have not been included in this study. The Ekistica dataset was the only dataset that contained some information regarding pre–2000 installations in the NT.

3.5. Analysis of the solar panel dataset

3.5.1. Data aggregation

Data on solar panel installations was entered into Excel. The data for both small- and large-scale installations was collated in relation to LGAs where possible since local councils are responsible for managing waste in the Northern Territory. LSIs were identifiable by name and location and thus could be clearly assigned to particular LGAs. Bushlight installations were identified by community name and maintenance run (shown on a separate map) so the majority of these were also able to be assigned to a particular LGA.

Aggregating CER information about SSIs by LGA was more challenging because the data available on PV installations is provided only by postcode. NT postcodes often cover large geographic regions, sometimes overlapping state boundaries. For example, 0872 covers most of central Australia (except Alice Springs), including some localities within South Australia (although CER excluded installations located outside of the NT in their customised data). Some postcode areas also cover two or more LGAs, such as 0822, which overlaps Litchfield, Tiwi Islands, Belyuen, West Arnhem and East Arnhem, and 0872, which includes places located within the McDonnell, Central Desert and Barkly local government areas. As a result, it was not possible to provide a clear estimate that relates solely to panels in any one LGA jurisdiction. Accordingly, Section 4 presents data by LGAs with overlapping postcode areas shown separately.

As noted in Section 1, some local governments have come together to form collaborative groups with regards to addressing waste management issues. Accordingly, the data was also aggregated at a broader regional level as follows:

- Central Australia, incorporating the Alice Springs, MacDonnell, Central Desert and Barkly LGAs;
- Big Rivers, incorporating the Katherine, Roper Gulf, Victoria Daly, West Daly and Coomalie LGAs; and
- Northern Region, encompassing the Greater Darwin Area – Darwin, Palmerston, Litchfield, Wagait, Belyuen LGAs and some unincorporated land – and Remote Northern area, which includes East and West Arnhem and the Tiwi Islands.

It was also noted in Section 1 that, in addition to the 17 LGAs, there are also areas of unincorporated land within the NT. These unincorporated areas are non-contiguous and occur as a clearly defined area around Yulara in Central Australia and as several areas in the Northern Region. For the purposes of this analysis, LSIs at Yulara have been included in the adjoining local government area (MacDonnell).

3.5.2. Calculation of solar panel life spans

Chowdhury et al [20, p. 5] identified four primary life cycle phases of any given PV panel during which waste may be generated – panel production, panel transportation, panel installation and use and EOL disposal – and described the various causes of solar panel PV failure. The waste trajectories forecast in our study does not include panel production as it is assumed that production waste is managed by the manufacturers.

Initially, a benchmark of 25 years was chosen based on other PV lifetime estimates within the literature, which are based on manufacturers' warranty guarantees of 'at least 80% output after 20–30 years of operation' [21, p. 1]. In estimating the volume of future PV waste, IRENA projects a regular loss scenario based on an average panel lifetime of 30 years, which it couples with an early-loss scenario, taking into consideration ''infant', 'mid-life' and 'wear-out' failures before the 30-year life span' [22, p. 11]. Japan's Guidelines on Management of End-of-Life PV Panels (April 2016) use a 25-year lifetime that assumes 'failure and/or warranty activation in 0.3% of panels installed each year' [22, p. 66]. First Solar also estimate a 25-year life span for solar panels in their recycling scheme [23]. In *PV Module Recycling: Mining Australian Rooftops*, however, Kang et al [21] assume a relatively conservative retirement age of 20 years in calculating solar panel waste trajectories. The 25-year benchmark therefore sat as a mid-range between IRENA's 30-year lifetime and Kang's 20-year lifetime.

However, given the evidence regarding solar PV panel disposals in the NT that emerged from the stakeholder interviews, the decision was made to calculate estimated panel waste trajectories that incorporated IRENA's [22, pp. 11,30] data on early losses, as it was felt that this was a more accurate reflection of the situation on the ground. Table 3.1 below indicates the nature and extent of these early losses and revised upper limit EOL time spans for the affected panels. It is worth noting that regardless of which schema is selected (IRENA vs Japan's Guidelines), panel waste begins to noticeably increase during the period 2030–2035, peaking between 2040 and 2050, consistent with the trend worldwide. The timing of the initial waste surge in 2030 also coincides with the probable retirement of the initial wave of PV installations that occurred during the 1990s, again reflected in worldwide trends. It is also important to note that our estimates are conservative, given the lack of readily available data on panel installations in the NT prior to 2000.

The IRENA report uses the Trina Solar TSM-DC05A.08 (60 cells, with a capacity of 270 watt-peak and weight of 18.6 kg) as their standard reference for a c-Si module. In making projections of volume and composition for future PV waste trajectories in the NT, estimates were made for panels installed during the periods 2001–05, 2006–10, 2011–5 and 2016–20, using a panel that was known to have been used in the Territory during each period. The exception was 2001–05; in this instance, an example from a 2005 solar panel buyer's guide has been used as the reference panel in the absence of further information (see Appendix 2 for details of sample modules used). We were unable to locate any specifications for modules used in the period 1996–2000, so the sample module used for the period 2001–2005 has also been used in relation to panels installed prior to 2001 (i.e. the Bushlight panels). The potential volume of panel waste by weight at the end of the upper limit projected life spans was calculated by multiplying the likely number of decommissioned panels with the sample module weight. Information about the number and type of thin-film panels installed in the NT since the introduction of solar energy was difficult to obtain, so the sample models cited in the IRENA report were used as the reference for these calculations: First Solar FS-4100-2 (100 W) Solar Panel for a standard CdTe panel and Solar Frontier SF160-S for a standard CIGS panel.

3.5.3. Calculation of panel types

The IRENA [22] report states that c-Si PV technology predominates worldwide, constituting

Table 3.1 Nature and extent of early loss failures for panels installed between 1996 and 2020, and revised upper limit EOL time spans for affected panels

Schema	Japan's Guidelines	IRENA Early-Loss scenario			IRENA Regular EOL
		"Infant failure" (1% of all panels, 1-4 years after installation)	"Midlife failure" (2% of all panels, after 10 years)	"Wear-out failure" (4% of all panels, after 15 years)	Regular EOL span (remaining panels, after 30 years)
Installation period	Year Panel reaches EOL (end span)	Year Panel reaches EOL	Year Panel reaches EOL	Year Panel reaches EOL	Year Panel reaches EOL
1996–2000	2025	2004	2010	2015	2030
2001–2005	2030	2009	2015	2020	2035
2006–2010	2035	2014	2020	2025	2040
2011–2015	2040	2019	2025	2030	2045
2016–2020	2045	2024	2030	2035	2050

around 92% of the market share. Similarly, NT providers, PWC and Ekistica, estimate that c-Si make up approximately 85–90% of panels installed in the NT [24 , 25]. This claim was consistent with the data available about brand, make and type of module of the 57 large-scale installations, which were primarily c-Si, although sample CIGS and CdTe panels comprise part of the DKA research installation. Worldwide, CIGS and CdTe panels make up 2% and 5% of the market share respectively of solar panel sales [22, p38]. For panels comprising SSIs, calculations of PV numbers, weight and composition in this study followed IRENA's breakdown, with the percentage of c-Si panels rounded up to 93%. Detailed data was available for 56% of the large-scale installations included in this study and these installations all consisted of c-Si panels. On this basis it has been assumed that all the remaining large-scale installations in the NT included in this study comprise c-Si panels.

3.5.4. Limitations of the solar panel datasets

In the course of seeking data, several limitations became apparent, including the lack of information regarding the number and distribution of pre-2000 installations in the NT; lack of readily accessible information on solar panel types (brands) and, in turn, detailed material composition data for different solar panel brands; lack of readily available information regarding numbers of panels that had already been removed/de-installed; and challenges posed by the provision of data regarding installations at postcode level. The implications of these limitations are discussed in more detail later in this report. *However, as a result of these limitations, the projections of future panel waste volumes, compositional breakdowns of waste materials and volumes of recoverable materials provided in this report are notional and should only be taken as a general guide.*

3.6. Sector interviews and consultations

In order to canvas views from throughout the sector, data was collected for this research through semi-structured interviews. A set of questions were prepared to be answered by all interviewees with the flexibility to ask additional questions during the interviews to clarify and further expand on certain issues. Interviewees included policy makers and regulators, systems engineers, installers, recyclers, energy providers, representatives from advocacy groups and environmental officers or waste managers from local government associations (LGAs). Owing to a lack of NT-based recyclers, the recyclers interviewed were from regions outside of the Territory, however their area of operations included the Northern Territory. The interviewees worked across the Northern Territory in Outer Regional, Remote and Very Remote regions.

Since the stakeholders were located across the NT, 17 interviews were conducted over the phone, with three face-to-face, and one interviewee sent the questions by email. The participants were first approached through a quick telephone call to gauge their interest in participating. If they were interested, a time for an interview was fixed. They were also emailed the Plain Language Statement and the Consent form. The interview questions and the data collection process had been submitted to and had the approval from Charles Darwin University's Ethics Committee. Data from the interviewees was deidentified and coded accordingly, to have only their geographical location and role in the solar PV life cycle included.

Due to the exploratory nature of this research, the sample sizes were not calculated using probability statistics. The selected interviewees were chosen through purposeful sampling (also known as purposive sampling) based on their role in the management of PV panels. The strategy of maximal variation sampling was also used to allow data collection from diverse individuals who hold different perspectives on solar PV management. Creswell and Clark point out that if participants with a different role are chosen 'then their views will reflect this difference and provide a good qualitative study with a complex picture of the phenomenon' [26, p. 176].

The interview questions were aimed at generating insights into the current PV panel removal practices, challenges and potential solutions associated with

managing PV panel waste. A trial of the survey questions was conducted with two stakeholder participants which resulted in further refinements to the questions.

Local government participation and representation in this study occurred via the direct involvement of representatives of different local councils and waste management working groups. As a result of this approach, eleven LGAs were represented either directly or indirectly. It should be noted that all 17 LGAs were contacted and invited to participate but some declined because they felt they could not contribute greatly to the project given their lack of resources, whilst others declined for reasons unknown and yet others did not respond to emails or phone messages. Attempts were also made to contact all 21 PV installers listed in the Northern Territory Yellow Pages on-line, but only five installers were able to be interviewed (although several others expressed a desire to participate but could not schedule a time). Nevertheless, this represents 24% of all NT installers. Given that these installers worked in Outer Regional, Remote and Very Remote regions and that other participants were also from Remote and Very Remote areas, the data gathered from the surveys has been taken to be representative of all the geographic regions across the Northern Territory. Recyclers included those currently operating in the NT and those looking to expand their business to include the Territory.

3.7. Final data analysis

Data from the sector interviews and consultations was imported into a research analysis software program called NVIVO. The team used a multi-step collaborative process to develop and test a project codebook for coding data in NVIVO. Several rounds of coding and memo writing resulted in identifying certain themes from the collected data. These themes and categories were aimed at answering the research questions and are used to report on key findings arising from the stakeholder interviews (Section 5). Information generated through the process of developing a solar panel database was then combined with the results of an analysis of the sector interviews and consultations and is presented as the resulting discussion (Section 6).

A snapshot of preliminary key findings was presented to stakeholders in two information sessions in March 2019 for input and feedback. A final draft of this report was then distributed to project partners, key stakeholders and individual expert colleagues for advice and input before final preparation.

PART 2: RESEARCH FINDINGS

Consideration of EOL management options for PV waste in the NT first required data regarding the nature and extent of this waste. Accordingly, the project sought to answer questions regarding the current volume of solar panels in the Territory, the likely solar panel waste trajectory over the next 20–30 years, the geographic spread of solar panels and volumes of different panel types and material composition. The latter data is important for considering the potential for recycling and recovery activities that may offset the costs of managing solar waste as well as addressing environmental concerns around the disposal of solar PV panels.

Quantifying the Territory's solar PV waste is undertaken in Section 4. A hypothetical exploration of possible economic returns from recycling PV modules and recovery of different materials that comprise solar panels is also presented. The findings from the stakeholder surveys are presented in Section 5. This section includes a description of current EOL practices in the Northern Territory and identifies a number of barriers and challenges to managing solar waste in the NT, as well as a range of potential solutions preferred by stakeholders.

Section 4: Quantifying Solar Panel Waste in the NT

In this section we have attempted to quantify the nature and extent of solar PV waste in the NT. Waste trajectories are presented for the Territory as a whole and by region. We then provide estimates by panel type, followed by material composition estimates. We explore the potential extent of recoverable materials, as well as hazardous components, based on their compositional breakdown. We then present some hypothetical economic returns derived from recycling the most common panel type installed in the NT. Detailed data regarding estimated waste volumes, panel types and recoverable and hazardous materials for each LGA and overlapping postcode areas are provided in Appendix 4.

It should be noted that the data presented in this section relates only to the solar panels installed in the NT to date. It does not forecast future installation rates; consequently, the estimates provided in this section should be considered underestimates as they do not include early failures of panels installed over the next 30 years.

4.1. Estimated waste volumes and trajectories

4.1.1. Northern Territory

Based on the available datasets, a minimum total of 396,088 PV panels have been installed in the Northern Territory since 1996. Of these, at least 80.09% are on small-scale installations (SSIs), primarily residential in the main urban areas of Alice Springs and Darwin. Overall, the PV panel waste trajectory for the NT is estimated to increase from 106.68 t (5,738 panels) in 2025 up to 4,398.90 t (228,930 panels) in 2050, with a sharp surge commencing from 2040 (Figure 4.1). These figures are underestimates of the total volume of waste that will accumulate, particularly in the period up to 2030, given that it is unknown how many solar panels were installed during the 1990s in the Territory and, as noted in the previous section, currently there is no requirement to track all panel installations and discards.

It was anticipated that across the major regions (Northern, Big Rivers and Central Australia), as well as all LGAs, panel waste trajectories would exhibit a similar upwards trend over time. This is not the case. As shown in Figure 4.2, these trajectories vary across the major regions and most likely reflect a combination of historic and demographic factors, such as the Alice Springs Solar City Program which ran from 2008 to 2013 [1].[6] It is also consistent with research by Best et al [2 , 3], the prevalence of particular housing tenures across different LGAs, and impact of particular government

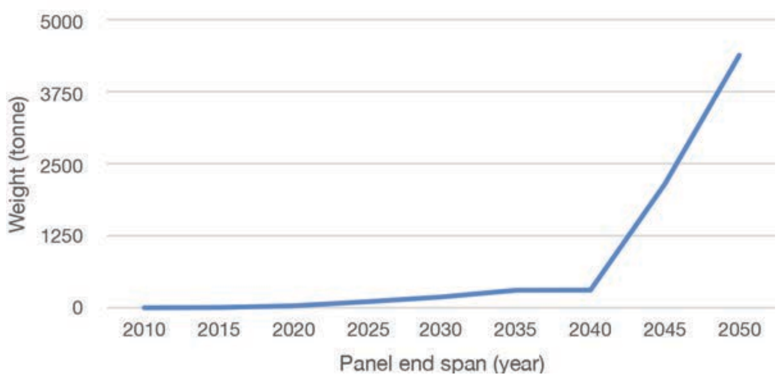

Figure 4.1 Estimated volume of solar PV waste for the NT from solar panels installed between 1996 and 2019

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6 During the Alice Springs Solar City program, 277 residential and 39 business PV solar systems were installed as well as 5 large-scale iconic projects. An additional 320 residential PV solar systems are estimated to have been installed over the same period, independently of the Solar City program (see Alice Solar City 2013).

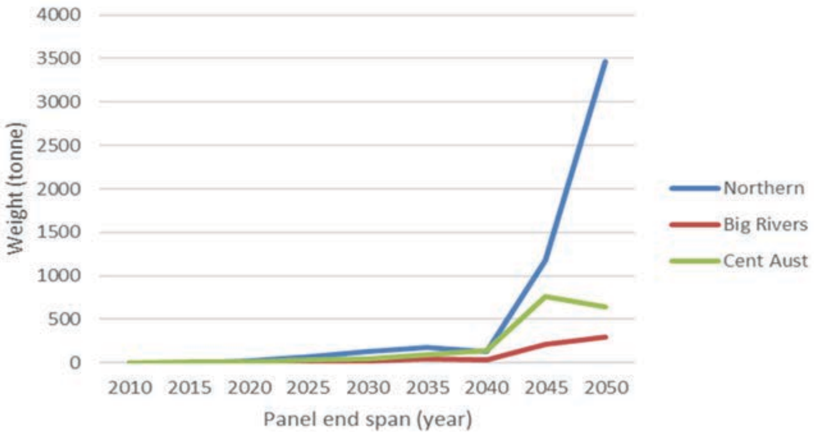

Figure 4.2 Estimated volumes of solar PV panel waste by region, to 2050

policies including subsidies for the installation of solar panels. The implications of this patterning for end-of-life management is discussed briefly later in this section.

4.1.2. Northern Region

The Northern Region includes the following Local Government Areas: Darwin City Council, Palmerston City Council, Tiwi Islands, East Arnhem, West Arnhem, Wagait, Belyuen, Litchfield and three unincorporated areas. Postcode 0822 also overlaps the Northern Region and parts of the Big Rivers Region and the West Daly LGA, as well as parts of other Northern Region LGAs. Of the 273,764 PV panels installed in the Northern Region, 83.89% occur in the Greater Darwin area (Figure 4.3) and, as shown in Figure 4.4, 47% occur in Darwin and 21% in Palmerston.

The significant increase in panels reaching their EOL between 2040 and 2050 in the Northern Region is not restricted to the Greater Darwin area. This trend is also the case for the Remote Northern LGAs. With the exception of the 0822 postcode area, volumes of panel waste remain small (less than 5 t) up until 2035, when there is a slight increase to around 20 t, followed by a sharp increase from 2045 onwards (Figure 4.5). The magnitude of this latter increase, projected to occur within a five-year period, will prove challenging for these remote LGAs and may require a change in waste management strategies within a relatively short period, to manage the increased volumes of waste at this time. It should be noted for these LGAs (excepting Postcode 0822 area), that this dramatic increase in volume can be almost entirely attributed to the establishment of large scale installations (LSI) in remote communities including

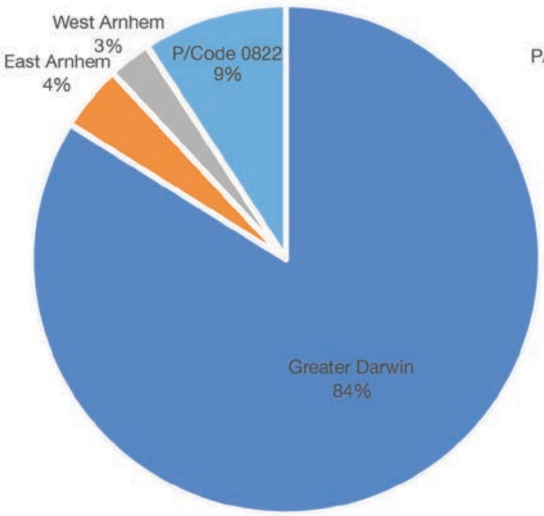

Figure 4.3 Percentage distribution of total panels installed in the Northern Region between 1996 and 2019, by LGA and overlapping postcode 0822.
Note: Areas with fewer than 100 panels appear here as 0.

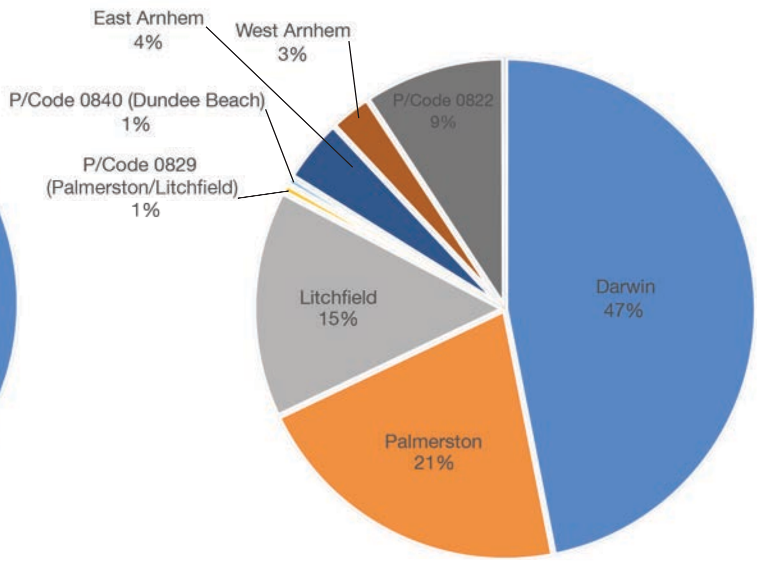

Figure 4.4 Detailed percentage distribution of total panels installed in the Northern Region between 1996 and 2019, by LGA and overlapping postcodes.
Note: Areas with fewer than 1,700 panels appear here as 0.

Maningrida, Warruwi, Gunbalunya, Minjilang, Milingimbi, Galiwinku, Gapuwiyak, Milyakburra and Ramingining in the 2016-2020 period. Figure 4.6 shows the waste trajectories in these LGAs excluding these LSIs. When these are excluded it is apparent that the increase in PV waste between 2040 and 2050 is small, being less than 22t.

Figure 4.7 below illustrates the anticipated volumes of panel waste that will occur in the Greater Darwin Region, by LGA and overlapping postcodes. As previously indicated, the majority of this waste will come from the Darwin LGA and volumes of panel waste will begin to increase sharply from 2040 in this LGA. In contrast, volumes of panel waste in the Wagait LGA and postcode areas 0840 and 0829 remain small (i.e. less than 30 t) overall.

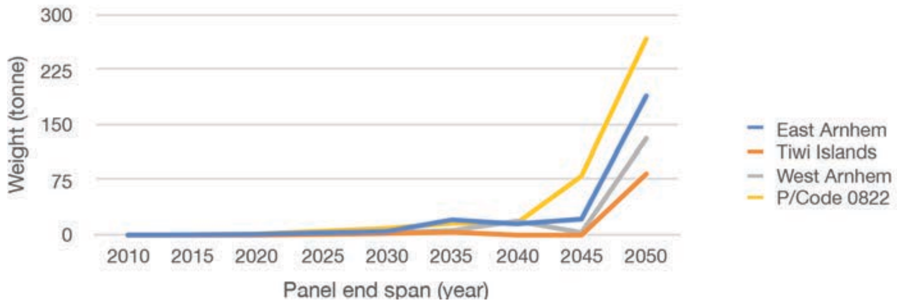

Figure 4.5 Estimated volumes of solar PV panel waste in the Remote Northern LGAs and postcode 0822

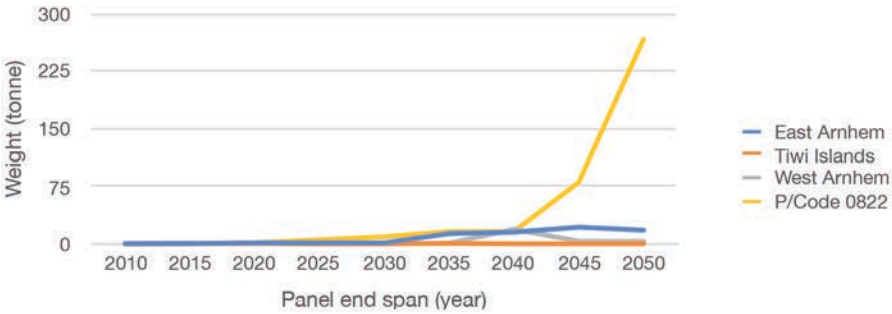

Figure 4.6 Estimated volumes of solar PV panel waste from small-scale installations (SSIs) only in the Remote Northern LGAs and postcode 0822

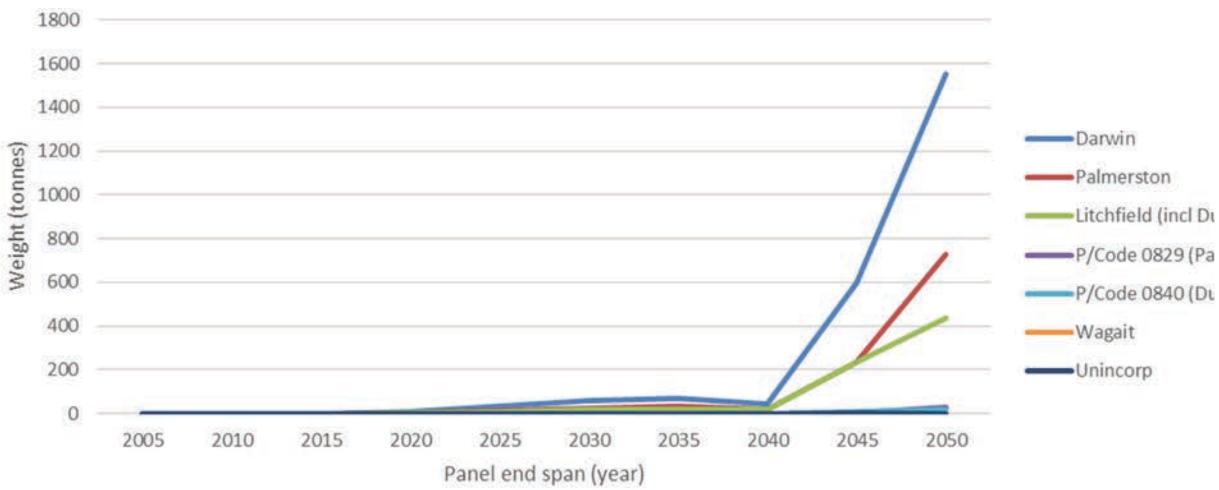

Figure 4.7 Estimated volumes of solar PV panel waste in the Greater Darwin Region and overlapping postcodes

4.1.3. Big Rivers Region

In this analysis, the Big Rivers Region includes the Coomalie, Katherine, Roper Gulf, Victoria-Daly and West Daly LGAs and overlapping postcode areas 0850 and 0852. Waste trajectories in the Big Rivers Region during the period 2030–2050 are highly variable (Figure 4.8).

For example, Roper Gulf is expected to experience an earlier small surge in PV panel waste (just under 25 t in 2035) compared to other LGAs before declining to about 6 t in 2045. However, after this time the volume rapidly increases to 53.44 t in 2050. In contrast, in postcode 0850, which covers both the Katherine LGA and part of the Victoria-Daly LGA, PV panel waste surges sharply after 2040 to peak at 137.25 t in 2045, before falling to around 104 t in 2050. In the Coomalie LGA the volume of solar panel waste remains very low (less than 3 t) up until 2040 when there is a small but steady increase in PV waste to 15.37 t in 2045 and 27.93 t in 2050.

The peak in panel waste from postcode 0850, which includes the Katherine LGA, reflects panels installed between 2011 and 2015 reaching their regular end of life and is consistent with the overall NT trend between 2040 and 2045. The decline after this time may reflect the LGA nearing 'saturation point' in terms of the number of suitable rooftops available for new solar installations and homeowners prepared to invest in solar PV, however it was beyond the scope of this study to test such assumptions.

4.1.4. Central Australia Region

Local government areas covered by the Central Australian Region for the purpose of this analysis included the Barkly, Alice Springs, Central Desert, MacDonnell and postcodes 0872, 0873 and 0874, which overlap two or more of these LGAs. It should be noted that postcode 0872 includes areas in all three Very Remote LGAs in this region (i.e. Barkly, Central Desert and MacDonnell).

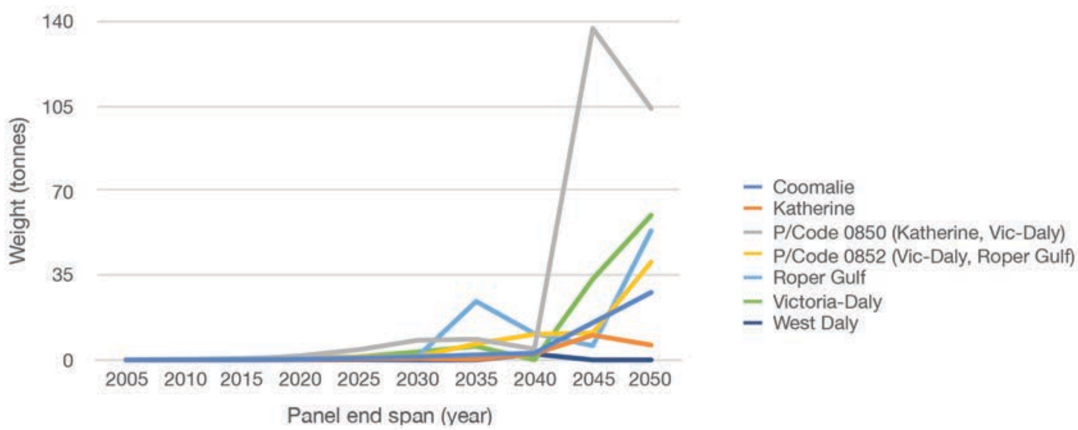

Figure 4.8 Estimated volumes of solar PV panel waste in the Big Rivers Region by LGA and overlapping postcodes

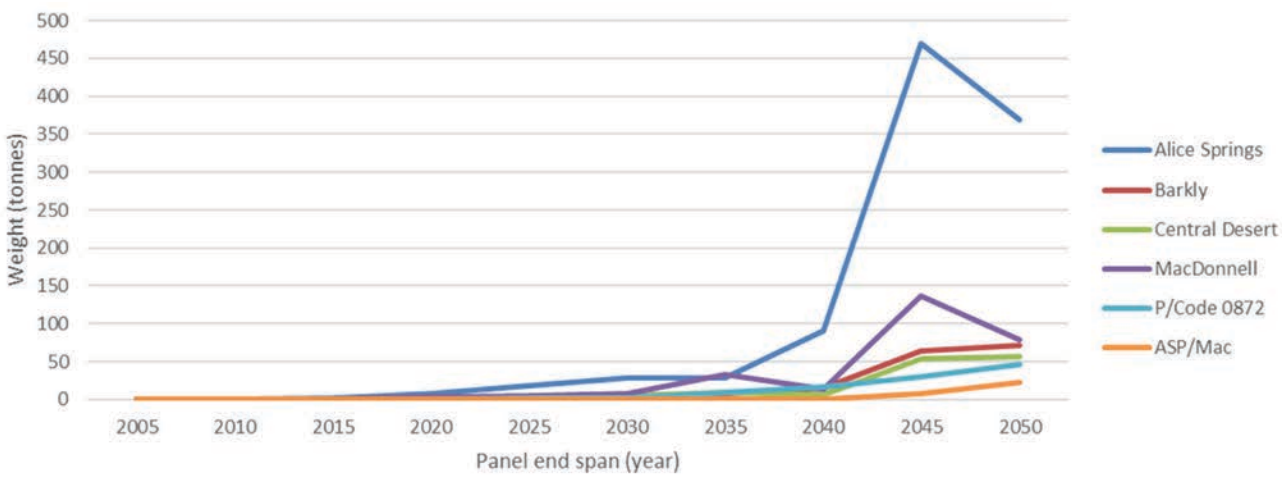

Figure 4.9 Estimated volumes of solar PV panel waste in the Central Australian Region by LGA and overlapping postcodes

Alice Springs will begin to see a steady increase in panel waste between 2025 and 2030, and MacDonnell between 2030 and 2035, whereas volumes in the other Central LGAs will remain small (i.e. less than 10 t) until after 2040 (Figure 4.9). This, in part, most likely reflects the impact of the Alice Solar City program which ran between 2008 and 2013. Volumes of panel waste in the Alice Springs and MacDonnell LGAs surge after 2040, peaking in 2045 at 469.17 t and 136.32 t respectively, and then decline. In contrast, in the Barkly and Central Desert LGAs, waste volumes will increase most sharply between 2040 and 2045 and then only slightly increase over the following five years.

4.2. Panel types

It was noted in Section 3 that details of the different types of panels installed are not readily available for SSIs. Instead, it has been assumed that the broad compositional breakdown of panels in these installations is 93% c-Si, 2% CIGS and 5% CdTe. It was also noted in the methodology section and in Appendix 1 that detailed data was available for 56% of the large-scale installations included in this study; these installations all consisted of c-Si panels. On this basis it has been assumed that all the remaining large-scale installations included in this study comprise c-Si panels. Table 4.1 below provides an estimated breakdown of the volumes of panel types across the NT. Details by LGA and overlapping postcode area are provided in Appendix 4.

Table 4.1 Estimated distribution of panel types by weight (tonnes) by region

Region	Panel type		
	c-Si	CIGS	CdTe
Northern (NR)	4901.37	91.18	136.73
Big Rivers (BR)	588.99	10.18	15.26
Central Australia (CA)	1667.13	27.13	40.73
NT Total	7157.50	128.49	192.72

4.3. Material composition

As noted elsewhere in this report, there is a lack of consistent data available regarding the composition of solar PV panels, complicated by the fact that different brands use different materials and different quantities of materials over time. To illustrate the degree of this variability, Tables 4.2–4.4 summarise the estimated compositional breakdown of PV panels by weight (tonnes) for the NT as a whole and the three broad regions, based on compositional data provided by IRENA [4, pp41-2] (Table 4.2), PV Cycle in BINE projektinfo [5] and IRENA (Table 4.3) and Sica et al [6, p2938] (Table 4.4). Compositional data for each LGA is provided in Appendix 4.

Overall, it is not surprising that glass comprises the most sizeable proportion of recyclable material, given that glass makes up anywhere between 65.8% and 97% by weight of a PV module. On the basis of these tables it is estimated that there is between 5,023 t and 6,892 t of glass collectively contained in solar panels installed in the Territory to date. Aluminium, which is mainly used in the frame of c-Si and CIGS panels, contributes the most significant mass of potentially valuable metal for recycling, being anywhere between 583 t and 1,253 t. The amount of silicon from c-Si panels is estimated to be between 207 t and 359 t.

Table 4.2 Compositional breakdown of materials by weight (tonnes), based on data provided by IRENA (2016)

Region	Material							
	Glass	Al	Si	Polymer	Cu	In	Ga	Se	Other
NR	3888.87	399.86	245.07	495.15	49.02	0.26	0.01	0.47	14.90
BR	468.51	48.30	29.65	59.86	5.93	0.03	0.00	0.05	2.16
CA	1313.70	135.68	83.36	168.21	16.67	0.08	0.00	0.14	6.67
NT	5671.08	583.84	358.08	723.22	71.63	0.36	0.01	0.67	23.73

Table 4.3 Compositional breakdown of materials by weight (tonnes), based on data provided by PV Cycle (2007 in BINE projektinfo 02/10) for c-Si and CdTe panels and IRENA (2016) for CIGS panels

Region	Material										
	Glass	Al	Si	Polymer	Zn	Ag	Cu	In	Ga	Se	Other (Pb, Cd, Te)
NR	3837.49	496.58	147.06	326.67	5.89	0.31	30.75	0.26	0.01	0.47	5.20
BR	1758.49	228.65	67.80	155.36	2.73	0.16	14.12	0.10	0.00	0.19	2.40
CA	1296.22	168.63	50.01	110.87	2.02	0.12	10.41	0.08	0.00	0.14	1.77
NT	6892.20	893.86	264.87	592.90	10.64	0.58	55.29	0.44	0.02	0.81	9.37

Notes: Table 3 uses compositional data provided by PV Cycle (2007, in BINE projektinfo 02/10) for c-Si and CdTe panels and IRENA data for CIGS panels (refer Section 3). Where percentages were cited as '<' a certain amount, the % has been rounded to be equal to that amount for the purpose of this study. For example, the amount of silver has been rounded up from <0.006% to 0.006%. This means that the figures for lead, silver and aluminium are slightly overestimated.

Table 4.4 Compositional breakdown of materials by weight (tonnes), based on data provided by Sica et al (2018)

Region	Material											
	Glass	Al	Si	Plastic	Zn	Cu	In	Ga	Se	Mo	Sn	Other (Pb, Cd, Te)
NR	3265.93	809.93	134.22	599.24	0.04	46.33	0.01	0.01	0.01	0.11	0.03	0.21
BR	594.58	151.58	25.12	111.64	0.00	8.67	0.00	0.00	0.00	0.01	0.00	0.02
CA	1162.63	291.75	48.35	215.43	0.01	16.69	0.00	0.00	0.00	0.03	0.01	0.06
NT	5023.14	1253.27	207.68	926.31	0.05	71.69	0.01	0.01	0.01	0.15	0.04	0.29

However, these compositional breakdowns should not be assumed to reflect the amounts of the various materials that can be recovered, as some material is lost through the recovery process(es). At best, the amounts in Tables 4.2–4.4 might be considered broadly indicative of upper-limit estimates of the quantities available for recovery.

4.4. Recoverable materials

The amount of recoverable materials will depend on the nature of the recovery treatment method(s). As noted in Section 2, Sica et al [6] observed that the process developed by Deutsche Solar in 2003 was capable of achieving high recovery rates (>80%) and similarly, First Solar's recycling program for CdTe panels resulted in recycling rates of 90% for glass and 95% for semiconductor material [6, p. 2939]. Therefore, in order to obtain estimates closer to what may be potentially recoverable, the data in Tables 4.2– 4.4 above was subject to Sica et al's [6, p. 2938] recovery rates and is presented in Tables 4.5–4.7. In addition to material lost during the recovery treatment(s), early losses of panels up to and including 2020 (i.e. panels which have already been discarded) also represent a loss of materials as these panels cannot be recovered and subject to any recovery treatment processes. The data in Tables 4.5–4.7 excludes these 'lost' volumes.

While the recoverable amounts of aluminium do not vary greatly, the amount of glass available for recovery is estimated to be between 4,815 t and 5,470 t and the amount of silicon available for recovery from c-Si panels is estimated to be between 174 t and 303 t. This is somewhat less than that suggested on the basis of the raw compositional data alone.

Other valuable materials, such as copper, silver, tin, gallium and indium, usually constitute very small traces (<1%) within the overall composition of PV panels, and these amounts also vary between panel brands and types produced by different manufacturers [7, p. 45, 8] and are thus difficult to quantify. When Tammaro et al [8] analysed the composition of 38 first- and second-generation PV panels produced between 1985 and 2012, they found that amounts of trace metals were also highly variable over time. Apart from the breakdown of rare metals in CIGS panels provided in the IRENA report, it was difficult to find a consistent breakdown of the percentages of 'other metals' within silicon panels (mainly silver, tin and lead) and thin-film CdTe panels. Flavia et al [9, p749] observed that it was difficult to compare data about metal content of PVs across the available academic literature because different panel components are 'frequently used to quantify the panel metal content'. Owing to this variability the figures below should be considered no more than a rough guide to the potential for recovering various metals, metalloids and non-metals.

As indicated in Tables 4.5–4.7 below, by 2050 the NT's PV waste will potentially yield between 34 t and 56 t of copper, between 0.05 t and 7.72 t of zinc, and less than a tonne each of tin, indium, gallium, selenium and molybdenum. However, the amount of these materials in this study's projections may be overestimates given that there is no data available about the number of CIGS panels installed in the NT.

Table 4.5 Estimates of net recoverable amounts of materials by weight (tonnes), based on an initial compositional breakdown using IRENA (2016) data and recovery rates provided by Sica et al (2018)

Region	Material						
	Glass	Al	Si	Cu	In	Ga	Se
NR	3758.36	398.40	207.55	38.10	0.19	0.01	0.38
BR	449.99	47.83	24.96	4.51	0.02	0.00	0.04
CA	1261.37	134.31	70.14	12.87	0.06	0.00	0.11
NT	5469.73	580.54	302.65	55.56	0.27	0.01	0.53

Note: Polymers, Pb and Ag not included in Sica et al's (2018) recycling rates and are therefore excluded from this table.

Table 4.6 Estimates of net recoverable amounts of materials by weight (tonnes), based on an initial compositional breakdown using PV Cycle (2007) and IRENA (2016) data, and recovery rates provided by Sica et al (2018)

Region	Material								
	Glass	Al	Si	Zn	Cu	In	Ga	Se	Other (Pb, Cd, Te)
NR	3708.71	494.78	124.54	5.28	23.90	0.19	0.01	0.38	0.17
BR	444.00	59.43	14.97	0.64	2.87	0.02	0.00	0.04	0.02
CA	1244.59	167.42	42.21	1.81	8.06	0.06	0.00	0.11	0.05
NT	5397.30	721.63	181.73	7.72	34.83	0.27	0.01	0.53	0.24

Note: Polymers, Pb and Ag not included in Sica et al's (2018) recycling rates and are therefore excluded from this table.

Table 4.7 Estimates of net recoverable amounts of materials by weight (tonnes), based on an initial compositional breakdown using Sica et al (2018) data

Region	Material										
	Glass	Al	Si	Zn	Cu	In	Ga	Se	Mo	Sn	Other (Cd & Te)
NR	3144.528	803.767	113.216	0.033	35.864	0.007	0.009	0.007	0.108	0.027	0.183
BR	564.554	148.317	20.891	0.004	6.615	0.001	0.001	0.001	0.012	0.003	0.020
CA	1106.198	286.044	40.291	0.010	12.761	0.002	0.003	0.002	0.032	0.008	0.054
NT	4815.281	1238.127	174.399	0.046	55.240	0.010	0.013	0.010	0.152	0.038	0.257

Note: Polymers, Pb and Ag not included in Sica et al's (2018) recycling rates and are therefore excluded from this table.

Silver is amongst the most valuable minerals to enter the waste stream from PV panels, although a large supply of panels is required to make recovery of silver financially viable [10 , 11]. Sica et al [6] do not include silver in their data, but on the basis of composition data provided by IRENA and PV Cycle (2007) (refer Table 4.3), the upper limit of silver yield from PV waste may be just over half a tonne by 2050.

However, this figure does not take into account the variation in the quantities of silver used in c-Si panel manufacture over time [6, p. 2942, 10]. The ITRPV claims that the median value of silver per c-Si panel declined from 100 mg in 2017 to 90 mg in 2018 and is expected to drop to 50 mg by 2028 [10, p. 12]. In their analysis of 38 sample panels, from 1985 to 2012, Tammaro et al [8] also found that the amount of silver in c-Si panel composition had reduced significantly since 2005 which they also attributed to cost. Thus, given that c-Si PV modules produced before 2010 probably yield more silver, 'much less quantity of waste may be processed before 2030 but with higher financial return for recycling per unit c-Si PV' [12, p. 8], which may be significant in the NT if a volume of pre-2000 panels (quantity currently unknown) reaches EOL between now and 2030. Conversely, although greater quantities of c-Si PV's produced after 2010 were installed in the NT, they are likely to yield less silver per panel when they reach their EOL, from 2040 onwards.

When the variability in silver content in c-Si panel production between 2000 and 2020 is considered (using data provided in the ITRPV 8th Edition [10] and shown in Table 4.8 below), it is clear that the estimated potential yield of silver is somewhat greater, compared to simply using a 'flat rate' of composition (used in Table 4.3) being in the order of 2.6 t in total by 2050 for the NT (Table 4.9). Note that including silver derived from CdTe

panels only adds an additional 0.03 t of silver overall, even allowing for no change in the amount of silver in these panel types over time. There is also an amount of silver that can be considered 'lost' in those panels that have already reached their EOL (either through early or regular loss up to and including 2020) and have been disposed of. The data in Table 4.9 shows these notional losses. Panels installed prior to 2000 have been excluded from this table as reliable data on silver content in panels from this period could not be located.

Overall, there is a certain degree of variability in the potential estimates of various materials that may be recovered from PV waste by 2050. Our literature review revealed much current research and development is centred on achieving greater panel efficiencies and material reductions per unit of power. According to Sica et al [6, p. 2942] this will see a 2% reduction in silicon usage, a 1% reduction in aluminium and 0.01% in other metals. There is also a high degree of uncertainty when these estimates are further considered in view of the likely technological advances in recovery treatment processes that will occur within the next 10 years. We conclude that the only thing that can be said with any certainty about recoverable waste from PV panels over the next 2–3 decades in the NT is that it will include substantial volumes of glass and aluminium.

Table 4.8 Average silver quantity per panel (g), for panels manufactured between 2000 and 2020, calculated for the c-Si sample modules used as the basis for projections in this report

Panel span	Module	No. of cells	Ag quantity (g/cell)	Ag quantity (g/panel)
2000–2005	Sunpower 2005 mono-Si, 210 W	72	0.5	36
2006–2010	Sunpower 2009 mono-Si, 215W	72	0.4	28.8
2011–2015	TDG T250M606, 2013 mono-Si, 255W	60	0.15	9
2016–2020	Hanwha Q.cell Q.Peak-G4.1 2017 mono-Si 295W	60	0.07	4.2

Table 4.9 Projected yield of silver by weight (t), c-Si PV panels, NT

Region	Panel end span						
	'Lost' quantity (to 2020)	2025	2030	2035	2040	2045	2050
NR	-0.017	0.027	0.035	0.071	0.233	0.521	0.567
BR	-0.008	0.005	0.005	0.077	0.056	0.093	0.065
CA	-0.022	0.020	0.017	0.136	0.260	0.326	0.130
NT	-0.047	0.052	0.057	0.284	0.549	0.949	0.753

4.5. Hazardous materials

4.5.1. Potential impacts documented by previous research

As noted by Sica et al [6, p. 2938]:

> *The main environmental issues associated with the production of c-Si and CdTe based modules concern the consumption of raw materials and energy as well as hazardous substances, such as Cd from thin-film modules and Pb from c-Si modules.*

Small traces of hazardous metals are potentially present in all PV modules although, as with traces of other rare metals, amounts of these toxic elements vary between panel types and makes, and over time [8]. The amount of lead in first-generation c-Si modules has come under particular scrutiny, as has the use of cadmium in second-generation thin-film CdTe panels. Exposure to these toxic substances can occur when panels are damaged or unencapsulated, either accidentally or through processing for waste management and recycling.

Tammaro et al [8] sought to investigate the potential environmental hazard of panels produced in the last 30 years by assessing the presence of up to 18 releasable metals. Envisaging a worst-case scenario 'for panels accidentally crushed and/or abandoned in the environment', Tammaro's research team applied a leaching test to samples of 38 PV panels (26 c-Si and 12 thin film) manufactured between 1985 and 2012 to examine their ecotoxicological effects. While levels of lead exceeding the European law limits from the Directive 98/83/EC for Drinking Water were present in 92% of the examined leachates obtained from c-Si panels manufactured before 1997, this level dropped to around 38% in post-1997 c-Si panels. Tammaro et al concluded this was because many manufacturers had refined their technology to reduce the amount of lead in c-Si modules because of concerns about its toxicity. Overall, they found that 'c-Si panels release a minor amount of metal and it was also verified that this release decreased in the last 30 years' [8, p. 402].

By contrast, cadmium was observed in *all* leachate examples after 2010, although on average the release of cadmium and other metals from thin-film PV's was greater than from c-Si panels. Tammaro's researchers attributed this to increased use of thin-film PV technology and the fact that this newer technology had not yet undergone the same degree of technical evolution as c-Si panels [8].

Rix et al [13, p. 10] note that toxicity studies indicate that cadmium is more toxic in its elemental form compared with the more stable CdTe compound. Nevertheless, while cadmium is not emitted during the routine functioning of a thin-film panel, CdTe is harmful if inhaled, for example, during manufacturing or recycling treatment processing. It is also harmful to aquatic life with long lasting effects — for example, if CdTe panels end up in landfill and toxic elements leach from the CdTe/CdS compound layers if they are damaged or unencapsulated [14 , 13].

Earlier studies on the leaching potential of lead from mc-Si panels and cadmium from CdTe panels found that 'high lead leaching occurs in low pH conditions, with leaching increasing substantially in broken or crushed panels that are exposed to low pH water' [15, p. 520]. More specifically, for mc-Si panels, lead leaching is greatest is low pH conditions but virtually nil if stored in pH conditions similar to that within the panel. Cadmium leaching is high regardless of the pH conditions but is highest in low pH conditions [15, p. 52]. More recent research aimed at investigating the potential release of toxic compounds from CdTe panels under conditions simulating those found in young and mature landfill environments also found that Cd leaching occurred to a far greater extent in acidic conditions mimicking those of a young landfill; the concentration of leachate in this sample was three-fold higher than permitted under the US Toxic Characteristic Leaching Procedure (TCLP) test[7] [14].

The NC Clean Energy Technology Centre [16, p. 8] describes mixed results from subjecting PV panels

7 The US EPA uses the Toxicity Characteristics Leaching Procedure (TCLP) to characterize the potential of a solid waste to leach when disposed in a landfill and determine whether a waste material should be classified as hazardous according to its toxic characteristic. If the waste fails the TCLP test, it must be disposed of in a hazardous waste landfill.

to the US TCLP test. They claim that some sources report that most modern PV panels pass this test, while others found that older (1990s) c-Si panels and perhaps some more recent panels do not pass the Pb (lead) leachate limits in the TCLP test. They also refer to research undertaken in Japan which found there was no detectable Cd leaching from cracked CdTe panels when exposed to simulated acid rain[16,p. 8] . In considering these results we note that it is unclear to what extent these sources have been subject to peer review and that some of this research does not appear to have been carried out independently of the PV panel manufacturers.

Tellurium is also considered toxic and should be handled with care according to the US National Centre for Biotechnology Information [17]. Although rare, health impacts may include short-term acute toxicity as well as longer-term chronic toxicity and exposure may occur through inhalation, ingestion, skin and/or eye contact. According to the Los Alamos National Laboratory 'Workmen exposed to as little as 0.01 mg/m3 of air, or less, develop 'tellurium breath', which has a garlic-like odor' [18]. However, exposure to tellurium is most likely to occur during manufacturing or recycling treatment processing.

4.5.2. Volumes of hazardous materials in PV panels in the NT

Table 4.10 summarises the potential volumes of lead, cadmium and tellurium in PV panels that reach their EOL in the NT, following PV Cycle's [5] compositional breakdown for these materials in c-Si and CdTe modules (<0.1% Pb in c-Si panels, <0.01% Pb in CdTe panels and 0.07% Cadmium in CdTe panels). A breakdown for CIGS is not provided by PV Cycle, however they provide a breakdown for CIS (copper indium diselendie cells) and the proportion of lead used in CIS (<0.1%) has been assumed to be the same in CIGS. This breakdown is very similar to Sica et al's (2018) composition for cadmium (0.08%) and tellurium (0.07%) in CdTe panels. Sica et al do not provide recovery rates for Pb so estimates for lead have only factored in the amount of lead that has already been 'lost' from discarded panels. After applying Sica et al's recycling rates to the volumes of cadmium and tellurium and allowing for the estimated 'lost' material from panels which have already been discarded, it is estimated that just over 7.2 t of lead waste will be produced from PV panels between 2021 and 2050 in the NT, and 0.13 t of cadmium waste will be produced over the same period. Although the amount of cadmium waste may appear insignificant when considered in these terms, as noted above, cadmium is far more hazardous than lead as a releasable metal.

It is estimated that in the order of 0.10 t of tellurium waste will be produced between 2021 and 2050 in the NT. As for all these estimates, caution is advised as the number of CIGS and CdTe panels installed to date in the Territory is unknown; these calculations have been based on a panel type breakdown of 93% c-Si, 2% CIGS and 5% CdTe.

Table 4.10 Estimated volumes (tonnes) of hazardous materials from NT PV panel waste

Region	Material			
	Pb	Cd	Te	Total hazardous materials
NR	4.988	0.093	0.076	5.158
BR	0.599	0.010	0.008	0.618
CA	1.697	0.028	0.023	1.747
NT	7.284	0.131	0.107	7.523

4.5.3. Conclusions regarding hazardous materials

A review of the relevant literature revealed mixed results regarding the nature and extent of the environmental impacts, but clearly suggested the main risk is leaching from damaged, crushed and/or unencapsulated panels. Accordingly, when considering collection and stockpiling, occupational health and safety issues must be considered. Our data indicates that potentially there may be 7.5 t of hazardous material from solar panel PV waste in the NT by 2050, comprising mostly lead (7.2 t). Whilst these numbers are not large, the potential environmental impacts should not be underestimated and stakeholders raised concerns around the safe handling, storage and disposal of solar PV panels as an issue, both in the interviews and information sessions.

Given the findings from previous research we suggest adopting a cautious approach. Provided the panels are protected from weather damage (e.g. hail, rain) and vandalism (e.g. rock throwing) and are not in direct contact with the soil, risks to the environment are likely to be minimal. Storage in neutral pH conditions, in leak-proof, sealed or lined containers, such as shipping containers, would provide an additional safety measure.

4.6. Waste volumes, variable trajectories and implications for EOL management

As stated earlier in this report, the projections presented in this study do not reflect the total number of PV modules installed in the NT and therefore underestimate the volume of waste that will be generated for local governments to manage as more PVs are discarded over the next few decades. This is because records of PV modules installed in the NT were generally not kept prior to 2000–01, making it difficult to project what magnitude of photovoltaic waste will need to be addressed in the coming decade. Neither are there readily available records of the type, brand and make of PV panels used in Territory installations, nor of those which have been removed and/or discarded. These data limitations have implications for estimating the amount of future PV waste and the volume of valuable and hazardous materials to be managed. *In light of the significant absences in data available about PV installations in the Territory, the projections of PV waste volumes and composition in this survey can only be read in terms of estimated magnitude of impacts.*

Generally, the amount of solar PV waste produced at the LGA, regional and even Territory level is a fraction of the waste forecast for other jurisdictions such as NSW–ACT and Queensland (refer Salim et al 2019). Waste volumes in the NT do not substantially increase until around 2040. This timing is consistent with the findings of Chowdhury et al (2020: 9), who suggest that a strategy for recycling and recovery will need to be established by that time. They, along with Salim et al (2019), note that, worldwide, the existing PV waste streams are not sufficient to make current recycling technologies economically viable.

Furthermore, while the overall solar PV panel waste trajectory estimated for the NT shows only a very slight increase up until 2040, followed by a sudden surge from less than 500 t to 4,500 t within a 10-year period, this pattern is not simply replicated at every regional, nor LGA level (Figure 4.10). We suggest that these different trajectories reflect the impacts of past programs and policies such as the Alice Solar City program, as well as the nature of housing and tenure types in the NT. Although it is beyond the scope of this study to calculate future solar panel PV installations (and therefore consider what the waste trajectory(ies) may look like beyond 2050) it is possible to make some predictions based on our observations and research to date. For example, it is unlikely that there will be any significant increase in the number of SSIs in communities that are powered by existing LSIs. Elsewhere, it is possible that if battery storage technologies improve capacity significantly and/or become considerably cheaper, this may prompt a wave of new PV installations as well as upgrades to existing systems to take advantage of this technology, including in locations that may be close to reaching ‘saturation’ point in terms of building stock suitable for PV technology and owners-occupiers willing to invest in solar systems.

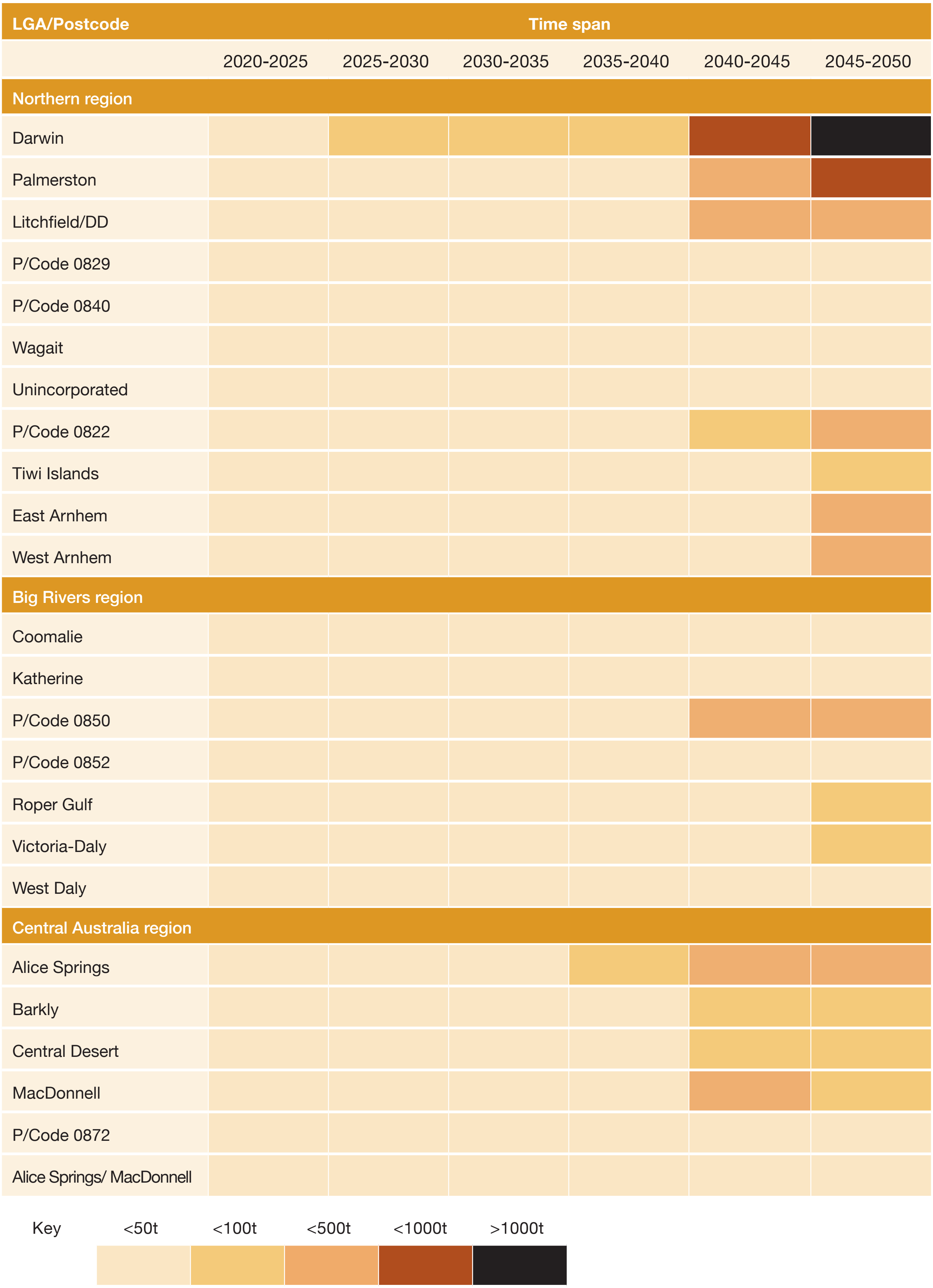

Figure 4.10 Variability in the timing and extent of PV waste (tonnes) by LGA and overlapping postcode areas, 2020–2050

It is also worth noting here that if the proposed Sun Cable solar farm proceeds, this would pose a significant PV waste challenge for the Barkly LGA much sooner than 2040. Even if only 1% of panels installed failed in the first year, this would mean an additional 220,000 solar panels, or around ca. 4,500 t of PV waste to be dealt with by 2025 (assuming construction was completed in 2023–24).

Although there is a range of potentially recoverable materials, only glass and aluminium will be recoverable in any large quantities. Strategies will need to be in place to address not only the hazardous materials, but also the quantities of polymers (estimated to be between 593 t and 926 t in total).

The variability in timing and quantities of waste poses challenges in terms of the ability to create economies of scale through collaborative efforts across LGAs prior to the 2040s. However, it may also create opportunities to pilot different strategies for managing PV waste ahead of the main peak in NT panel waste. The extent to which it may be possible to offset some of the costs of managing the disposal of discarded panels through the recovery of valuable materials and recycling panels is explored below.

4.7. Materials recovery and potential economic returns

In attempting to assess the economic returns from the recovery of valuable materials from discarded panels, it must be stated at the outset that it is difficult to make predictions for the period 2021–2050 given the likely changes in the regulatory environment, evolution of recycling technologies and commodity prices for materials such as glass, aluminium, copper, silicon, silver, indium, gallium and selenium. What may be uneconomic in the current policy and technological environment might become cost-neutral or even generate a return in the future. IRENA[19, p. 50] noted that while solar PV raw material availability was not a major issue in the short term, in the long term this may change for certain critical materials, which in turn would result in higher prices that would improve the economics of recycling activities.

The following exercise is therefore intended to simply provide an 'order of magnitude' guide as to the upper limits of the potential returns from materials recovery and recycling. Tables 4.11–4.13 provide estimates of potential returns, based on the commodity market prices provided in Appendix 5. The figures in Tables 4.11–4.13 are upper limit estimates as they do not include the costs of dismantling, transportation and processing, nor any transactional costs associated with the sale of various materials (e.g. commissions etc). The upper limit for total revenue derived from recycling silver from c-Si panels altogether for the period 2021–2050 is just over $2m. As other rare minerals comprise a very small percentage of the total composition of a PV panel, the potential revenue derived from recovering these materials is minimal (Table 4.13). In contrast, aluminium appears to be the most profitable material for recovery, worth potentially up to about $3.2m for the Territory as a whole.

Table 4.11 Upper limit total revenue ($) from recycling various PV panel materials, 2021–2050, based on estimated net recoverable amounts shown in Table 4.7

Region	Material				
	Glass (cullet)	Al	Si	Zn	Cu
NR	314,452.81	2,080,953.18	501,689.93	107.75	305,295.02
BR	56,455.42	383,991.52	92,575.21	11.94	56,310.68
CA	110,619.84	740,567.38	178,540.87	31.83	108,628.04
NT Total	481,528.07	3,205,512.09	772,806.02	151.53	470,233.74

Note: Glass cullet – lower range of $100 has been used.

Table 4.12 Upper limit total revenue ($) derived from recycling silver from c-Si panels, based on estimated yields shown in Table 4.9

Region	Panel end span						
	Up to 2020 ('Lost' revenue)	2025	2030	2035	2040	2045	2050
NR	-13,150.41	21,626.88	27,409.89	56,166.50	184,184.93	412,574.24	449,411.23
BR	-6,654.42	4,040.19	4,277.84	61,157.32	44,204.38	736,73.97	51,571.78
CA	-17,190.59	15,526.99	13,308.85	107,579.84	206,287.12	257,858.90	103,143.56
NT Total	-37,074.64	41,273.27	45,155.01	224,586.78	434,676.43	751,474.51	596,759.17

Table 4.13 Upper limit total revenue ($) derived from recycling Indium, Gallium, Selenium, Molybdenum and Tin, based on estimated net recoverable amounts shown in Table 4.7

Region	Material				
	In	Ga	Se	Mo	Sn
NR	3,044.67	3,730.02	467.84	3,684.08	652.90
BR	337.50	413.47	51.86	408.38	72.37
CA	899.55	1,102.04	138.22	1,088.46	192.90
NT Total	4,281.72	5,245.54	657.93	5,180.92	918.17

Note: Indium calculated at $447.33/kg

It is clear from our data that the bulk of solar PV panel waste in the Territory up to 2050 will comprise c-Si modules. It is therefore appropriate to consider the potential returns from these in greater detail. An alternative approach to gauge potential economic returns is to consider the potential return per unit power. Kang et al [12] have calculated (using their third methodology) upper and lower estimates for the potential profit from recycling c-Si panels in an Australian context. These estimates range between $0.04/W and $0.12/W and have included profits from recycled silicon, copper, aluminium, silver and glass, as well as accounting for avoidance costs of landfill etc. Using these figures and applying them to our assumed panel types over time provides broad estimated returns for recycling c-Si panels installed over the last 25 years (Table 4.14).

Table 4.15 indicates the potential (hypothetical) profit from recycling c-Si panels, applying these upper and lower estimates and taking into account the estimated number of panels which have probably already been discarded and are therefore not available for recycling (i.e. those with end spans up to and including 2020). In considering these figures it should be noted that Kang et al's (2015) analysis reflects urban contexts; the figures in Table 4.15 are likely to be overestimates, given that factors such as higher transportation costs in regional and remote areas have not been included. The estimates below also partially reflect commodity prices at the time of Kang's analysis, i.e. 2015, and the recycling technology available at that time.

These hypothetical returns suggest that recycling c-Si panels will provide only modest profits up until the mid-2040s. After this time the potential profit from recycling these panels may exceed $1m in the Northern Region and in the Central Region (upper estimate). However, it should be noted that the potential profits from the Central Region peak in the mid-2040s and thereafter decline, reflecting the region's solar PV waste trajectory generally.

Table 4.14 Lower and upper estimates of the potential profit derived from recycling c-Si panels in an Australian context (following Kang et al's 2015 third methodology)

Installation year	Capacity per panel	Lower limit profit per panel ($)	Upper limit profit per panel ($)
2001–2005*	210W	8.40	25.20
2006–2010	215W	8.60	25.80
2011–2015	255W	10.20	30.60
2016–2020	295W	11.80	35.40

*As noted in Section 3, the sample module for 2001–2005 has also been used as the 'standard' for panels installed in the period 1996–2000, in the absence of any detailed specifications for panels from this earlier period.

Table 4.15 Potential (hypothetical) profit ($) from recycling NT c-Si panels, 2025–2050 (following Kang et al's 2015 methodology 3)

Region	Estimate	Panel end span					
		2025	2030	2035	2040	2045	2050
NR	Lower	37,215.53	68,879.50	97,180.35	70,617.70	590,305.15	1,997,962.76
	Upper	111,646.58	206,638.50	291,541.05	211,853.10	1,770,915.44	5,993,888.29
BR	Lower	4,848.76	8,432.67	24,336.58	18,082.12	105,625.57	167,355.04
	Upper	14,546.28	25,298.02	73,009.74	54,246.36	316,876.70	502,065.11
CA	Lower	14,711.70	24,073.65	44,731.84	76,464.08	357,687.18	346,957.06
	Upper	44,135.09	72,220.95	134,195.51	229,392.24	1,073,061.54	1,040,871.17

4.8. Concluding remarks

Although the volumes and trajectories presented in this section should be considered to be no more than a rough guide, it does appear that economies of scale with regard to panel discards will be difficult to achieve until at least the mid-2040s. This is in part because waste trajectories vary across the regions and LGAs; not all of the latter experience a surge or peak of solar PV waste at the same time. Given that the potential economic returns from recycling c-Si panels also appear to remain relatively modest up until the mid-2040s, the capacity to off-set some of the economic costs of managing the NT's solar PV waste through recycling appears limited. These findings echo those by Salim et al[20, p. 9] which suggest that current recycling technologies for PV panels are not economically viable and current panel waste streams are not sufficient to create an economy of scale.

Consequently, a key challenge is to identify a least-cost or low-cost option(s) to address solar panel discards between now and 2040, which will also (preferably) contribute to regional economic development. The precise nature of this option may differ from region to region, and may also change over time. An additional challenge will be ensuring that whatever solar PV waste management strategy(ies) are identified will be able to cope with the substantial surge in solar PV waste that will occur within a short (i.e. five-year) timeframe.

These challenges and others are explored in further detail in the following section, as well as the current practices and potential solutions, based on interviews with a cross-section of stakeholders.

Section 5: Stakeholder Interviews

This section reports on the results from interviews carried out with various stakeholders associated with solar PV EOL management in the Northern Territory. The questions were aimed at understanding current PV disposal polices at the interviewees' organisation, reasons for removing PV panels in their region, current practices of PV panel disposal, costs involved in removing and disposing PV panels, barriers faced by the stakeholder in disposing PV panels, their suggested solutions for better managing waste arising from PV panels and their prediction of trends in solar PV installations.

5.1. Survey participants

The survey findings are based on responses from 21 stakeholders who agreed to participate in the study. Details regarding the interview methodology including the selection process are described in Section 3 and a copy of the survey questionnaire is at Appendix 3. We believe this sample size compares well with the results of a recent Australia-wide survey[1] which gained 57 participants in total, although none of these 57 were from the Territory.

Survey participants included policy makers and regulators, systems engineers, installers, recyclers, energy suppliers, representatives from Local Government Associations (LGAs) and Advocacy groups. Of these, just over 38% of participants represented the local government sector (Figure 5.1). The next largest cohort were solar panel installers. It should be noted that owing to a lack of NT-based recyclers, all of the participating recyclers were based outside of the Territory but were seeking to grow their businesses in the NT.

Our survey participants worked across the NT in urban and non-urban environments, with 52.6% working in Outer Regional areas, 42.1% in Remote areas and 57.9% in Very Remote areas. The responses to the survey questions therefore capture perspectives ranging from communities in Very Remote areas, to the larger urban centres in Remote and Outer Regional areas of the NT.

Participants' responses to the remaining survey questions can be broadly grouped into the following six primary themes:

- current policy/programs;
- current disposal practices;
- rationale for removing panels;
- challenges and barriers faced by stakeholders in managing or disposing of the removed panels;
- solutions suggested by the stakeholders for managing waste arising from removed Solar PV panels; and
- predicted trends for future PV panel installations.

These are discussed in the remainder of this section.

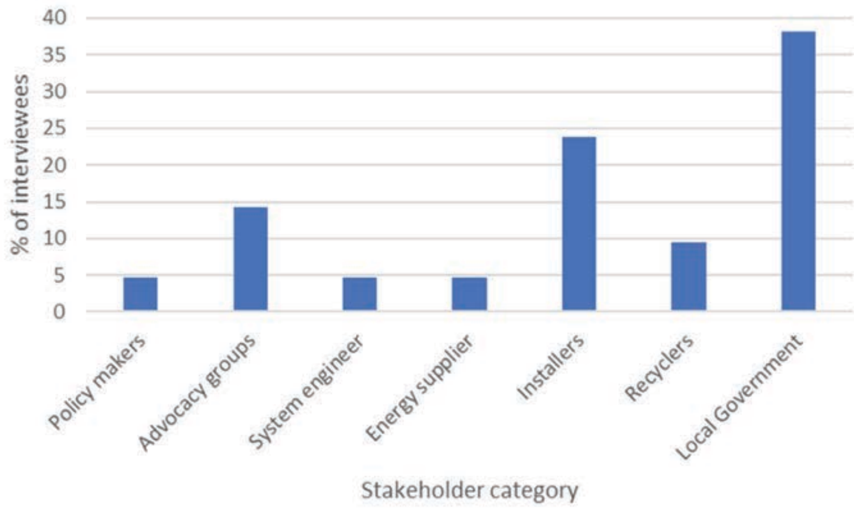

Figure 5.1 Survey participants by stakeholder category

5.2. Current policy/programs

Participants were asked whether their organisation currently had any policies, strategies or programs in relation to e-waste more broadly and solar panels (their installation/usage and disposal) more specifically. Those who answered in the affirmative were asked to describe these in detail.

Other than the recyclers, most participants (85.7%) indicated that they did not currently have any policies in place regarding solar panels. One participant indicated that they were waiting for policy to be developed at the national level, whilst another identified the lack of clear regulation around solar panel disposal as an issue in terms of policy development. Interestingly, and perhaps in light of the obvious lack of policies highlighted in Sections 1 and 2, the majority of responses to this question tended to focus on descriptions of their current disposal practices. Broadly, these practices included separation, reuse, partial recycling, stockpiling and sending to landfill or waste management facilities (WMFs) and are discussed in more detail below. The current policy environment is an issue to which we return elsewhere in this section.

5.3. Current disposal practices

The participants were then asked if their organisation dealt with old PV panels/panels that had been removed and if so, how their organisation dealt with them. Since different stakeholders have a different role in the life cycle of the PV panel, not all of them were directly involved with removal and disposal. Table 5.1 summarises the role of participants, with some stakeholders such as LGAs, installers and recyclers dealing directly with the removed PV panels. It also shows how some stakeholders may have multiple roles in managing the life cycle of a solar PV panel.

LGAs are responsible for PV panels brought to the waste management facility (WMF). Owing to a lack of policy at the National and Territory level, the LGAs are making independent decisions on whether to accept the removed solar PV panels or not. Of the interviewed LGAs, 50% said they were accepting and stockpiling, 37.5% mentioned they were not accepting panels and 12.5% responded that no PV panels had been brought to their WMF yet. It was also pointed out by one interviewee that lack of options for disposing panels is also resulting in illegal dumping of PV panels since consumers often do not know where to take the old PV panels.

Table 5.1 Summary of the role(s) of participants in managing the solar PV panel life cycle

Participant category	Role(s) in managing the PV panel lifecycle	Direct involvement in removal and/or disposal (Y/N)
LGA	Contributing to policy development; managing waste management facilities; managing removed panels;	Yes
Installers	Installing and removing panels; managing removed panels (stockpiling)	Yes
Recyclers	Recycling PV panels	Yes
Advocacy groups	Lobbying policy and decision makers regarding PV panels and/or solar waste	No
System Engineers	Specifying and designing PV systems	No
Energy providers	Commissioning Contractors (Installers) for installing/removing PV panels	No
Policy makers	Developing policies regarding waste management	No

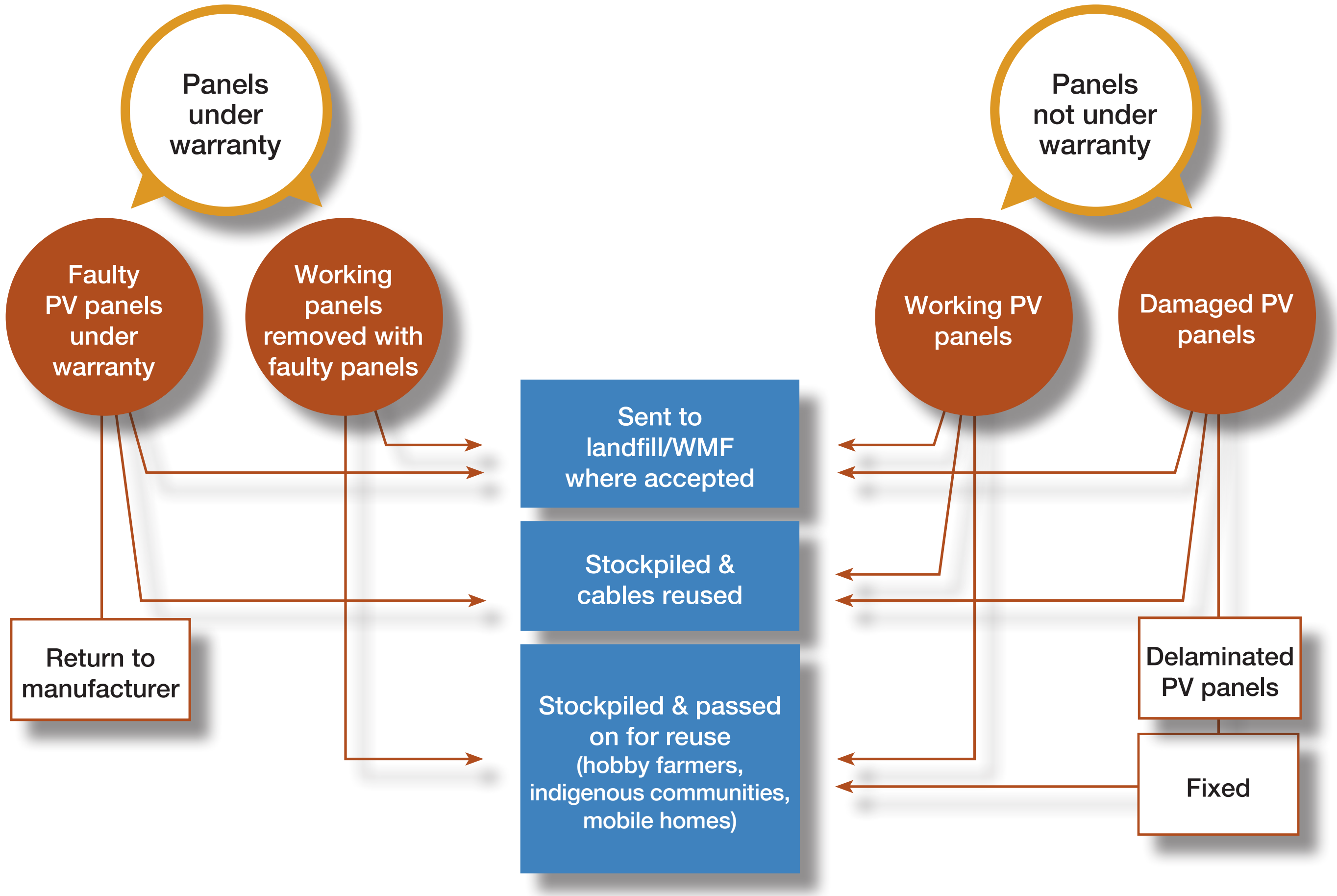

Figure 5.2 Disposal practices described by installers who participated in this study

The installers we interviewed were all accredited by the Clean Energy Council (CEC) and CER and therefore had the responsibility of installing, removing and disposing of solar PV panels in accordance with Australian Standards as well as guidelines and criteria established by CEC and CER. Figure 5.2 shows the disposal practices described by these installers.

Faulty panels still under warranty are returned to the manufacturer by installers and a replacement set of panels installed, which is paid for by the manufacturer. Some manufacturers, like LG, pay for the faulty panels to be shipped back. Several manufacturers only pay for a new set to replace faulty panels, but the installer must find ways of disposing of them. In such cases, where only a few PV panels are faulty but the whole system is replaced, the installer has to find ways of disposing both working and faulty panels. The installers send the panels to the WMF where permitted. In localities where the local WMF is not accepting PV panels, the installers either stockpile the panels or pass the working panels onto Indigenous communities, hobby farmers, or mobile home owners, for example. Some parts of the stockpiled panels, such as cabling, are occasionally reused.

When the removed panels are old and working but not under warranty, the installers again have the option of either sending them to WMF, if it is accepting, stockpiling them or reusing them in ways shown in Figure 5.2. If the removed panels are damaged and not under warranty, the installer either sends them to the WMF where permitted or stockpiles them for lack of other options.

The recyclers interviewed mentioned they are dismantling (or disassembling) the panels by separating the glass cover and the aluminium frame. One recycler crushes the wafer before sending it overseas for further processing and materials recovery. Another recycler is stockpiling and waiting for processing technology to develop in Australia.

The varying disposal practices described above highlight that in the Northern Territory, there is no single solar PV 'waste flow'; instead there are varying waste mobility flows including 'after-lives' for those solar panels which retain their functionality. This is a theme which is discussed in greater detail in Section 6.

5.4. Rationale for removing panels

As this study is concerned with EOL management of solar PV waste, it was important to understand the circumstances in which solar panels in the NT transitioned from a functional object to waste. The literature review in Section 2 identified several reasons why PV panels may fall victim to an early EOL or 'death'. The most common were either technical and physical failures during operation caused by severe environmental conditions, although poor design and manufacturing defects [2, p. 5], damage during the transport or installation stages [3, p. 28] and unexpected external factors, such as natural disasters [4], also occur.

Given that the removal of PV panels is the first step on their journey towards becoming waste, participants were asked if their organisation had removed any panels in the last five years and the reasons for that removal. Figure 5.3 illustrates the various reasons identified by participants for the removal of PV panels by their organisation. Weather played an important role, with panels getting damaged from hail, water and wind. One installer estimated that 15% of panels fail owing to water and rust damage. Vandalism was also cited as another typical reason for the early loss of PV panels in some remote communities; as one interviewee from a Very Remote region explained:

> *Those particular panels were removed because some kids had thrown some stones. (LGA, Very remote area)*

Several participants also referred to technical failures such as delamination, or inverter failure, as the reason for their removal. Only 20% of installers mentioned removing panels that were old and reaching EOL. Most installers indicated that they had rarely removed panels that were at the end of their performance life.

> *We've removed some from cyclone or vandalism damage but not from end-of-life situations. (Installer, Outer Regional area)*

Often the damage from weather, vandalism or technological failure might impact only a few panels but the whole solar system is removed and replaced. Some of the respondents mentioned that it is not very easy to replace old panels with new if they are not of the same electrical properties. An installer explained that:

> *Generally, if you're trying to replace a system, two panels from a system from 10 years ago, those panels will probably be 190 watts and the smallest panels you can buy nowadays are probably 270 watts. Those 270-watt panels won't work with the 190-watt panels. They're not allowed to be installed because they're electrically too far apart in difference. (Installer, Outer Regional area)*

A recycler raised the issue of the mismatch between the life span of inverters and the life of a PV panel. Most often, the performance warranty for the PV panels and the inverter are different[8]. This implies that inverters need to be replaced one or more times in the course of PV systems' service life. The interviewee pointed out that when the inverters get replaced, consumers take advantage of this to upgrade to a whole new system. In doing so, the consumers receive government rebates, a fresh warranty and a newer, cheaper system.

Participants also said that PV panels were removed during refurbishments. A representative from one of the advocacy groups was concerned that government-funded building upgrades in remote communities do not appear to include provisions for the 'proper disposal' of PV panels in the contracts. They expressed concern that large volumes of PV panels might end up in landfills as the contracts for demolition works do not specify whether the existing panels should be carefully removed and reinstalled or disposed of.

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8 According to Ristow et al (2008) an inverter might have a 10-year warranty but this falls short of the performance warranty of the PV panels which can be between 25–30 years.

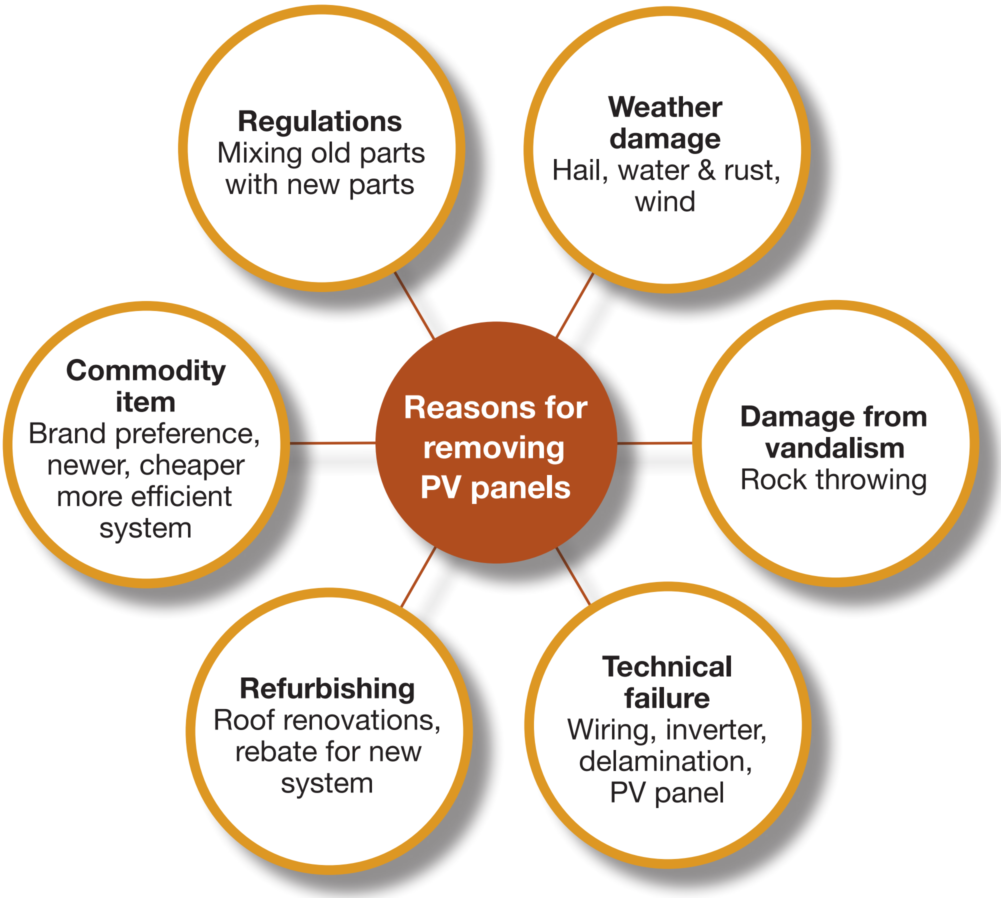

Figure 5.3 Reasons identified by study participants for the removal of solar PV panels in the NT

More importantly, responses to this question revealed that changing consumer attitudes or behaviour towards solar panels played a critical role in their removal. Some interviewees suggested that solar panels were turning into consumer items, with old panels being prematurely removed and replaced with new ones even though the original panels were still performing after the warranty period. They indicated that, similarly to mobile phones, consumers have brand preferences and want to upgrade to bigger systems with the latest technology and that this was made easier owing to the constantly reducing cost of solar PV panels. As one interviewee remarked on this phenomenon:

It's become a consumer item where just like if you move into a new house and the fridge doesn't fit into the fridge space, most of the time you don't pull the kitchen apart, you just go and buy a new fridge, and so solar PV is becoming a bit like that in the consumer items sense where people have their preferences on brands. (Installer, Outer Regional area)

Several participants commented on the role of government rebates as an incentive to prematurely remove solar PV panels before they had reached the end of the predicted warrantied period (i.e. reached regular EOL), noting that consumers do not get any 'CER credits' for replacing a few panels but do get rebates if they are putting in a completely new system[9]. The installers and recyclers we interviewed indicated

9 According to the CER website, in some instances, small-scale technology certificates (or the rebate) were previously issued for replacement panels. While current eligibility criteria states that systems for which one, some or all panels have been replaced, and that have previously received small-scale technology certificates, will not be eligible to receive additional small-scale certificates. CER acknowledges there will be a transition period as some consumers had scheduled work before the change in criteria. In these circumstances, applications for replacement panels were still considered for small-scale technology certificates for installations up to 31 January 2018. Consumers are also eligible if they install an additional separate system with a capacity of no more than 100 kW or, if they are increasing capacity, provided the total capacity remains less than 100 kW.

that consumers were typically replacing a whole system after only 10 to 12 years. Since there is no readily available single database which tracks all solar PV panel installations and de-installations, quantifying this information was beyond the scope of this study. Nevertheless, this finding has potentially significant implications for the timing of the predicted solar PV waste surge in the NT and is discussed in more detail in Section 6.

From the responses to this question it is apparent that solar PV panels in the NT are not just simply removed because they have reached the end of their warranty period (i.e. reached regular EOL) or because of technical failures (either inherent or resulting from the harsh physical environment). Our research revealed a range of social and economic reasons not previously discussed in the literature that prompted the premature removal of solar PV panels. These range from vandalism to removal during refurbishments to removals arising from the treatment of solar panels as a consumer item. The implications of this finding for EOL management is discussed in more detail in Section 6.

5.5. Challenges and barriers in solar PV panel waste management

Participants were asked two questions in relation to challenges and barriers in solar PV waste management. One question asked what they saw as the major challenges associated with dealing with solar panel waste in their geographic area and/or the NT and/or Australia more broadly. They were also asked what they saw as the major challenges and barriers associated with recycling and renewables, both currently and in the future.

Different stakeholder groups identified different sets of challenges, which are summarised in Figure 5.4. For example, the LGAs do want to put PV panels in landfill and find lack of policy direction a big barrier. Further, they do not know where to send the PV panel waste and want to educate the consumers about proper disposal of PV panels. The installers need a place where they can dispose of the panels locally and want to educate consumers that they do not need to upgrade their PV panels unless required. The advocacy groups are aiming at changing the NT Government tendering process so that PV panel disposal is included in the costs of refurbishment and are pushing for setting up recycling businesses in the NT. The biggest challenge for the recyclers is diverting panels from the landfill towards their collection points. The systems engineers, as well as the energy suppliers, are concerned about the costs of transporting small quantities of PV panels from Very Remote regions and thereby the economic feasibility of any recycling option. On the other hand, the challenge for the policy makers is to form appropriate recycling policies, with limited information available on further reprocessing options for PV panels.

Barriers to managing solar PV waste identified by participants were grouped into the following themes, with the three most frequently cited barriers discussed in more detail below:

- costs associated with collecting and transporting removed panels;
- not knowing what to do with removed PV panels;
- lack of policy direction by the Government for PV panel collection or disposal;
- lack of information on PV panel recycling;
- lack of PV panel tracking;
- small volumes of waste in remote regions;
- lack of repair and reuse options; and
- warranty of products.

Stakeholder	Costs	Environmental impact	Not knowing next step
LGA	Long distances, high costs for sending materials interstate for recycling High travel costs to remote communities for replacing PV panels Cost of licensing landfills if PV panels are listed waste	Proper disposal of hazardous materials in PV panels No re-processing in the NT, all waste has to go interstate/ overseas which adds to the carbon footprint and potentially negates the value of recycling Good to track panels to understand their impact from the time it leaves the community to when it is recycled	No idea of disposing solar panels Not knowing how to divert panels from landfill Not knowing where to send the stockpiled PV panels Managing PV waste is a new concern Lack of existing infrastructure to manage collection, storing PV panels Hard to predict future technology and therefore management of PV panels Not knowing whether landfill licensing is required for proper disposal
Installers	Labour costs or replacing panels, rewiring, complying to standards Location, distance, transport costs a barrier Responsibility of paying for disposal		Just somewhere to take the decommissioned panels Storing PV panels is an issue Not knowing where PV panels are recycled in Australia Concern that large number of panels that will be coming off in the future with no measures for managing waste in place
Advocacy groups	Costly to transport Licensing is costly	Need for properly disposing panels with Cadmium Telluride Need for industry to work towards improving technology to remove the contaminant and toxins Ethical issues with overseas recycling because some of the chemicals in the PV modules can be harmful. Need for systems, processes and technology to ensure development is not at the expense of the environment	
Recyclers	Logistics of collection from distant places, in the NT Cheaper for consumers to dispose at RWMF than to send to recyclers Not economical to buy recycling machinery without enough PV panel volumes		
System designers	Cost of disposal an issue	Main structures are glass, silicon and aluminium, with very little toxins	Managing PV panel waste will be an issue in the future when the current panels are decommissioned
Policy makers	Travel time to communities is the main cost when replacing PV panels	Clean energy at front end should not result in the back end clogging up landfills	
Supplier	Challenge to recycle since economics is not there	Not managing PV waste would be an antithesis to the actual green image of the technology Even if panel is damaged, any heavy metals are still bound in the laminates and not a risk to the environment	

Figure 5.4 PART A Challenges identified by participants regarding solar PV waste management

Stakeholder	Information dissemination	Lack of policies	Reusing	Recycling
LGA	Increasing awareness in the community regarding proper disposal Need for informing public about proper disposal in different languages Unsure of reliability/ longevity of various brands	Need for careful demolition of buildings with panels so that they are not broken Emphasis on renewables uptake but should be on the end of useful life too Very little regulation regarding disposal	Finding the market for old panels	Difficulty in finding recyclers for the solar panels Finding the market for recycling Need for separating recyclable materials in panels Challenge of knowing what market, what material, what commodity is useful and then direct waste streams Will be a challenge to recycle the large numbers of PV panels decommissioned in the future Currently low volumes of PV panels in the NT not economically viable to establish a recycling industry
Installers	Educating consumers that panels good for 30 years don't need to be changed after 10		Need for a place where old panels can be tested and made available for reusing	
Advocacy groups	Need for educating the manufacturer, supplier, end user about EOL Lack of information about how to recycle With 25 years performance warranty, people see it as a less urgent issue	End of life to be considered in tendering process as well Govt to get policy right- not just driving renewables uptake but ensuring correct disposal through tendering process Conflicting policies- solar renewable energy to help with greenhouse gases throwing PV panel toxins into the environment Push for renewables without consideration for how they will be disposed Careful messaging so that people don't stop using renewables	Business plan around reusing and recycling panels Need for finding ways for reusing	No economics in any kind of recycling in remote communities. Setting up a system to do recycling properly Regions forgotten in recycling programs
Recyclers		To divert panels from landfill that are accepting solar panels A network of drop off points for collection to be established and legislative support for recycling is required		
System designers			Not made to be unmade Panels not usually repairable, so just replaced Panels are not compatible-different cells have different efficiencies, different terminals for connecting- not standard	
Policy makers		Need for understanding the logistics of transporting, further processing of PV panels and Public consultation before policy is formed		
Supplier				Finding ways to make recycling of panels from remote communities viable

Figure 5.4 PART B Challenges identified by participants regarding solar PV waste management

5.5.1. Costs associated with managing PV waste

Just over 90% of interviewees cited costs involved with disposing of panels as the biggest challenge. These costs were related to removing and transporting removed PV panels, their disposal, licensing of WMF sites to accept e-waste, as well as environmental costs. When participants were asked if they were able to estimate how much it currently costs to remove and dispose of a solar panel in their geographic area, responses varied.

The largest cost identified was removing and transporting PV panels form remote communities. Several participants broke down this cost, distinguishing between travel costs, labour costs and actual cost of the system, reflecting their familiarity with working in remote areas where travel costs comprise a significant part of any job cost and are frequently a separate line item in tenders or quotes to undertake work outside of the major urban centres. One participant estimated that if it costs $10,000 for a new system, then more likely it will be $2,000 for labour costs and $8,000 for travel costs. Another estimated $800 for labour for panel removal and $500 for disposal. One participant drew attention to the fact that travel costs may include a vehicle rate ($4/km), an hourly rate for the time spent in transit (which could be in excess of $100/hour), an overnight allowance and finally the labour cost of removing and installing new panels. Yet another said it cost $8/km for travel and $120/tonne for disposal. It was clear from the responses to this question that in Remote and Very Remote regions a significant proportion of the costs relate to travel, rather than the cost of labour for the actual removal.

The installers showed concern about the responsibility of disposal costs. Although the cost of replacing panels still under warranty is born by the manufacturer, this does not extend to covering the disposal costs associated with the panels that have been removed. Rather than absorb this cost or pass it on to the customer, installers either stockpile the panels themselves or dispose of them at landfills (WMFs) where this is permitted. As one installer explained:

> *A lot of the time the end customer doesn't want to pay for the disposal, so then it comes down to the installers and we've got tight margins in the industry. The cheapest guy usually wins, and the cheapest guy usually takes it to landfill. (Installer, Outer Regional area)*

Responses to this question also revealed that the cost of disposal with a recycler, where available, is far more than landfill disposal. For example, the recyclers may charge between $10 to $25 per panel for recycling, whereas the landfill charges per tonne of waste.

Some local government participants expressed concern that if PV panels are listed as e-waste in the NT then the WMFs would require licenses to stockpile them. This licensing would have a cost implication for the LGAs.

In addition to economic costs, respondents were concerned about the environmental costs associated with managing solar PV panel waste. Whilst respondents were keen to maintain the green image of renewables, there was some angst that the environmental costs of disposal, such as transport emissions and managing toxic constituents, would be 'an antithesis to the actual green image of the technology' if systems are not put in place to manage the waste. Some participants indicated that a lack of knowledge regarding the toxic constituents of solar panels presented a challenge. More specifically, some interviewees expressed concern that they had limited knowledge on how to identify panels containing toxins and ways of disposing those panels.

The available evidence suggests different costs play an important role in influencing the waste management/ disposal choices made by different stakeholders. The issue of costs and who pays is considered in greater detail in Section 6.

5.5.2. Not knowing what to do

'Not knowing what to do' was the next biggest barrier to managing solar PV waste, cited by 85.7% of the respondents. Disposal of solar PV panels was identified as a 'new issue' by some local government participants

with responses indicating a clear uncertainty about how to manage this waste stream. Those WMFs that accept solar PV panels have the additional burden of stockpiling them and then identifying where they can be sent for further processing. As one respondent from a Very Remote region asked,

> *You can collect the panels, but then where do you send them?*
> *(Local government participant, Very Remote region)*

Installers are also faced by the same dilemma of what to do with the panels after they have been removed and are currently stockpiling or passing them on for reuse since there are no facilities for solar PV panel disposal or collection points in towns or remote communities. These kinds of responses are consistent with the situation at the national level whereby much of the current debate about managing solar PV panel waste is set against a context of uncertainty where stakeholders are at a loss about the next step.

5.5.3. Lack of policy

In view of the responses to the earlier question regarding policies and programs, it was not surprising that lack of policy was identified as a barrier by over one third of the participants and specifically, the lack of policy direction and regulations relating to EOL management at the Northern Territory level. With no specific guidelines on solar waste management, operators of WMFs are left to make a call on whether they accept solar PV panels or not. In localities where neither these facilities nor recyclers are accepting the panels, it falls by default to the installers to manage this waste, either by stockpiling or disposing of them in other unregulated ways. At least one respondent also felt that it was the role of government to identify markets for recycling.

Conflicting policies were identified as a challenge too. As noted in Section 1, the NT Government is promoting the use of renewable energy and encouraging greater uptake through various policies and programs. However, as one respondent pointed out:

> *They're [the NT Government] really driving renewable energies and promoting the interest around solar with their grants and their policy development to decrease their greenhouse gas reductions and that, but their solution is actually creating another significant environmental risk for the community in the waste management, particularly through local government.*
> *(Advocacy group representative, Outer Regional area)*

Recyclers trying to divert solar PV panels from landfill are also looking for policy support and cited the example of e-waste policy in Victoria. In Victoria, landfills are not permitted to accept e-waste, which in that State includes PV panels, thus consumers there are forced to use alternative methods of disposal, such as recycling.

The above data clearly indicates that lack of specific policies on disposal is impacting various stakeholder categories. Data suggests decisions regarding disposal are being made not only by the agencies responsible for waste management, but also by other stakeholders in the sector.

5.5.4. Other barriers

Participants referred to several other challenges including the small volumes of waste generated in remote areas, the apparent lack of repair and reuse options, lack of a mechanism to track PV panel movements, and the need for information across the solar PV panel supply chain, from the manufacturer through to the end user, amongst others.

5.6. Stakeholders' preferred solutions for managing solar PV panel waste

Interviewees were asked about their organisation's preferred options, ideas or solution(s) for the future management of old panels. These suggestions were broadly grouped as follows:

- policy and regulatory reform;
- collection points and stockpiling PV panels;
- recycling PV panels;
- education regarding solar PV panel waste;
- product stewardship;
- life extension; and
- working in partnerships to find solutions.

Table 5.2 indicates solutions proposed by different stakeholder categories. In considering the solutions preferred by the different stakeholder groups, it became apparent that some solutions were more important to particular stakeholder groups than others, which broadly corresponded to that stakeholder's position or role in the life cycle of a solar PV panel. For example, solutions preferred by local government participants tended to be concerned with aspects of waste disposal they were responsible for, namely providing collection services, regulations around collection, sending collected panels for recycling, informing consumers about proper disposal, connecting to product stewardship schemes and extending landfill life by diverting PV panels. Similarly, the solutions suggested by recyclers were related to the need for collection points, regulations, recycling, information and extending life but not product stewardship or backloading. Solutions preferred by policy maker representatives centred on policy and regulatory reform, product stewardship and recycling.
Overall, it appears that extending the life of PV panels and recycling enjoyed the broadest support amongst the participants. The need for policy formation and regulatory reform was also supported by all of the stakeholder groups that have some level of responsibility for and/or interest in managing solar PV waste. The solutions proposed by the stakeholders are discussed in more detail below.

5.6.1. Policy formation and regulatory reform

The call for the establishment of polices as a solution was not surprising in light of the lack of policy and regulations referred to previously in this report. The participants representing policy makers, local

Table 5.2 Solar PV waste management solutions proposed by different stakeholder groups

Stakeholder Category	Solutions						
	Policy & Regulatory reform	Collection points for stockpiling PV panels	Recycling	Education	Product stewardship	Extend-ing life	Working in partnerships
LGA's	✓	✓	✓	✓	✓	✓	
Installers	✓	✓	✓	✓	✓	✓	✓
Recyclers	✓	✓	✓	✓		✓	
Advocacy groups	✓		✓	✓	✓	✓	✓
Systems engineers			✓			✓	
Energy suppliers		✓	✓			✓	
Policy makers	✓		✓		✓		✓

government, installers, recyclers and advocacy groups identified the need to establish guidelines regarding the disposal of solar PV panels (Table 5.2). These participants also identified the need for regulatory reform at different levels. For example, nationally, via changes to 'CER regulations'[10] to allow for 'mix and match' (i.e. cobbling together a 'new' system from components salvaged from different old installations). At the NT level, participants identified a need for regulations created by the EPA regarding the disposal of PV panels and reform through the inclusion of PV panel disposal costs in Government contracts for infrastructure projects.

While identifying the necessity for clear regulations for accepting and stockpiling PV panels at Regional Waste Management Facilities (RWMFs), participants highlighted the need for a clear policy on whether solar PV panels can or should be considered e-waste and combined with existing e-waste recycling practices. The need for public consultations before rolling out such a policy was also identified by interviewees. Perhaps most importantly, participants recognised the need to align policies that encourage the use of solar PV as a renewable energy source with EOL management. This is a significant policy gap that was described earlier in this report (Section 1) and is discussed in further detail in Section 6.

5.6.2. Collection points and stockpiling

Participants representing the LGAs, installers, recyclers and energy suppliers, all referred to the establishment of collection points for stockpiling PV panels (Table 5.2). Key features of this solution are the establishment of collection points within remote communities, major centres and/or at RWMFs. Panels may then be stockpiled either at the collection point, to obtain greater volumes before being sent to major centres, or stockpiled at a major centre/RWMF. One participant suggested that shipping containers could be used for panel storage which can then be shipped directly to recycling centres. Another suggested that partial dismantling (removal of the aluminium frame and glass covers) would facilitate easier stockpiling. Backloading was identified as a mechanism to transport PV panels from remote areas to collection points with one participant specifying that backloading should occur via non-food product carrying trucks. The need for good signage at stockpiles in remote regions was also identified along with the need for the EPA to direct stockpiling regulations.

5.6.3. Recycling

When discussing recycling as a potential solution for managing solar PV waste, participants' responses included:

- those relating to the actual practice of recycling (e.g. establishing a local recycling option in the NT, which would also lead to reduced transport emissions; recycling to occur at the point of removal rather than at some more distant location; partial dismantling – removal of aluminium frames and glass – prior to sending to recyclers to reduce the volume of panels transported and, presumably, the cost);
- those expressing concerns associated with recycling (e.g. ensuring that recycling is not a cost to the installer or consumer; finding a low carbon solution for transport when sending the panels to the recycler (there may be little value in recycling but potential in materials [recovery]); and
- those identifying outstanding issues associated with recycling more broadly (e.g. encouraging research into reuse and recycling panels; considering product stewardship programs; products should be 'made to be unmade'; and the need for solar PV design to allow for easy disassembly for recycling).

The use of landfill fees as a mechanism to encourage recycling and discourage consumers from disposing of panels in landfill was identified, as was the need for demolition permits to clearly state whether panels are to be recycled or sent to RWMFs.

5.6.4. Engagement and information

Having access to information on recycling, stockpiling and managing toxins in PV was seen as a solution by

10 CER requirements refer to the need to meet relevant Australian Standards including AS/NZS 3000, Electrical installations, which includes Wiring rules.

local government participants, installers, recyclers and advocacy groups. In addition, the need for engaging with consumers and informing them about responsible disposal practices and future disposal costs, as well as discouraging the premature (i.e 10–12 years after installation) replacement of solar panels was also identified.

5.6.5. Product stewardship

Some local government, policy maker, installer and advocacy group participants identified product stewardship as their preferred solution. Under the product stewardship model suggested by the interviewees, responsibility for managing solar PV waste would ultimately fall back onto, and be paid for by, the manufacturer. One interviewee pointed out the need for existing product stewardship schemes to consider options for Remote and Very Remote areas. This highlights our earlier observations from the literature review (Section 2) that many potential solutions to address solar PV panel waste are developed within densely populated urban areas and to date have not been subject to evaluation in more sparsely settled regions.

5.6.6. Life extension

Extending the functional life of solar PV panels was suggested by several stakeholders. The need for research regarding remote monitoring of PV panels and other strategies for increasing the longevity of panels was also identified. Some other strategies suggested were using solar PV panels from reliable manufacturers as they are more likely to last longer; establishing test centres (i.e. a place for testing, repairing and re-packaging used PV panels prior to reuse); donating used panels for reuse (for example, to hobby farmers, Indigenous communities, people seeking to establish their own off-grid solutions); repair and re-sale (i.e. re-laminating delaminated panels and offering them with replacement warranties); and discouraging the premature (i.e. within 10–12 years of installation) removal of functional panels. As noted earlier in this section, regulatory reform to allow for the mix and match of components from different systems was also identified as a way to encourage greater reuse of parts. It is important to note that a combination of these strategies would be more likely to result in extended PV panel life.

5.6.7. Working in partnerships

The need for a collaborative approach by industry and government in managing solar PV waste was highlighted by several participants. For example, co-funding research into reuse options and effective disposal of PV panels, designing panels for disassembly and manufacturing panels with less contaminants, were all ways that respondents felt would contribute towards reducing future solar PV waste.

Collectively, these results highlight the need for a wide-ranging set of solutions and interventions at different levels in order to reduce waste in landfills and turn waste into a resource. It reinforces the need to adopt a systemic approach to managing solar PV panel waste that is cognisant of the complexity of this particular waste stream and the varied waste mobility flows/after-lives that occur, whilst understanding the particular behavioural drivers underpinning consumption (installation) of ever-increasing volumes of solar PV panels.

5.7. Future trends in solar PV panel installations and removals

The estimated waste trajectories described in Section 4 only related to panels installed between 1996 and 2019. These estimates must be considered underestimates of the likely volumes of solar PV waste because they do not include early EOL losses of panels that are installed in the future (i.e. from 2020 onwards). Accordingly, understanding trends in future panel installations and removals is important in terms of being able to identify mechanisms to reduce these early EOLs (and therefore reduce the waste burden) that will be overlaid onto our trajectories calculated in Section 4.

5.7.1. Installations

Participants were asked a series of questions about their organisation's future solar PV installations, installations by other organisations and likely trends in the future uptake of solar PV panels in their geographic

area. All respondents forecast an upward trend in the future uptake of solar PV panels in their geographic area, with more panels being installed on residential, commercial and government buildings. Solar farms were also referred to as well as installations in at least six homelands. Several respondents commented specifically that more installations were occurring on commercial (business) and government buildings, as well as in remote communities. The role of government policies and programs as a likely driver of this trend was also noted by several participants, specifically that government subsidies encourage the uptake of solar (one interviewee stated that with the rebate 'uptake triples') as do programs such as Solar Setup and the Rooftop Solar on Schools program. While some participants found it difficult to quantify the likely number of future installations in their geographic area, estimates by others ranged from as few as 12 panels up to 2000; other interviewees responded by referring to the additional systems' capacity, which ranged from 3 MW up to 50 MW.

While respondents were generally aware of some future installations proposed by NT Government agencies such as the Department of Housing and Community Development, details of these installations are held by those agencies. Local government participants noted the potential for solar farms and proposals for stores in communities to install solar PV systems, highlighting the growing organisational and community support for renewables. Participants from advocacy groups flagged that industry was also becoming more interested in solar PV installations.

5.7.2. Removals

Participants were also asked a series of questions regarding de-installations by their organisation and in their geographic area. In contrast to the responses regarding future installations, participants were generally much less certain regarding the extent of recent panels removals in their geographic area. Some responses highlighted that because the removal work was organised by another agency, that they did not have access to that information. Others indicated that their solar PV systems were relatively new and therefore they were not anticipating any panel removals in the next five years. Notably, other than one participant who referred to the removal of solar panels in terms of KW capacity, none of the respondents provided estimates as to the likely extent of the panel removals.

5.8. Key findings

On the basis of the interviews with stakeholders, several key findings emerged:

- there is a real need for policy development and regulatory reform regarding solar PV waste management;
- solar PV panels are often removed prematurely (i.e. before reaching EOL), and for reasons other than technical failures or adverse weather impacts;
- there are no clear directions on 'what to do next' after PV panels are removed; and
- there is a gap between NTG policies such as the renewables policies, waste policies and policies relating to the scope of infrastructure tenders.

The implications of these findings for the management of the Territory's solar PV waste are discussed in more detail in conjunction with other findings from this study in the final part of this report.

PART 3: DISCUSSION AND RECOMMENDATIONS

The final aim of this study was to identify potential solutions for managing solar PV waste in the NT, however it became apparent in the course of this research that a series of broader recommendations were necessary in relation to the management of solar PV waste, including policy and regulatory reform, education and overcoming other challenges and barriers. As such, the final part of this report draws together results from the literature review and Part 2 in a discussion that highlights our findings and the implications for waste management in the NT (Section 6) before offering a series of recommendations (Section 7). These findings and proposals align with a circular economy (as opposed to a straightforward linear supply chain perspective). Collectively, these results strongly suggest that action is required on multiple fronts and at different levels in order to effectively manage the waste arising from solar PV panels, reflecting the ecology of this sub-sector. Interventions at all stages from manufacturing to disposal are required by various stakeholders.

Section 6: Discussion and Implications

In this section we combine the results of the literature review in Section 2 and the quantitative and qualitative results from Part 2 and discuss our findings in terms of the implications for the management of the NT's solar PV waste.

6.1. Nature of the sector

The data in Section 5 revealed that in the Territory there is no single solar PV waste 'flow', with panels being sent to WMFs, stockpiled (either at WMFs or elsewhere), partially dismantled and sent for recycling, or entering the used panel market, for example, off-grid solutions on hobby farms and on mobile homes/RVs. It also revealed that more than one stakeholder category plays a direct role in dealing with the removal and disposal of PV panels, for example, installers acting as proxy disposal points. Therefore, managing the NT's solar PV waste will require a collaborative approach between different levels of government, industry and consumers.

6.2. Policy development and regulatory reform

6.2.1. Policy, regulations and guidelines

It was noted earlier that the NT (and Australia more broadly) lacks clear policies regarding the management and disposal of solar PV waste, despite encouraging the uptake of solar PV installations through a range of government subsidies and programs. This policy disconnect was also noted by our participants, with representatives from local government, installers, recyclers, advocacy groups and policy makers all identifying the clear need for regulatory reform. The impact of this policy vacuum is evident in the current disposal practices that occur in the Territory whereby decisions regarding disposal are being made not only by local governments, but by other stakeholders in the sector, such as installers and recyclers.

It was noted in Section 1 that in Australia (with the exception of Victoria) solar panels are not considered to be e-waste, although they have been so classified by the EU since 2012. It was also noted that whilst solar PV panels are not included as a specific class of hazardous or listed waste under Schedule 2 of the *NT Waste Management and Pollution Control (Administration) Regulations*, some materials which may be found in first- and second-generation solar panels, such as lead, cadmium, tellurium, selenium and encapsulated, chemically-fixed, solidified or polymerised wastes, are included as listed wastes. This inconsistency may be a factor underpinning the current, somewhat ad hoc, approach to managing solar PV waste in the NT: Some local governments have refused to accept solar PV panels at their WMFs while others have decided to accept the panels but stockpile them.

The results of our study strongly indicate that not only is clear and unambiguous policy required, but also clear regulations regarding the collection, transport, stockpiling and disposal methods for solar PV panel waste. Interviews with stakeholders and feedback received during the information sessions revealed that there are concerns regarding whether landfills are allowed to store solar PV panels and that further information regarding the likely risks arising from the improper treatment of solar PV waste, and clear guidelines on best practice in this regard, are urgently required.

In developing policy, associated regulations and guidelines, it is important to recognise that solar waste flows do not follow a single path and that regulatory reform should continue to allow these variable waste flows. For example, by permitting appropriate repair, reuse and recycling (discussed in more detail below), as well as recognising the multiple players in this space. We believe a more flexible approach is essential if the NT is to be able to maximise any opportunities arising from the need to manage this waste. A flexible approach is also warranted given the nature of the forecast solar PV panel waste trajectories in the NT which tend to be characterised by relatively small–modest volumes of waste, followed by a sudden and dramatic increase within a very short space of time (i.e. 5–10 years). The implications of this are twofold: firstly, that the ways of managing waste may have to change over time and

secondly, that what may be uneconomic up to that point may become cost-neutral or provide a return on investment. Another point regarding the need for flexibility is that the PV manufacturing technology as well as recycling technology is a rapidly evolving space, so ideally, any policy and regulatory reform needs to be responsive to and accommodate these likely changes with relative ease.

Decisions regarding the best way(s) to manage the Territory's solar PV waste both now and in the future should be underpinned by a good understanding of the nature and extent of that waste (i.e. a robust evidence base). Policy reform considerations should also include the need for panel tracking, which is discussed in more detail below.

Similarly, the issue of who pays for solar PV waste management is discussed later in this section but should also be considered within the context of policy and regulatory reform.

6.2.2. EOL management and government infrastructure contracts

As noted above there is an apparent policy disconnect between encouraging the use of renewables, solar PV in particular, and EOL management of solar PV waste. This is of concern given that uptake of solar PV is increasing in the NT and this trend is expected to continue, including through various Government programs. Interviewees identified the need for government works tenders/contracts to include clear directions regarding the treatment of existing panels and, if panels are being replaced, clear directions around the disposal of removed panels.

6.3. Solar PV panel databases and tracking

It was noted in Section 1 that the *NT Waste Management Strategy* identified the disparate data on waste flows and trends as one of several challenges for waste management in the Territory and this is certainly the case regarding solar PV panel waste. Currently, there is not a readily accessible fit-for-purpose database which tracks all solar PV panel installations and removals in the Territory. This became apparent when attempting to generate a database from which to calculate the NT's future solar waste trajectories and also in the stakeholder interviews in the discussions around recent panel removals and future installations.

The largest database (in terms of including both SSIs and LSIs) is that held by CER. However, the presentation of system installation numbers by postcode limits its usefulness as a waste management tool as some postcodes overlap more than one LGA area and system installation numbers are not the same as panel numbers. Additionally, there is no legal requirement for household consumers to register their solar system with CER unless they are seeking the rebate (or a small-scale technology certificate). Furthermore, there appears to be virtually no data on the number of solar PV panels installed in the NT prior to 2000, nor is there readily accessible data on the type of panels (c-Si, CdTe, CIGS) installed in the Territory. Finally, none of the three databases which we drew upon (from CER, PWC, Ekistica) were established with a view to enabling solar PV waste management decisions.

As it was beyond the scope of this study to validate the recorded panel numbers by direct observation on the ground (i.e. undertake ground-truthing) it is unknown to what extent the existing data sources reflect the actual numbers of panels in the NT, (including roof-mounted, ground-mounted arrays, and stockpiles of used panels held by Installers and at WMFs, for example). Consequently, the data presented in Section 4 on the waste trajectories for the NT, regions and individual LGAs, is therefore best understood in terms of appreciating the magnitude of impact rather than absolute figures. Whilst this type of data is useful in terms of facilitating a preliminary understanding of the issue, it is less useful in terms of facilitating business/ investment decisions because of these limitations.

Modifications to the way the CER data is collected and presented would be a significant improvement that would benefit LGAs in the NT and across Australia in understanding their potential solar PV waste burden as well assisting business to consider what the potential

opportunities there may be in this space. However, such changes would not entirely offset the fact that the CER databases were not established for the purposes of facilitating waste management decisions.

Another option to assist in managing waste flows could be through a barcode system linked to a centralised database with individual panels' barcodes scanned and their location recorded each time they are moved. Panel tracking for the duration of each panel's life span would facilitate more accurate forecasts and modelling of future solar PV waste flows. The ability to track individual panels would also be useful in establishing a quality system for the panel reuse market, akin to 'paddock-to-plate' tracking seen in the agricultural sectors. In the case of solar panels, panels could be tracked from the time they leave the manufacturers through to their final disposal. In addition to location data, other data that might be collected could include data on the panel's performance and repair history, which would be immensely useful in the context of selling panels that have not yet reached their EOL in a used panel market.

6.4. Variability in solar PV waste trajectories

Our research indicates that future solar PV waste trajectories across the Territory are not all the same. This finding was somewhat unexpected; it was anticipated that solar PV waste trajectories across the territory would essentially exhibit the same trend (albeit with different volumes), as evident at the Territory level, i.e. a sharp surge from 2040. Instead, waste trajectories vary across the three major regions and across LGAs. As discussed below, this makes achieving economies of scale through collaboration across LGAS more difficult but may provide opportunities for trialling different approaches to solar PV waste management in particular areas, ahead of the main waste surge in the 2040s. Those LGAs which experience a smaller waste surge prior to the 2040s include East Arnhem, Roper Gulf and MacDonnell. The magnitude of the increase in solar PV waste also varies with some LGAs, such as Barkly Shire and Central Desert Shire, likely to experience a much steadier increase than others, such as Darwin.

6.5. Solar Panel life spans in the Northern Territory

6.5.1. Reasons for removal including changing consumer attitudes and behaviour

The data from the stakeholder interviews suggests that in the NT panels are removed for a range of socio-economic reasons beyond simple technical failures (either as a result of the physical environment or inherent manufacturing defects). These socio-economic reasons included removal during refurbishments, removal as a result of vandalism and removals arising from the treatment of solar panels as consumer items akin to mobile phones, and appear to have received little, if any, attention in previous research regarding EOL removals. Our research also suggests that government policies and programs aimed at promoting the renewables sector, such as subsidies and rebates for new solar installations, can also encourage the premature removal of functional solar PV panels. Consequently, it appears that solar PV panel life spans may be shorter in the NT, with panels being removed prematurely, perhaps by as much as 18–20 years earlier (assuming an upper limit of 30 years warranty for panels) or 10 years earlier (assuming a panel has a 20-year warranty).

Through this study the participants put forward the view that the majority of panels are being replaced after only 10–12 years. Such a scenario has significant implications regarding the timing of the surge in the NT's solar PV waste. Our solar waste trajectories presented in Section 4 allowed for both early EOL and regular EOL losses following IRENA [1]. The waste trajectory for the NT showed the main solar PV waste surge in the NT, beginning in 2040 (reproduced here as Figure 6.1). If the removal of solar panels after only 12 years is indeed widespread and represents a 'mainstream' practice in the Territory, then the surge in PV waste will occur much sooner. Figure 6.2 illustrates the waste trajectory for the NT with a regular EOL of 12 years (rather than 30) whilst retaining the same 'infant' and 'mid-life' losses; there are essentially no 'wear-out failures' at 10 years as removal occurs around this time.

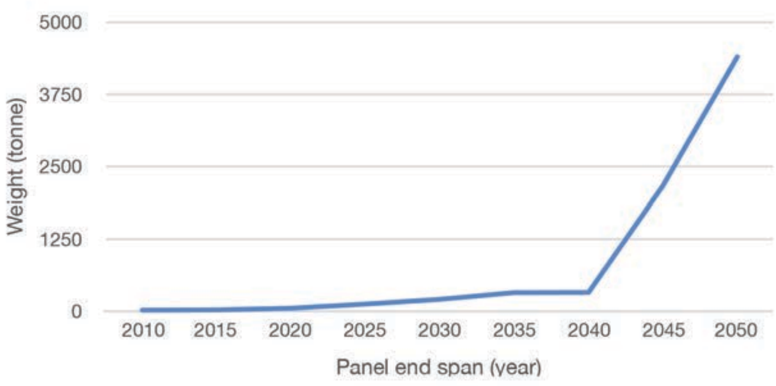

Figure 6.1 Estimated volume of solar PV waste for the NT (regular EOL is 30 years)

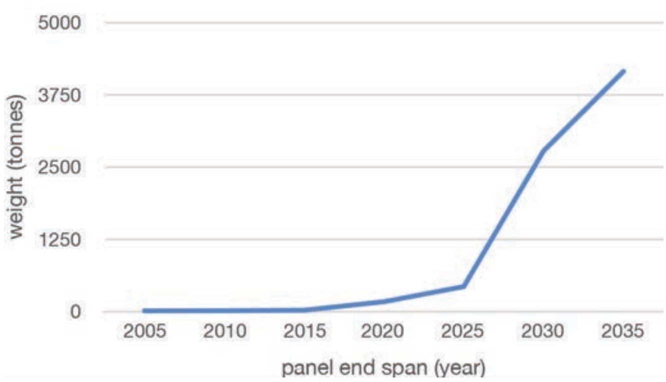

Figure 6.2 Estimated solar PV waste trajectory for the NT (regular EOL is 12 years)

In this scenario, instead of having 20 years to plan for a significant waste surge, the NT has only five years to plan before waste begins to surge in 2025, although in this scenario the surge is slightly less steep, growing from an estimated 421 t in 2025 to 2778 t in 2030 to 4159 t in 2035.

The finding that solar PV panels in the Territory are removed for a wide range of socio-economic as well as technical reasons, and the possibility that some panels are being removed prematurely (i.e. before they reach regular EOL), highlights the importance of this study as the first to consider EOL management of solar PV waste in regional and remote settings and reinforces the need to continue to develop a robust evidence base directly related to the Territory. Clearly, future modelling of solar PV waste trajectories needs to consider early EOL losses arising from factors other than technical failure.

6.6. Need for information

6.6.1. Raising general public awareness and information

Public awareness of the issues surrounding the disposal of solar PV waste needs to be raised now in order to help reduce the sharp surge expected in solar waste. It was noted above that solar PV panels are increasingly viewed as consumer items. Newer models, which are cheaper, more efficient and provide greater wattage, enable customers to upgrade with relative ease and low cost. There needs to be a clear distinction drawn between ‘functional obsolescence’, whereby new technology makes an older, but functioning, product seem outmoded, and actual EOL whereby the product no longer functions at all. Engaging consumers and providing information regarding ways to increase longevity, pay for disposal, as well as environmentally responsible ways of disposal could encourage shifts in consumer attitudes and behaviour.

6.6.2. Information and knowledge sharing amongst stakeholders

The data yielded strong evidence that various stakeholders are unclear what to do with solar PV panels once they have been removed. In the absence of existing policy and clear regulations, guidelines should be provided to local government and installers regarding the safe handling, transport, collection (including stockpiling) and disposal of solar PV waste. Advice regarding disposal should also be provided for different categories of consumers: residential, commercial and government. With the increasing number of solar panels being installed on government buildings, managing these panels should be incorporated into the general asset management processes, underpinned by the principle of extending solar PV life through various means, such as remote monitoring to capture possible defects before they require major intervention such as replacement.

6.7. Economies of scale, transport logistics and implications for recycling

Achieving economies of scale and overcoming transport logistics issues will be challenging. Notwithstanding the limitations of the data referred to above, our estimates suggest that in the Territory solar PV waste volumes will not be sufficient to allow for economies of scale until the 2040s, and possibly not even then, let alone at the regional or LGA level. The variability in waste trajectories across the Territory referred to earlier will make this all the more difficult. Economies of scale was also among the issues identified by stakeholders, specifically that without economies of scale, the cost of managing PV waste will be much higher.

Transport logistics also loomed large as an issue in the literature review and in the stakeholder interviews. Stakeholders identified transport costs as a significant component of the cost of managing solar PV waste. Data suggests that the costs for removing and transporting PV panels from Very Remote regions was far greater than for towns where the electrical contractors are based. An example of the cost breakdown for removing and replacing PV system (excluding the cost of new panels) in a remote community compared to that in a town is shown in Figure 6.3. In this hypothetical example, the cost of replacing the system from town would be $1,050 whereas the cost of replacing in a Very Remote community is more likely to be $4,230.

Replacing PV panels in a community 300 km away from a town:

Travel cost = $4 per km = 4 x 300 x 2 = $2400

Sitting costs for trip =
$100 per hour = 100 x 6 hours = $600 for a round trip

Labour cost for replacing for
5 broken panels @ $150 per hour = $150 x 5 = $750

Overnight changes = $180 per night = $180

Cost of disposal to landfill = $300

Total costs = $4230

Replacing PV panels in a town:

Labour costs = $750 for labour

Cost of disposal to landfill = $300

Total costs = $1050

Figure 6.3 Example of cost comparison of replacing panels in a community 300 km away from town versus in a town

In addition to the economic costs associated with transport over long distances, stakeholders also raised concerns about the potential environmental costs through increased emissions. This issue was also identified in the literature review.

One factor which may increase the likelihood of the Territory achieving economies of scale with regards to solar PV waste is the proposed Sun Cable solar farm. As briefly noted in the introduction to this report, this could potentially create a significant PV waste issue for the Territory prior to 2030 simply through the early failure of a percentage of the panels installed. However, assessing whether this would make the establishment of a full PV recycling and materials recovery facility in the NT viable was beyond the scope of this study.

Overall, our findings are consistent with those elsewhere [2 , 3 , 4], namely that current low waste volumes present economic obstacles for the development of recycling processes. From the literature review it seems that most, if not all, of the potential solutions to recycling PV waste require large volumes (i.e. in the order of 20,000 t) drawn from relatively small catchment areas, in the order of 100 km or 250 km. In the case, as seems likely, that the Territory is unable to achieve economies of scale for some time (if ever), then potential solutions to managing the Territory's solar PV waste need to be re-positioned as least or low-cost options that aim to bring maximum environmental and economic benefits for the Territory.

6.8. Options for EOL management of solar PV waste in the NT and regional development opportunities

The literature review revealed that options for managing solar PV waste overseas included disposal in landfill, incineration and reuse and recycling of the solar panels. Interestingly, none of the stakeholders we interviewed referred to landfill or incineration as a preferred potential option; all of the options proposed by the interviewees can be broadly described as diversion from landfill and include reducing waste through reuse/life-extension and recycling.

6.8.1. Reducing waste through panel retention and reuse

Any waste management strategy starts with reducing waste and therefore the first step in managing waste arising from solar PV panels should be to reduce the number of panels becoming waste. Earlier, we noted that it appears that solar PV panels are increasingly viewed as consumer items, somewhat akin to mobile phones, and that there is a need for consumer education. Specifically, this education needs to inform consumers that solar panels are not like mobile phones and do not need replacing every few years and that there are environmental consequences regarding their disposal, irrespective of whether they have reached the end of their warranty period or not. Retention and use for as long as possible should be encouraged, along with responsible disposal.

Although this study has focussed on the potential for managing solar PV waste through recycling, options to extend panel life (through repair and reuse) was a solution proposed by the stakeholders. From our interviews and discussions with the study participants it is clear that some solar panels do experience what may be described as a 'second-life' or 'after-life', consistent with previous observations and research that there is no single waste flow for solar PV panels.

Our research has clearly shown that not all panels that are removed have reached their regular EOL (i.e. warranty period). Interviews with stakeholders revealed that an entire array of panels may be replaced even if only one or two panels are no longer functional, or that sometimes entire systems may be replaced because it is convenient to do so when carrying out other works (e.g. building upgrades) or to access existing subsidies for new installations. This results in functional panels becoming waste prematurely. Instead, every effort should be made to encourage the reuse of functional panels, either in-situ (e.g. during building upgrades), or at a new location.

Although less research has been carried out regarding the reuse of panels, Wade et al [5] identified some issues associated with reuse, including that the panel has a shorter life expectancy in its new location (i.e. may have less warrantied time left before regular EOL), a lower conversion efficiency of the reused panels, as well as some additional labour costs as more care must be taken in the removal and dismantling of the old system to ensure that the panels remain intact (undamaged). We note that Wade et al's research was undertaken in a European context; what may be uneconomic in that setting could be economic in the Northern Territory where long distances to recycling centres mean that reuse locally (for example, elsewhere in a community or small town) may be a more cost-effective approach.

6.8.2. Potential for the 'used panel' market

Our literature review and some interviewees indicated that there is an emerging, informal (and largely unregulated) market for second-hand panels in Australia. This demand

appears to come from consumers who cannot afford new systems, those who are looking to live off-grid (e.g. people with 'weekenders' or hobby farmers who are looking for relatively inexpensive ways to meet their energy needs), remote and/or Indigenous communities and other organisations seeking to reduce their electricity bills, and mobile home and caravan owners. The development of testing centres that test and certify the performance of panels that have been removed would facilitate the expansion of this emerging market and reduce the number of functional panels being sent to landfill or for recycling. Co-location of test centres at, or nearby, existing WMFs, would enable them to also act as sales centres/outlets and create efficiencies in the supply chain. Such centres could also facilitate the development of a spare-parts market, by salvaging functional components from old panels which could be used for repairs, thus contributing to the circular economy. This would help overcome legacy issues in an industry which has seen many manufacturers come and go. Test centres such as that proposed here would provide potential business and/or employment and training opportunities. As noted above, the ability to track individual panels would greatly contribute to the expansion of the second-hand market through its ability to provide certainty for consumers; they could purchase used panels with greater confidence. Again, however, policy and regulatory reform need to occur to facilitate such opportunities.

6.8.3. Recycling vs collection and stockpiling

One of the aims of this study was to examine the potential for recycling of solar PV panels to offset the cost of managing this type of waste. The relatively small volumes of waste in the NT, lack of recycling facilities and distances to recycling centres interstate, discussed earlier in this section, suggests that currently, it does not make economic sense to recycle solar PV panels. The materials recovery analysis and hypothetical explorations of potential economic returns in Section 4 also supports this conclusion. Nevertheless, despite these challenges, recycling was identified as a preferred solution across all stakeholder categories.

The data gathered by this study suggests that, currently, many stakeholders struggle with two aspects of PV panel recycling: firstly, the costs of collection and transportation of PV panels from remote locations, and secondly, the lack of recycling centres in the NT. Presently, there are no recyclers fully processing the modules in Australia and only a few commercial recyclers based overseas. Some recyclers partially dismantle the panels before they are sent overseas for the final materials recovery treatment. Others accept and stockpile whilst waiting for recycling technology to develop to the point where it is economically feasible to process them onshore.

Another issue raised by interviewees and participants in the information sessions in connection with recycling and materials recovery relates to the difficulties around finding markets for the range of recovered materials. Our estimates suggest that the materials available for recovery in the greatest volumes are derived from c-Si panels: glass, aluminium, silicon, polymers (including plastics) and copper. The potential value of these materials in the future is difficult to predict owing to a range of factors, including changes in commodity prices. Further, future supply of these materials may change as manufacturers seek to substitute expensive materials with cheaper ones; there has already been a significant decline in the silver content of solar panels, for example. For some materials, such as silver, the challenge will be finding a market when the supply of that material in reasonable quantities cannot be guaranteed into the future.

One potential mechanism to mitigate the collection and transport costs associated with managing solar PV waste (including recycling) may be a form of decentralised collection points. Previous research suggested catchment areas of up to 250 km may be the optimum distance, which minimises the impacts from transport emissions yet captures a reasonable number of panels [6]. Collection points in towns and larger communities would also assist in reducing illegal dumping. Some of these collection points might also function as longer-term stockpiles, providing a location where installers could dispose of the panels, rather

than stockpiling them individually. Panels removed from smaller communities, homelands and pastoral and mining settlements could then be transported to these collection points using reverse logistics (i.e. backloading) when such opportunities arise to reduce costs, rather than making specific trips. Locating these collection points at or near existing WMFs in the larger centres would result in further transport efficiencies. To further reduce transport and environmental costs, initial dismantling could occur at the collection points. Initial dismantling would involve removing the aluminium frame and glass, which could either be sold for scrap (in the case of the former) and initial treatment of the glass. The remaining elements of the panel (which would now weigh much less and take up less space) could then be sent to recyclers for further processing once a certain volume was reached.

Given the current challenges associated with recycling and the need for a cost-effective approach(s) towards managing solar PV waste, it is not surprising that collection and stockpiling was identified as an option by stakeholders. This option increases the volumes of panels available and may be cost-effective if combined with an efficient collection network. Collection and stockpiling (with some limited dismantling) until it becomes worthwhile to recycle, either by reducing costs to transport interstate for processing and/or waiting until new technological processes appropriate for use in regional and remote settings are created, appears to be the simplest low-cost approach in the current circumstances.

6.8.4. Regional development opportunities

A key aim of this study was to consider what opportunities are associated with the need to manage solar PV waste in the NT. The Australian Government's 'Developing the North' agenda and the NT Government's renewables policy are likely to result in the growth of the NT's existing waste management sector through the need to manage the solar PV waste generated by these initiatives. Approaching solar PV waste management issues from the dual perspectives of waste management and regional development seeks to maximise both the environmental benefits and economic opportunities. If considered solely from an environmental perspective then one potential solution would be to send all solar PV panels interstate which would remove the environmental hazard but represent an ongoing economic cost to the Territory that may not be able to be offset (given the lack of economies of scale, limited potential returns from materials recovery and lack of recycling facilities for solar PV waste in the NT).

In considering these potential opportunities we reiterate the points made earlier in this section that, in the NT, there is no single solar PV waste flow, there are multiple stakeholders and forecast solar PV panel waste trajectories are characterised by relatively small–modest volumes of waste, followed by a sudden and dramatic surge within a very short space of time (i.e. 5–10 years). Some opportunities which may appear uneconomic or very modest currently may generate more substantial returns in the future. The variation in estimated waste trajectories across the three main regions and LGAs should be viewed as an opportunity to pilot and trial various methods, in advance of the major waste surge.

Collection and stockpiling (with initial dismantling), establishment of testing centres, creation of outlets for used panels sales (and/or parts) and greater emphasis on 'retain and repair' all provide potential business and/or employment opportunities for the Territory. For example, collection and stockpiling might be activities undertaken by either local government or in partnership with the private sector (e.g. local businesses) with appropriate policy and regulation in place. These collection points could operate separately from or in conjunction with test centres, again which might be run by the private sector. Given that transport costs were identified by stakeholders as a key challenge in the management of solar PV waste, one way to mitigate these costs is by undertaking as much work on-site as possible, e.g. removal and initial dismantling by local residents (subject to gaining the appropriate training, qualifications etc). Innovative ways of employing reverse logistics/backloading might see local people being paid to take solar panels to collection points or larger centres when they are travelling to these destinations

anyway. However, in order to realise any of these opportunities, policy and regulatory reform, as well as further investigations, are required.

6.9. Further research

From this study it is apparent that there is a need for further research in a number of areas. Earlier we identified the need for ground-truthing to more accurately determine the number of existing solar PV panels in the Territory and the need to pilot trials of solar PV waste management strategies ahead of the main surge in 2040. We propose there is also a need to consider economies of scope, as well as research into panel manufacture and design.

By investigating the potential possibilities for achieving economies of scope, we may be more likely to identify opportunities that will benefit those in regional and particularly remote areas. Economies of scope work particularly well with areas of small populations. The benefit is in 'sharing inputs like infrastructure and overheads' and this provides an incentive to produce things together [7]. For example, rather than selling just one good, a shop in a small town can survive by selling that good and having a café. This principle can be applied to RWMFs too. Rather than just collecting waste and having a shop for selling reusable waste, a repair and second-hand market shop for solar panels might be added to the existing infrastructure. Similarly, a recycling plant solely for recycling PV panels might not be an economic option but if it recycles other similar infrastructure waste then it might be economically feasible; the potential for a dual recycling plant that is capable of processing both solar PV panels and solar thermal systems (such as solar hot water systems with flat plate collectors) should be explored. Modifying existing machinery so that it can treat glass from a range of different sources (e.g. broken windows, solar panels, glass containers) might also be a cost-effective way of dealing with the largest material category (by volume) produced by solar PV waste as well as from other waste streams.

Although we have discussed repair, reuse and recycling it should be pointed out that generally, solar PV panels (and particularly those installed in the NT up to 2020) have not been designed to be dismantled or repaired. As one of our study participants pointed out, they are not 'made to be unmade'. This design aspect needs to be researched further to allow better options for recycling panels. One of the systems engineers indicated that they would be happy to recommend panels 'designed for disassembly' rather than those that are not. There are some promising developments in this regard with Japanese company NPC claiming to have an automated PV panel disassembly machine that separates the glass from the remainder of the panel without breaking it [8]. This type of machine would allow easier removal of the aluminium and glass which together may constitute anywhere between 83% and 97% of the total panel composition, are recyclable, and whose removal would reduce volumes to be transported to distant recyclers [9].

6.10. Who pays for recycling and the potential of a product stewardship approach

The data gathered indicates that there are several costs involved in EOL management of PV panels. For Remote regions, the removal of panels involves extremely high travel costs, labour costs for removal and finally, costs of disposing them at WMFs where permitted or recycling. However, as noted in Section 2, recycling also involves other costs including the cost of processing the material (materials recovery) and transportation of the recovered materials to their final destinations.

From our research it is evident that installers do not want to pay for these costs, nor pass them on to consumers. Manufacturers will cover the cost of replacing panels which are still under warranty but not costs associated with the disposal of the old panels, even if this involves recycling. It was pointed out by a participant in one of the information sessions that since consumers save money from solar PV systems (either through savings on their electricity bills and/or by receiving credits/cash-back from electricity retailers), disposal costs should be paid by them.

Under the EU WEEE Directive's extended producer responsibility principle, responsibility for the post-consumer stage of a solar PV product's life cycle is shifted (physically and/or economically; fully or partially) upstream towards the producers (manufacturers). Similarly, a report for Sustainability Victoria argues that product stewardship is the best option for managing future solar PV waste in Australia and is most likely to be successful when the waste is generated in large amounts with little or no recycling. This suggests that whilst product stewardship might be an option for jurisdictions with high volumes of solar PV waste, the efficacy of this model in regional and remote areas is still to be tested, a point also made by our participants during the interviews and information sessions. The model of product stewardship preferred by our participants would see responsibility for managing solar PV waste (both physically and economically) fall back onto the manufacturer, which implies a co-regulatory approach at least, rather than being a voluntary program. Additionally, other product stewardship schemes have not always considered the costs borne by local government in implementing these models and any financial arrangements need to include the costs associated with, for example, licensing and stockpiling [10]. The extent to which any product stewardship scheme would apply to existing solar PV panels is currently unclear.

Given that a range of stakeholders are involved in the management of solar PV waste, it is perhaps more logical to consider how these costs and the responsibility for disposal could be shared. More collaborative approaches were suggested, whereby government, industry and researchers could model potential solutions more suited to the Territory's particular circumstances.

Recommendations for managing the NT's solar PV waste are presented in the following section.

Section 7: Summary and Recommendations

In this final section we present a series of recommendations for consideration, not just by policy makers but by all stakeholders.

1. Previous research and our data indicates that there are multiple solar PV waste flows and stakeholders involved in this sector. **Rather than consider solar waste management issues through the lens of a straightforward supply chain, it should be conceived of as a complex system with responsibility for managing this waste shared amongst governments, industry and consumers. It follows that solutions need to involve a range of stakeholders and a collaborative approach.**

2. Currently, solar PV waste management practices in the Territory are occurring within a policy vacuum. There is a clear disconnect between the current push to encourage renewables (and uptake of solar PV systems) and absence of any clear policy regarding the management of solar PV waste. Furthermore, Schedule 2 of the *NT Waste Management and Pollution Control (Administration) Regulations*, includes some materials which may be found in solar panels such as cadmium, lead, selenium, tellurium, and encapsulated, chemically fixed, solidified or polymerised wastes, as listed wastes. **It is recommended that solar PV panels should not be landfilled. It is further recommended that solar panels be listed as a class of waste under Schedule 2 of the Regulations.** This would resolve the current ambiguity that exists in relation to whether or not solar panels are listed waste.

3. **It is evident from our research that not only is clear and unambiguous policy required, but also clear regulations regarding the collection, transport, stockpiling and disposal methods for solar PV panel waste.** The data yielded strong evidence that various stakeholders are unclear what to do with solar PV panels once they have been removed. Further information regarding collecting, stockpiling, transporting and disposing of solar PV waste and clear guidelines on best practice in this regard is urgently required for local government and solar PV installers.

4. Decisions regarding the best way(s) to manage the Territory's solar PV waste both now and in the future should be underpinned by a good understanding of the nature and extent of that waste (i.e. a robust evidence base). It was noted in Section 1 that the *NT Waste Management Strategy* identified the disparate data on waste flows and trends as one of several challenges for waste management in the Territory and this is certainly the case regarding solar PV panel waste. **Our research has demonstrated a clear need for the creation of a readily accessible, centralised fit-for-purpose database that captures all panel installations and removals, as well as details regarding panel types and brands, aggregated to local government area level.** We suggest that as the databases held by CER are likely the most comprehensive, changes to the way that data is collected and presented may to be the most cost-effective approach.

5. In the absence of any centralised fit-for-purpose database, our estimates of the nature and extent of the Territory's solar PV waste, both now and in future trajectories, can only be read in terms of magnitudes of impact. **In order to more accurately gauge the nature and extent of this waste, we recommend that ground-truthing be undertaken in small pilot areas** to capture existing roof-mounted panels, ground-mounted arrays, stockpiles of panels held by installers and others and those at existing waste management facilities. This would provide researchers, decision-makers and potential investors with a better idea as to how closely or otherwise existing databases reflect the magnitude of the Territory's solar PV waste.

6. Key amongst our research findings was that in the Territory solar PV panels are being removed for a range of reasons and some are being removed prematurely, i.e. before they reach regular EOL. It is possible therefore that the Territory's solar PV waste burden may begin to surge as early as 2025, rather than 2040. **A range of measures are therefore required to reduce the potential waste burden in the future, including public and other stakeholder information, and life extension through retention, repair and reuse.**

7. Our research revealed that changing consumer attitudes and behaviour towards solar panels was a contributing factor to their premature removal; specifically, that solar PV installations are viewed as consumer items which can be frequently upgraded at relatively little cost. **A public awareness program is required that explains to consumers that solar panels are not like mobile phones and do not need replacing every few years and that there are significant environmental consequences to consider regarding their disposal, regardless of whether they have reached the end of their warranty period or not.**

8. An unintended consequence of current Government legislation and programs aimed at encouraging solar PV panel uptake, is that they appear to be encouraging the premature removal of solar PV panels before the panels have reached their regular EOL. **All Government legislation and programs relating to solar PV panel uptake and usage should be reviewed and amended where appropriate to ensure that premature removal of solar PV panels is not encouraged.**

9. The data yielded strong evidence that various stakeholders are unclear what to do with solar PV panels once they have been removed. **There is an obvious and urgent need for information dissemination to these stakeholders in particular. In the absence of existing policy and clear regulations, guidelines should be provided to local government and installers regarding the safe handling, transport, collection (including stockpiling) and disposal of solar PV waste.**

10. An increasing number of solar PV installations are occurring on government buildings. Participants in this study identified the need for **government works tenders/contracts to include clear directions regarding the treatment of existing panels and, if panels are being replaced, clear directions around the disposal of those panels.** Additional measures to extend the life of solar PV panels installed on government buildings might include the use of remote monitoring devices to warn of early defects (which may be able to be repaired) before they require major interventions (panel or entire system replacement). Additionally, CER rules could be changed to discourage certificates for replacing working PV systems.

11. Achieving economies of scale (volumes) and overcoming transport logistics will be challenging. Our research suggests that, at the present time, least or low-cost option(s) should be pursued. **In the current circumstances, collection and stockpiling, with some limited dismantling, appears to be the best approach until such time that economies of scale (or scope) can be achieved and/or future developments in recycling technology make regional and remote processing feasible.** Given the issues relating to economies of scale, we suggest that **effort is invested in identifying to what extent economies of scope may help offset the costs of managing solar PV panel waste.**

12. Collection and transport costs emerged as a key issue in both the literature and during the stakeholder interviews. **One potential mechanism to mitigate these costs may be a form of decentralised collection points in towns and major communities. Reverse logistics (opportunistic backloading)** should be encouraged wherever possible to further reduce transport costs.

13. **We believe that collection and stockpiling (with initial dismantling), establishment of testing centres, creation of outlets for used panel sales (and/or parts) and greater emphasis on 'retain and repair' all represent potential business and/or employment opportunities for the Territory. These opportunities should be explored in greater detail, including pilot trials, ahead of the main waste surge expected in the NT.**

14. The literature review revealed that there is considerable research and development work focussed on solar PV recycling, materials recovery processes and techniques. Regardless of the process used, solar PV panels are not made to be unmade, which adds to the costs and complexity associated with recycling. **There is a clear need to invest in research in panel design and, specifically, 'design for disassembly'.** Not only would this facilitate module recycling generally, it would also facilitate greater repair and reuse of panel components.

15. Product stewardship has been proposed as a potential solution for managing solar PV waste. **It is vital that any model of product stewardship consider how regional and remote areas will be effectively serviced by that model prior to implementation.**

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Section1: Setting the scene

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Section 2: Literature review

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Appendix 1: Large-scale installations (LSIs) excluded from this study

Information about large-scale installations was available on the CER's large-scale installation certificate register. However, the number of solar panels in each large-scale installation was not specified on the public CER certificate register, so additional data was sought from the NT PowerWater Corporation (PWC) who provided a customised dataset in relation to their installations for the NT Solar Energy Transformation Program (SETuP). Information about panel numbers was sought from other sources, such as the Global Energy Observatory [http://globalenergyobservatory.org] and the Desert Knowledge Australia Solar Centre (DKASC) [http://dkasolarcentre.com.au/], as well as reports, articles and media releases relating to specific installations. Where no information about panel numbers was available, an estimate was derived from comparison to installations in the PWC dataset with a similar kW capacity and from the same time period.

Detailed data regarding panel types was available for 30 of the 57 LSI installations; given that these installations all consisted of c-Si panels, it was assumed that, with the exception of the 10 installations excluded from this study, the remaining 17 installations also consisted of c-Si panels.

Of the 10 LSI installations (totalling an estimated 35,364 panels), three were excluded as there was no publicly accessible information regarding their capacity available, five were excluded because no information regarding panel composition or weights for that particular type/brand could be located (Heliostats, Helicol solar water heaters, various at DKA), and two were excluded because they comprised third-generation solar panel types (CPVs). Most of these installations were located in the Central Australian Region and included: Alice Springs Airport Solar, Alice Springs Airport Solar – Carpark, DKA Solar Centre, Alice Springs Aquatic & Leisure Centre, Yuendumu Sun Farm, Lajamanu Sun Farm, Hermannsburg Sun Farm, Barramundi Group Solar NT, Borroloola Utility Array 1 and Timber Creek Utility Array 1.

Appendix 2: Modules used as the standard reference panels in this study

Panel Type	Installation period	Reference source & Module	Details
c-Si Modules			
	1996–2000	Renew Energy 'Solar Panel Buyers Guide', 2005 SunPower 2005 specs Mono-Si	16 kg. SPR-210. 72 cells. 210 W
	2001–2005	Renew Energy 'Solar Panel Buyers Guide', 2005 SunPower 2005 specs Mono-Si	16 kg. SPR-210. 72 cells. 210 W
	2006–2010	DKASC SunPower 2009 specs. SunPower 5.8 kW, Mono-Si, Fixed	15 kg. 72 mono c-Si cells, 215 W
	2011–2015	DKASC TDG Solar. TDG T250M606. 2013.	19.5 kg. 60 mono c-Si cells, 255 W
	2016–2020	DKASC Hanwha Q. Cell Q.PEAK-G4.1 (2017)	18.5 kg, 60 mono c-Si cells, 295 W
CdTE Modules			
	2000–2020	IRENA – First Solar FS-4100-2	12kg. 216 cells. 100 W
CIGS Modules			
	2000–2020	IRENA – Solar Frontier SF160-S	20kg. n/a cells. 160 W

Appendix 3: Stakeholder survey questionnaire

End-of-life management of Solar Panels in the NT

Survey for Sector Stakeholders
Preliminaries
Project description, Ethics, informed consent

Questions

1. Could you please start by broadly describing your organisation, its key purpose/role and how you see that relating to the regulation, manufacture, supply, distribution, management, transport, and/or disposal, of solar panels and/or solar panel waste? *(e.g. disposal through Council landfill/waste management; responsible for regulatory environment, supply and install solar panels; design, build and maintain RE systems that utilise solar panels)*

2. Which LGA or LGAs does your organisation cover?
All of NT Alice Springs Town Council Barkly Regional Council Belyuen RC

Central Desert RC Coomalie RC Darwin City Council East Arnhem

Katherine Town Council Litchfield RC MacDonnell RC Palmerston City Council

Roper-Gulf RC Tiwi RC Victoria-Daly RC Wagait RC West Arnhem

West Daly

3. Does your organisation currently have any policies, strategies or programs in relation to e-waste more broadly, and solar panels (their installation/usage and disposal) specifically? If yes, can you please describe them? *(if yes, ask if they are willing to share that info with us if it's in the form of policy docs? If it's on a website, get the address. If it's not relevant, they can just say that this question isn't relevant for their organisation)*

4. Does your organisation currently deal with old panels/panels that have been removed? If yes, can you please describe what it is that your organisation does with them? *(e.g. removes panels and transports them to a collection point; accepts panels at landfill; stockpiles)*

5 . Is your organisation planning to install any panels in the next five years? If so, can you please describe where, how many (what size installation) and what type of panels will be installed? (Rough estimates are OK here if that is the best info that they currently have.) *(This information will not be shared outside of the research team.)*

6. Are you aware of any other organisations in your geographic area that are planning to install solar panels in the next five years? If so, can you tell us who? *(This information will not be shared outside of the research team.)*

7a. Has your organisation removed any panels within the last five years? If so, can you please describe where from, how many and what type of panels they were, and who removed them, and where did they go? *(This information will not be shared outside of the research team.)*

7b. Can you tell us why the panels were removed? *(e.g. had reached their end of life, were no longer working, had been damaged, were removed as part of a larger demolition or renovation project)*

8. Is your organisation planning to remove any solar panels or solar hot water systems from your geographic area in the next five years? If so, can you please describe why, where from, how many (size/number) and what type of panels?

9. Are you aware of any other organisations in your geographic area that are planning to remove solar panels or hot water systems in the next five years? If so, can you tell us who? *(This information will not be shared outside the research team.)*

10. Are you able to estimate how much it currently costs to remove and dispose of a solar panel in your geographic area? If so, are you able to share these figures with us?

11. Have you noticed any particular trends around solar panel usage in your geographic area over the last five years? *(e.g. more businesses or govt buildings with panels, or just generally more or less panels, no real changes/steady, reached saturation point)*

12. What do you see as the major challenges associated with dealing with solar panel waste in your geographic area and/or NT and/or Australia more broadly?

13. What are your organisation's preferred options/solutions/ideas for the future management of old panels?

14. What are your organisation's current policies and activities in relation to recycling and renewables? What do you see as the major challenges and barriers associated with this, both now (currently) and in the future?

15. Finally, is there anything else like you'd like to say regarding recycling, renewables and end-of-life planning for solar panel waste?

16. Would you like to be kept informed of the progress/results of the research? If so, please provide your preferred contact details.

Appendix 4: Detailed data for LGAs and overlapping postcode areas

CENTRAL AUSTRALIAN REGION

Table A4.1 Total weight (tonnes) of solar PV panels reaching EOL to 2050, by LGA and overlapping postcodes, Central Australian Region

LGA	Panel end span (year)									
	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Alice Springs	0.00	0.13	1.24	7.53	17.97	28.12	28.23	90.89	469.17	369.41
Barkly	0.00	0.06	0.28	1.24	2.79	4.28	8.52	15.02	63.56	71.97
Central Desert	0.02	0.10	0.28	1.01	2.06	4.99	9.02	7.09	53.44	56.47
MacDonnell	0.01	0.34	0.82	3.01	4.36	8.59	32.65	13.40	136.32	79.63
Postcode 0872	0.00	0.08	0.33	1.00	1.88	2.31	9.08	16.89	30.78	45.78
Alice Springs/MacDonnell	0.00	0.00	0.00	0.08	0.41	0.82	0.98	0.00	7.62	22.84

Table A4.2 Estimated distribution of panel types by weight (tonnes), by LGA and overlapping postcodes, Central Australian Region

LGA	Panel type		
	c-Si	CdTe	CIGS
Alice Springs	962.75	30.00	20.00
Barkly	161.16	3.93	2.62
Central Desert	133.37	0.67	0.45
MacDonnell	276.90	1.34	3.96
Postcode 0872	102.00	3.68	2.45
Alice Springs/MacDonnell	30.97	1.07	0.71

Table A4.3 Estimated compositional breakdown of materials by weight (tonnes), all panels, by LGA and overlapping postcodes, Central Australian Region

(Based on compositional data from IRENA 2016 & PV Cycle 2007)

LGA	Material												
	Glass	Al	Si	Polymers	Zinc	Ag	Cu	In	Ga	Se	Pb	Cd	Te
Alice Springs	758.535	97.694	28.883	64.429	1.174	0.077	6.079	0.056	0.002	0.104	1.002	0.021	0.021
Barkly	125.302	16.300	4.835	10.718	0.194	0.010	1.007	0.007	0.000	0.014	0.164	0.003	0.003
Central Desert	99.720	13.368	4.001	8.710	0.160	0.008	0.807	0.001	0.000	0.002	0.134	0.000	0.000
Mac-Donnell	206.970	27.753	8.307	18.081	0.332	0.017	1.675	0.003	0.000	0.005	0.278	0.001	0.001
Postcode 0872	81.131	10.372	3.060	6.857	0.123	0.006	0.649	0.007	0.000	0.013	0.105	0.003	0.003
Alice Springs/ MacDonnell	24557.175	3146.995	929.140	2078.885	37.272	1.965	196.561	1.990	0.071	3.696	31.789	0.746	0.746

Table A4.4 Estimated net recoverable materials by weight (tonnes), all panels, by LGA and overlapping postcodes, Central Australian Region

(Based on compositional data from IRENA 2016 & PV Cycle 2007 with Sica et al (2018) recovery rates)

LGA	Material									
	Glass	Al	Si	Zinc	Cu	In	Ga	Se	Cd	Te
Alice Springs	729.3078	97.32307	24.45716	1.052632	4.723156	0.04182	0.001971	0.082843	0.020492	0.016728
Barkly	120.3965	16.14849	4.071577	0.172793	0.777732	0.005434	0.000256	0.010765	0.002663	0.002174
Central Desert	95.70663	13.23072	3.36623	0.142627	0.62281	0.000893	4.21E-05	0.001769	0.000437	0.000357
MacDonnell	197.7451	27.34307	6.957237	0.294775	1.286896	0.00179	8.44E-05	0.003546	0.000877	0.000716
Postcode 0872	77.66863	10.23706	2.567214	0.109055	0.499627	0.005076	0.000239	0.010055	0.002487	0.00203
Alice Springs/ MacDonnell	23.76092	3.139113	0.78779	0.033461	0.152934	0.001489	7.02E-05	0.00295	0.00073	0.000596

Note: Silver (Ag) and Lead (Pb) are not shown here as Sica et al (2018) do not provide recovery rates for these elements.

Table A4.5 Projected yield of silver by weight (kg), c-Si panels, by LGA and overlapping postcodes, Central Australian Region

LGA	End Span						
	'Lost volume (to 2020)	2025	2030	2035	2040	2045	2050
Alice Springs	9.557	12.505	10.843	29.440	164.696	212.448	79.285
Barkly	2.031	1.919	1.523	12.049	26.901	28.187	14.459
Central Desert	1.694	1.135	1.178	14.330	12.703	22.236	10.312
MacDonnell	6.086	2.225	2.385	64.034	24.012	49.353	12.187
Postcode 0872	2.25	1.697	0.790	15.430	30.264	13.458	9.822
Alice Springs/MacDonnell	0.036	0.124	0.249	0.211	0.000	3.331	4.900

Table A4.6 Estimated hazardous materials by weight (tonnes), all panels, by LGA and overlapping postcodes, Central Australian Region

(Based on compositional data from IRENA 2016 & PV Cycle 2007)

LGA	Material			
	Total Pb	Total Cd	Total Te	Total Hazardous materials
Alice Springs	1.002	0.021	0.021	1.044
Barkly	0.164	0.003	0.003	0.17
Central Desert	0.134	0.000	0.000	0.134
MacDonnell	0.278	0.001	0.001	0.28
Postcode 0872	0.105	0.003	0.003	0.111
Alice Springs/MacDonnell	31.789	0.746	0.746	33.281

BIG RIVERS REGION

Table A4.7 Total weight (tonnes) of solar PV modules reaching EOL to 2050, by LGA and overlapping postcodes, Big Rivers Region

LGA	Panel end span (year)									
	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Coomalie	0.000	0.010	0.049	0.263	0.751	1.262	2.085	2.790	15.373	27.937
Katherine	0.000	0.000	0.027	0.165	0.396	0.574	0.265	2.539	10.267	6.166
Postcode 0850	0.000	0.044	0.137	1.749	4.266	8.142	8.570	4.529	137.259	104.104
Postcode 0852	0.000	0.053	0.221	0.562	1.133	1.354	6.699	10.611	11.216	40.511
Roper Gulf	0.000	0.236	0.588	1.240	1.170	1.403	24.220	10.888	5.892	53.447
Victoria-Daly	0.006	0.046	0.091	0.492	1.364	3.320	5.648	0.000	33.499	59.892
West-Daly	0.000	0.000	0.026	0.052	0.105	0.000	0.000	2.433	0.000	0.000

Table A4.8 Estimated distribution of panel types by weight (tonnes), by LGA and overlapping postcodes, Big Rivers Region

LGA	Panel type		
	c-Si	CdTe	CIGS
Coomalie	47.75	1.67	1.11
Katherine	19.28	0.67	0.45
Postcode 0850	254.34	8.68	5.79
Postcode 0852	68.52	2.48	1.66
Roper Gulf	97.24	1.10	0.73
Victoria-Daly	103.42	0.56	0.37
West-Daly	2.44	0.11	0.07

Table A4.9 Estimated compositional breakdown of materials by weight (tonnes), all panels, by LGA and overlapping postcodes, Big Rivers Region

(Based on compositional data from IRENA 2016 & PV Cycle 2007)

LGA	Material												
	Glass	Al	Si	Polymers	Zinc	Ag	Cu	In	Ga	Se	Pb	Cd	Te
Coomalie	37.8962	4.8532	1.4326	3.2067	0.0575	0.0030	0.3033	0.0031	0.0001	0.0058	0.0490	0.0012	0.0012
Katherine	15.3031	1.9595	0.5784	1.2947	0.0232	0.0012	0.1225	0.0013	0.0000	0.0023	0.0198	0.0005	0.0005
Postcode 0850	201.5470	25.8397	7.6301	17.0672	0.3061	0.0161	1.6134	0.0162	0.0006	0.0301	0.2610	0.0061	0.0061
Postcode 0852	54.5167	6.9677	2.0555	4.6066	0.0825	0.0044	0.4361	0.0046	0.0002	0.0086	0.0704	0.0017	0.0017
Roper Gulf	73.6449	9.7755	2.9173	11.3884	0.1168	0.0059	0.5945	0.0020	0.0001	0.0038	0.0981	0.0008	0.0008
Victoria-Daly	77.3974	10.3687	3.1027	6.7572	0.1242	0.0063	0.6262	0.0010	0.0000	0.0018	0.1039	0.0004	0.0004
West-Daly	1.9679	0.2490	0.0732	0.1652	0.0029	0.0002	0.0157	0.0002	0.0000	0.0002	0.0025	0.0001	0.0001

Table A4.10 Estimated net recoverable materials by weight (tonnes), all panels, by LGA and overlapping postcodes, Big Rivers Region

(Based on compositional data from IRENA 2016 & PV Cycle 2007 with Sica et al (2018) recovery rates)

LGA	Material									
	Glass	Al	Si	Zinc	Cu	In	Ga	Se	Cd	Te
Coomalie	36.52477	4.822371	1.209984	0.051395	0.235052	0.002315	0.000109	0.004586	0.001134	0.000926
Katherine	14.70381	1.941038	0.487003	0.020686	0.094622	0.000935	4.41E-05	0.001852	0.000458	0.000374
Postcode 0850	194.0965	25.65436	6.439121	0.273491	1.249415	0.012061	0.000569	0.023893	0.00591	0.004825
Postcode 0852	52.27158	6.887821	1.727163	0.073371	0.336232	0.003432	0.000162	0.006798	0.001682	0.001373
Roper Gulf	69.94078	9.574474	2.428942	0.102968	0.454045	0.001473	6.94E-05	0.002918	0.000722	0.000589
Victoria-Daly	74.61492	10.30682	2.621708	0.111086	0.485461	0.000767	3.61E-05	0.001435	0.000376	0.000307
West-Daly	1.851574	0.241564	0.060384	0.002567	0.011882	0.000143	6.72E-06	0.000152	6.99E-05	5.7E-05

Note: Silver (Ag) and Lead (Pb) are not shown here as Sica et al (2018) do not provide recovery rates for these elements.

Table A4.11 Projected yield of silver by weight (kg), c-Si panels, by LGA and overlapping postcodes, Big Rivers Region

LGA	End Span						
	'Lost volumes' (to 2020)	2025	2030	2035	2040	2045	2050
Coomalie	0.374	0.424	0.418	2.125	5.006	6.725	5.993
Katherine	0.195	0.307	0.222	0.057	4.558	4.491	1.322
Postcode 0850	1.557	1.881	3.063	9.585	8.120	60.038	22.336
Postcode 0852	1.452	1.017	0.399	10.838	19.005	4.904	8.750
Roper Gulf	4.262	1.000	0.322	48.316	19.503	2.576	9.817
Victoria-Daly	0.651	0.466	0.932	7.030	0.000	15.212	12.898
West-Daly	0.021	0.027	0.000	0.000	0.635	0.000	0.000

Table A4.12 Estimated hazardous materials by weight (tonnes), all panels, by LGA and overlapping postcodes, Big Rivers Region

(Based on compositional data from IRENA 2016 & PV Cycle 2007)

LGA	Material			
	Total Pb	Total Cd	Total Te	Total Hazardous materials
Coomalie	0.0490	0.0012	0.0012	0.0514
Katherine	0.0198	0.0005	0.0005	0.0208
Postcode 0850	0.2610	0.0061	0.0061	0.2732
Postcode 0852	0.0704	0.0017	0.0017	0.0738
Roper Gulf	0.0981	0.0008	0.0008	0.0997
Victoria-Daly	0.1039	0.0004	0.0004	0.1047
West-Daly	0.0025	0.0001	0.0001	0.0027

NORTHERN REGION – Remote Northern

Table A4.13 Total weight (tonnes) of solar PV modules reaching EOL to 2050, by LGA and overlapping postcodes, Remote Northern region

LGA	Panel end span (year)									
	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
East Arnhem	0.000	0.135	0.434	1.103	1.315	1.319	13.335	15.253	21.767	17.791
Tiwi Islands	0.005	0.015	0.030	0.493	0.000	0.000	0.473	0.000	0.000	0.000
West Arnhem	0.006	0.019	0.242	1.061	0.924	0.216	0.727	18.978	3.436	3.162
Postcode 0822	0.000	0.050	0.273	1.410	5.289	9.187	16.068	16.182	80.315	266.557

Table A4.14 Estimated distribution of panel types by weight (tonnes), by LGA and overlapping postcodes, Remote Northern Region

LGA	Panel type		
	c-Si	CdTe	CIGS
East Arnhem	251.98	2.53	1.69
Tiwi Islands	90.39	0.04	0.03
West Arnhem	164.37	1.10	0.73
Postcode 0822	373.60	13.04	8.69

Table A4.15 Estimated compositional breakdown of materials by weight (tonnes), all panels, by LGA and overlapping postcodes, Remote Northern Region

(Based on compositional data from IRENA 2016 & PV Cycle 2007)

LGA	Material												
	Glass	Al	Si	Polymers	Zinc	Ag	Cu	In	Ga	Se	Pb	Cd	Te
East Arnhem	190.3576	25.3164	7.5594	16.5349	0.3026	0.0154	1.5374	0.0047	0.0002	0.0088	0.2539	0.0018	0.0018
Tiwi Islands	66.9493	9.0410	2.7118	5.8779	0.1085	0.0054	0.5427	0.0001	0.0000	0.0001	0.0904	0.0000	0.0000
West Arnhem	123.6861	16.5382	4.9461	10.7840	0.1980	0.0100	1.0002	0.0020	0.0001	0.0038	0.1657	0.0008	0.0008
Postcode 0822	296.5012	37.9697	11.2080	25.0881	0.4496	0.0237	2.3729	0.0243	0.0009	0.0452	0.3836	0.0091	0.0091

Table A4.16 Estimated net recoverable materials by weight (tonnes), all panels, by LGA and overlapping postcodes, Remote Northern Region

(Based on compositional data from IRENA 2016 & PV Cycle 2007 with Sica et al (2018) recovery rates)

LGA	Material									
	Glass	Al	Si	Zinc	Cu	In	Ga	Se	Cd	Te
East Arnhem	183.4282	25.15676	6.385514	0.270668	1.191327	0.003459	0.000163	0.006851	0.001695	0.001383
Tiwi Islands	64.88899	9.034236	2.303304	0.097555	0.423004	5E-05	2.36E-06	9.9E-05	2.45E-05	2E-05
West Arnhem	119.4372	16.46785	4.186589	0.17741	0.776732	0.001492	7.04E-05	0.002956	0.000731	0.000597
Postcode 0822	286.3446	37.80383	9.485199	0.402894	1.842721	0.01817	0.000857	0.035994	0.008903	0.007268

Note: Silver (Ag) and Lead (Pb) are not shown here as Sica et al (2018) do not provide recovery rates for these elements.

Table A4.17 Projected yield of silver by weight (kg), c-Si panels, by LGA and overlapping postcodes, Remote Northern Region

LGA	End Span						
	'Lost volumes' (to 2020)	2025	2030	2035	2040	2045	2050
East Arnhem	2.979	1.726	1.101	27.879	27.325	9.519	32.144
Tiwi Islands	0.075	0.143	0.286	1.567	0.000	0.000	13.280
West Arnhem	1.206	1.737	0.550	2.215	34.001	1.502	22.553
Postcode 0822	2.044	2.617	2.741	12.174	28.994	35.129	57.191

Table A4.18 Estimated hazardous materials by weight (tonnes), all panels, by LGA and overlapping postcodes, Remote Northern Region

(Based on compositional data from IRENA 2016 & PV Cycle 2007)

LGA	Material			
	Total Pb	Total Cd	Total Te	Total Hazardous materials
East Arnhem	0.2539	0.0018	0.0018	0.2575
Tiwi Islands	0.0904	0.0000	0.0000	0.0904
West Arnhem	0.1657	0.0008	0.0008	0.1673
Postcode 0822	0.3836	0.0091	0.0091	0.4018

NORTHERN REGION – Greater Darwin Region

Table A4.19 Total weight (tonnes) of solar PV modules reaching EOL to 2050, by LGA and overlapping postcodes, Greater Darwin Region

LGA	Panel end span (year)									
	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Darwin	0.000	0.008	0.498	7.413	31.460	59.061	67.509	44.854	596.818	1552.719
Palmerston	0.000	0.023	0.251	3.018	13.679	25.718	33.432	19.065	234.044	727.781
Litchfield/Dundee Beach	0.000	0.019	0.220	2.990	10.518	19.580	20.536	16.917	237.159	436.151
Postcode 0829	0.000	0.000	0.001	0.016	0.324	0.637	1.164	0.112	1.283	27.072
Postcode 0840	0.000	0.000	0.007	0.088	0.361	0.667	0.744	0.642	6.854	17.289
Wagait	0.000	0.000	0.000	0.005	0.013	0.026	0.015	0.000	0.428	0.353
Unincorporated (Top End)	0.000	0.000	0.000	0.015	0.031	0.061	0.000	0.000	1.424	0.000

Table A4.20 Estimated distribution of panel types by weight (tonnes), by LGA and overlapping postcodes, Greater Darwin Region

LGA	Panel type		
	c-Si	CdTe	CIGS
Darwin	2259.51	60.51	40.34
Palmerston	1000.58	33.86	22.57
Litchfield/Dundee Beach	704.59	23.70	15.80
Postcode 0829	28.93	1.01	0.67
Postcode 0840	25.19	0.87	0.58
Wagait	0.80	0.03	0.02
Unincorporated (Top End)	1.45	0.05	0.03

Table A4.21 Estimated compositional breakdown of materials by weight (tonnes), all panels, by LGA and overlapping postcodes, Greater Darwin Region

(Based on compositional data from IRENA 2016 & PV Cycle 2007)

LGA	Material												
	Glass	Al	Si	Polymers	Zinc	Ag	Cu	In	Ga	Se	Pb	Cd	Te
Darwin	1765.012	228.780	67.785	150.212	2.710	0.142	14.130	0.113	0.004	0.210	2.306	0.042	0.042
Palmerston	792.455	101.641	30.017	67.126	1.204	0.063	6.344	0.063	0.002	0.117	1.027	0.024	0.024
Litchfield/ Dundee Beach	557.820	71.567	21.138	47.260	0.848	0.045	4.466	0.044	0.002	0.082	0.723	0.017	0.017
Postcode 0829	22.955	2.940	0.868	1.942	0.035	0.002	0.184	0.002	0.000	0.003	0.030	0.001	0.001
Postcode 0840	19.979	2.560	0.756	1.691	0.030	0.002	0.160	0.002	0.000	0.003	0.026	0.001	0.001
Wagait	0.631	0.081	0.024	0.053	0.001	0.000	0.005	0.000	0.000	0.000	0.001	0.000	0.000
Unincorporated (Top End)	1.147	0.147	0.044	0.097	0.002	0.000	0.009	0.000	0.000	0.000	0.001	0.000	0.000

Table A4.22 Estimated net recoverable materials by weight (tonnes), all panels, by LGA and overlapping postcodes, Greater Darwin Region

(Based on compositional data from IRENA 2016 & PV Cycle 2007 with Sica et al (2018) recovery rates)

LGA	Material									
	Glass	Al	Si	Zinc	Cu	In	Ga	Se	Cd	Te
Darwin	1706.31	228.016	57.42524	2.431125	10.98466	0.084387	0.003978	0.167166	0.04135	0.033755
Palmerston	766.2866	101.3254	25.43553	1.080307	4.933145	0.047245	0.002227	0.09359	0.02315	0.018898
Litchfield/ Dundee Beach	538.7376	71.25643	17.88891	0.759772	3.468474	0.033045	0.001558	0.06546	0.016192	0.013218
Postcode 0829	22.25356	2.938257	0.737249	0.031315	0.143212	0.00141	6.65E-05	0.002792	0.000691	0.000564
Postcode 0840	19.31134	2.550687	0.640073	0.027187	0.124288	0.001215	5.73E-05	0.002407	0.000595	0.000486
Wagait	0.608667	0.080475	0.020201	0.000858	0.003918	3.76E-05	1.77E-06	7.45E-05	1.84E-05	1.5E-05
Unincorporated (Top End)	1.101802	0.145852	0.036625	0.001555	0.007095	6.65E-05	3.14E-06	0.000132	3.26E-05	2.66E-05

Note: Silver (Ag) and Lead (Pb) are not shown here as Sica et al (2018) do not provide recovery rates for these elements.

Table A4.22 Projected yield of silver by weight (kg), c-Si panels, by LGA and overlapping postcodes, Greater Darwin Region

LGA	End Span						
	'Lost volumes' (to 2020)	2025	2030	2035	2040	2045	2050
Darwin	5.585	12.837	18.762	16.020	80.357	267.718	336.997
Palmerston	2.54	5.352	7.766	11.210	34.150	102.376	156.383
Litchfield/Dundee Beach	2.378	4.549	6.491	7.761	30.314	104.133	93.578
Postcode 0829	0.012	0.083	0.149	0.250	0.199	0.560	5.808
Postcode 0840	0.069	0.154	0.209	0.160	1.146	2.996	3.709
Wagait	0.002	0.005	0.010	0.003	0.000	0.186	0.074
Unincorporated (Top End)	0.003	0.006	0.012	0.000	0.000	0.290	0.000

Table A4.23 Estimated hazardous materials by weight (tonnes), all panels, by LGA and overlapping postcodes, Greater Darwin Region

(Based on compositional data from IRENA 2016 & PV Cycle 2007)

LGA	Material			
	Total Pb	Total Cd	Total Te	Total Hazardous materials
Darwin	2.306	0.042	0.042	2.39
Palmerston	1.027	0.024	0.024	1.075
Litchfield/Dundee Beach	0.723	0.017	0.017	0.757
Postcode 0829	0.030	0.001	0.001	0.032
Postcode 0840	0.026	0.001	0.001	0.028
Wagait	0.001	0.000	0.000	0.001
Unincorporated (Top End)	0.001	0.000	0.000	0.001

Appendix 5: Commodity prices used in calculating upper limit economic returns from materials recovery

Commodity	Price $AUD	Rate	Date	Source
Aluminium	2589	Per tonne	Dec 2019	https://www.lme.com/en-GB/Metals/Non-ferrous/Aluminium#tabIndex=0
Copper	8,512.58	Per tonne	Dec 2019	https://www.lme.com/Metals/Non-ferrous/Copper#tabIndex=0
Silver	24.64	Per troy ounce (spot price)	Dec 2019	https://www.lme.com/Metals/Precious-metals/LME-Silver#tabIndex=0
Zinc (LME)	3,298.02	Per metric ton (official cash ask)	Dec 2019	https://www.fastmarkets.com/commodities/exchange-data/lme-base-metal-prices-and-charts
Silicon metal	2.01	Per lb	2018	https://www.usgs.gov/centers/nmic/silicon-statistics-and-information
Glass (cullet)	100-149	Per tonne delivered	2014	Sustainability Victoria 2013-14. Market Summary – recycled glass *https://www.sustainability.vic.gov.au › Recycled-materials-in-pavement*
Indium	447.33	Per kg	Dec 2019	https://www.kitco.com/strategic-metals/ - Indium
Gallium	415.17	Per kg	Dec 2019	https://www.kitco.com/strategic-metals/ - Gallium
Selenium	29.23	Per lb	2018	https://www.usgs.gov/centers/nmic/selenium-and-tellurium-statistics-and-information
Molybdenum	15.50	Per lb	Feb 2020	https://www.lme.com/en-GB/Metals/Minor-metals/Molybdenum-Platts#tabIndex=0
Tin (LME)	24,223.51	Per tonne	Feb 2020	https://www.bloomberg.com/markets/commodities/futures/metals
Tellurium	119.87	Per kg	Oct 2018	https://prd-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/atoms/files/mcs-2019-tellu.pdf
Cadmium	4.23	Per kg	2018	https://www.statista.com/statistics/598234/cadmium-price-average-in-the-united-states/

LME prices are all cash as at 4th Dec 2019 except where otherwise noted. US prices converted to $AUS at the rate of 1USD = 1.46189AUD (XE currency converter rate as at 5th Dec 2019).