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Decommissioning and Recycling of End-of-Life Photovoltaic Solar Panels in Western Australia

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Abstract: Academics predict that a significant volume of end-of-life (EOL) photovoltaic (PV) solar panel waste will be generated in the coming years due to the significant rise in the production and use of PV solar panels since the late 20th Century. This study focuses on identifying a sustainable solution for the management of EOL PV solar panel waste by triangulating the information collected on areas such as the current state, the key barriers, and the key enablers with respect to managing EOL PV solar panel waste, specifically in Western Australia (WA). The data were collected using online survey questions and interviews with users of PV solar panels, sellers of PV solar panels, recyclers of PV solar panels, and local governments in Western Australia. Findings reveal that although there is a low generation of PV solar panel waste at present, it is concerning that WA lacks systems and infrastructure to manage this waste. Introducing and implementing an Extended Producer Responsibility (EPR) policy, banning EOL PV solar panels from landfills, and, finally, increasing financial investment in this study area through grants, subsidies, and loans could be a sustainable solution for the management of EOL PV solar panel waste in WA.

Keywords: photovoltaic; decommissioning; recycling; Western Australia; solar panel; end of life

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1. Introduction

After the discovery of the PV effect by Alexandre Edmond Becquerel in the late thirties of the 19th Century, the first silicon monocrystalline solar cells were developed after a century in 1941 [1]. Three and a half decades after the introduction of silicon monocrystalline solar cells, the global capacity to produce renewable solar energy reached 500 Kilowatts (KW) [1]. Similarly, in 2017, the capacity increased to 400 Gigawatts (GW) [2], and it is expected to increase to 4500 GW by the end of 2050 [2]. We can observe that the increase in the use of PV solar panels has led to an increase in global capacity to produce renewable energy. This has helped us reduce our carbon emissions from using fossil fuels, to some extent. According to IEA [3], 1 GW of PV solar energy reduces 1.4 million tons (MT) of CO_2 emissions each year compared to coal-powered electricity.

However, global PV solar panel waste is anticipated to reach 1.7 MT to 8 MT before 2030, and it is anticipated to reach 60 MT to 78 MT before 2050 [2,4]. Similarly, according to RystadEnergy [5], the material recovered from EOL PV solar panel waste will be worth $2.7 billion by the year 2030, and it will be worth $80 billion by the year 2050. As of 2018, 1.95 million PV solar panels have been deployed in Australia [6]. Based on the quantity of PV solar panels deployed between 2001 and 2018, it is predicted that 817,941 tons of EOL PV solar panel waste will be generated before 2047 in Australia [6,7].

Similarly, Australia's total amount of EOL PV solar panel waste is expected to increase by 1700% between 2019 and 2030 [8]. If true, Australia will generate around 1 MT to 8 MT of EOL PV solar panel waste before 2060 [9]. Accordingly, the recovered materials from this waste stream will be worth close to $1.2 billion in Australia [9]. Therefore, this suggests that a significant volume of EOL PV solar panel waste will be generated in the coming

years due to the significant rise in the production and use of PV solar panels since the late 20th Century [7,10].

In WA, 392,572 houses out of 1,070,962 houses had PV solar panels installed, as per the 2016 Australian Census [11]. Now, as of 2023, a total of 483,885 PV solar panel units have been installed [12]. Similarly, an estimated 39.4% of dwellings in WA have PV solar panels installed [13]. It is estimated that WA generates 2812 MW of electricity from PV solar panels [13]. However, most of the damaged or outdated solar panels are currently disposed of in landfills, and experts have long warned that, by 2035, more than 100,000 tons of modules will be sent to landfills [14].

As any other product, PV solar panels also have an average usage life. Islam et al. [6] claim that a photovoltaic solar panel average usage life is between 20 to 30 years. Also, Xu et al. [10] explain that, as the photovoltaic solar panel is a new technology with a long average usage life, during the first 25 years of its development phase, the recycling of waste solar panel was not a major concern.

In several major PV installation nations, such as China, the United States, Brazil, Germany, the United Kingdom, Thailand, Japan, India, Italy, and Finland, EOL PV management is still in its infancy and has not received much attention [15]. In 2019, more than one-third of the installed solar PV capacity worldwide was located in China [15]. The National Solid Waste Law of China sets out requirements for the classification, collection, transportation, disposal, and recycling of solid waste, but does not explicitly address EOL PV solar panel waste [16]. This indicates that the EOL PV solar panel waste in China is currently being managed under the category of solid waste.

In the United States of America (USA), a federal statute known as the Resource Conservation and Recovery Act (RCRA) was passed in 1976 to govern the management and disposal of solid and hazardous waste [16]. The RCRA was later amended to include hazardous waste from EOL PV solar panels, although it did not explicitly address EOL PV solar panel waste management [16]. Both nations have set rules and regulations for the handling of EOL PV solar panel waste, but there are still a number of issues that need to be resolved, such as the lack of technology and expertise among recyclers, the lack of financial incentives to encourage recycling, and the necessity for more affordable and ecologically friendly EOL PV solar panel recycling and disposal options [16].

However, countries such as Germany, Italy, and Finland, which are member states of the EU, have been held accountable for the collection, transport, and treatment of EOL PV solar panels since 14 February 2014 as per the revised WEEE Directive, which provides the framework for the management of EOL PV solar panels under the extended producer responsibility (EPR) scheme [6]. Therefore, in comparison, Australia, China, and the USA do not have any clear regulations to manage EOL solar PV waste [6].

The provincial differences in EOL PV solar panel waste treatment costs, capacities, or investment decisions of waste treatment facilities are not emphasized in China's national-level waste management plans or policies, which could lead to policy failure or ineffectiveness, as well as to local environmental problems such as illegal landfills [15]. Similarly, different states in the USA have different legislation and norms, rendering it challenging to ensure EOL PV solar panel waste management techniques are standardized and consistent across the country [16]. Likewise, there is no national-level plan for the management of EOL solar PV waste in Australia [6].

Now, compared to any other waste stream, photovoltaic solar panel waste also has the potential to create environmental, economic, and social issues if they are not managed properly in time. Also, as the Dutch philosopher Desiderius Erasmus said, "Prevention is better than cure" [17]. Hence, we need to prevent EOL PV solar panel waste from becoming a problem in the future. However, most recent research focuses on increasing the effectiveness of PV solar panel manufacturing processes, and there are currently very few studies relating to the dismantling and recycling of solar panels at their EOL, and the absence of solar panel recycling facilities globally supports this

claim [10]. Similarly, there are not many academic papers on the management of EOL PV solar panels in Australia [6].

According to Islam et al. [6], studies focusing on solar PV waste in the Australian context are authored by Mahmoudi et al. [9], who forecasted the amount of solar PV waste generation, by Salim et al. [18], who investigated the drivers of, barriers to, and enablers of EOL management of solar PV, and, again, by Mahmoudi et al. [19], who conducted a comprehensive evaluation of environmental impacts and economic feasibility assessment of the treatment of the discarded PV panel.

Referring to the direct quote above, only four academic papers are related to Australia, and no academic paper is relevant to Western Australia. Hence, more academic research is required in this area of study to prevent the issues that would arise from failure to prepare for the predicted bulk of EOL PV solar panel waste disposal in the near future. This study is the first academic research paper considering the decommissioning and recycling of EOL PV solar panels in Western Australia. This study aims to find sustainable solutions to the decommissioning and recycling of EOL PV solar panel waste in Western Australia (WA) to answer the broader research question of how EOL PV solar panel waste can be managed sustainably in WA.

2. Materials and Methods

This research study was guided by the applied research approach. As this study aims to find sustainable solutions for the decommissioning and recycling of EOL PV solar panel waste in WA, an applied research approach was deemed an ideal guiding framework since there are no previous studies in the context of WA in this area of study. Kumar [20] explains that information collected through applied research is used to increase knowledge, forecast future trends, formulate policies, and implement policies. Similarly, the findings from this study will help policy formation, administration, and knowledge building.

The four main questions that this study explored are as follows. Question No. 1: what is the current state of EOL PV solar panels decommissioning and recycling practices in WA? Question No. 2: what are the key barriers to decommissioning and recycling EOL PV solar panels in WA? Question No. 3: what are the key factors that could enable the decommissioning and recycling of EOL PV solar panels in WA? Question No. 4: what could be a sustainable solution proposal for the decommissioning and recycling of EOL PV solar panels in WA?

This study used a mixed methods approach by considering both qualitative and quantitative research procedures. A few disciplines primarily apply qualitative or quantitative research methodology [20]. However, there are some areas where it is necessary to integrate and use both qualitative and quantitative research methodologies [20]. This strategy is referred to as the mixed-method approach [20]. To examine the diversity of a phenomenon or variation, the study should use a qualitative research methodology, commonly referred to as an unstructured approach to enquiry [20]. The current state of EOL PV solar panel management could vary from one recycling company to another recycling company, from one state to another state, and from one country to another country. Hence, in this study, a qualitative research methodology was used to determine the current state of EOL PV solar panel decommissioning and recycling in WA.

Similarly, a quantitative research methodology, usually referred to as a structured approach to investigation, is advised when attempting to quantify the scope of a problem or subject [20]. Different barriers affect EOL PV solar panel waste management to different extents, and different enabling factors promote EOL PV solar panel waste management to different extents. Hence, for the purpose of this study, a quantitative research methodology was deemed appropriate to identify the key barriers and enabling factors for EOL PV solar panel decommissioning and recycling in WA, and, since both techniques are essential for this study, a mixed-method approach was selected for this study.

An online survey questionnaire and an interview questionnaire were developed to collect data for this study. To get a specific insight into the issue, the questionnaire included

specific questions related to sellers of solar PV, users of solar PV, solar PV recyclers, and local governments.

The online survey questionnaire was distributed to participants using Curtin student access for the Qualtrics cloud-based software (version XM). A database list was created for existing users, sellers, recyclers, and local governments using Google. For sellers, recyclers, and local governments, their contact email addresses were collected and stored in the database. Then, an email recruitment letter for an interview was sent to the collected email addresses. Again, an email recruitment letter for an online survey was sent to those who did not respond to the email recruitment letter for an interview within 14 days of the recruitment email being sent.

For existing users, the addresses of 200 randomly selected houses from eight different suburbs within a 50 km radius of Perth CBD with solar panels visible on their roofs were collected and stored in the database. Then, a recruitment letter for an online survey was delivered to their addresses to collect the data.

The population of solar panel users consisted of individual houses with solar panels on their roofs that were located within 50 km of Perth Central Business District (CBD). The population of solar panel sellers consisted of businesses operating within 50 km of Perth CBD. The population of EOL PV solar panel recyclers consisted of businesses within WA. The population of local government representatives consisted of councils within 50 km of Perth CBD.

The sample of users of solar panels included 200 randomly selected houses from eight different suburbs within a 50 km radius of Perth CBD with solar panels visible on their roofs. The sample of sellers of solar panels included 46 randomly selected solar panel sellers operating within a 50 km radius of Perth CBD. The sample of recyclers of solar panels included 18 non-ferrous metal recycling centers, glass recycling centers, or Waste Electrical and Electronic Equipment (WEEE) recycling centers operating within a 50 km radius of Perth CBD; this also includes the only recycling company that claims to recycle EOL PV solar panel waste in WA. The sample of local government representatives included 32 councils operating within a 50 km radius of Perth CBD. Hence, the total sample size for this study was 296 stakeholders.

3. Data Analysis

3.1. Users of PV Solar Panels in WA

Among the 29 participants who filled out an online survey form, 18 participants were existing users of PV solar panels. This indicates that 62.07% of the respondents were users of PV solar panels in WA.

The following questions were asked to the users of PV solar panels to collect data for Research Question 1: what is the current state of EOL PV solar panel decommissioning and recycling practices in WA?

3.1.1. Question 1

When asked 'have you ever had a rooftop photovoltaic (PV) solar panel installed at your home or work?', 16 respondents answered that they had a rooftop photovoltaic (PV) solar panel installed at their home or work. This means that 94.12% of the respondents had a rooftop photovoltaic (PV) solar panel installed at their home or work. One respondent (5.88%) answered that they do not have a rooftop photovoltaic (PV) solar panel installed at their home or work.

3.1.2. Question 2

When asked how long it has been since they first installed PV solar panels at their residence/business, two of the respondents (12.50%) answered that it has been less than 1 year since they had PV solar panels installed at their residence/business.

Six of the respondents answered that it has been more than 1 year and less than 5 years since they had PV solar panels installed at their residence/business. This means that for

37.50% of the respondents it has been more than 1 year and less than 5 years since they had PV solar panels installed at their residence/business.

One of the respondents (6.25%) answered that it has been more than 5 years and less than 10 years since they had PV solar panels installed at their residence/business.

Seven of the respondents (43.75%) answered that it has been more than 10 years and less than 20 years since they had PV solar panels installed at their residence/business.

3.1.3. Question 3

When asked 'have you ever replaced your solar panels?', 13 respondents (86.67%) answered that they had not replaced their solar panels since they had installed them.

Two respondents (13.33%) answered that they had replaced their solar panels.

3.1.4. Question 4

When asked when they had last replaced their old PV solar panels, two respondents (100%) answered that they had replaced their old PV solar panels between 10–15 years following installation.

3.1.5. Question 5

When asked what the reason was for them to replace their existing PV solar panels, one respondent (50%) answered that they needed more energy/electricity, so they added new ones on top of the existing capacity. This indicates that the solar panels had not reached their EOL and were not actually replaced, but new PV solar panels were added to fulfil the increased energy/electricity requirement of the respondent.

One respondent (50%) answered that their solar panels were still working, but their energy generation capacity had reduced, so they decided to replace them with new solar panels.

3.1.6. Question 6

When asked how they disposed of the old PV solar panels, one respondent (50%) answered that the supplier of the new PV took it away at no extra cost to the respondent.

The other respondent (50%) answered that they gave them to someone who wanted to use them.

The following question was asked to the users of PV solar panels to collect data for Research Question 2: what are the key barriers to decommissioning and recycling EOL PV solar panels in WA?

3.1.7. Question 7

When the respondents who had replaced their solar panels were asked what barriers they had to overcome while disposing of their old PV solar panels, one of the respondents answered that they did not have to overcome any barrier while disposing of their EOL PV solar panels, as the installer of new panels removed them. Similarly, the other respondent also answered that they did not have to overcome any barrier while disposing of their EOL PV solar panels, as someone came along and asked to take them after they were removed from the roof.

The following question was asked to the users of PV solar panels to collect data for Research Question 3: what are the key factors that could enable the decommissioning and recycling of EOL PV solar panels in WA?

3.1.8. Question 8

When asked what they thought the factors that could enable the decommissioning and recycling of EOL PV solar panels could be in WA, one of the respondents answered "Scale to reduce cost vs. value of recovered materials" and the other respondent answered "A market for their reuse or recycling".

The following questions were asked to the users of PV solar panels to collect data for Research Question 4: how do we overcome barriers in optimizing resource recovery from EOL PV solar panels and promote a circular economy?

3.1.9. Question 9

When the respondents who had not yet disposed of their PV solar panels were asked how they planned on disposing of them when their EOL was reached, 12 out of 13 respondents gave the following answer, as shown in the Table 1 below. One respondent did not provide any answer.

Table 1. How do you plan on disposing of them?

When It Is Time for You to Dispose of Your Existing PV Solar Panels, How Do You Plan on Disposing of Them?
Respondent 1: I have regular yearly maintenance checks performed, no date for disposal has yet been identified.
Respondent 2: not thought about it as of yet.
Respondent 3: contact the electrician.
Respondent 4: not sure yet.
Respondent 5: haven't thought about it.
Respondent 6: hire someone to dispose of it.
Respondent 7: would only dispose of to upgrade system. Would require installer of new system to dispose of it responsibly.
Respondent 8: find a lower use application for them or recycle them.
Respondent 9: check where can dispose of . . . no idea.
Respondent 10: will replace them when possible to recycle them.
Respondent 11: recycling if possible.
Respondent 12: not sure.

3.2. Local Government in WA (Online Survey)

Among the 29 participants who filled out an online survey form, nine participants were representing local government in WA. This indicates that 31.03% of the respondents were representing local government in WA. However, it is important to note that only seven participants answered the online survey question, and two participants abandoned the online survey in the early stages. Since only seven participants completed the survey, the total number of participants for data collection and data analysis was seven for local government in WA.

The following questions were asked to the participants who were representing local government in WA to collect data for Research Question 1: what is the current state of EOL PV solar panels decommissioning and recycling practices in WA?

3.2.1. Question 1

When asked if the local government for which the respondent is working is taking responsibility for the management of the EOL PV solar panel waste in their LGA, seven respondents answered that they are not taking any responsibility for the management of the EOL PV solar panel waste in their LGA. This means that 100% of the local government councils participating in this study are currently not taking any responsibility for the management of the EOL PV solar panel waste in their LGA.

3.2.2. Question 2

When asked how they are currently managing their EOL PV solar panel waste in their LGA, three respondents (42.86%) answered that they send it to a third-party recycling

company within Australia. One respondent (14.29%) answered that they send it to a landfill. Three out of seven respondents gave the following answer, as shown in Table 2 below.

Table 2. How do you currently manage your EOL PV solar panel waste?

Local Government Response
Solar panel waste is not appearing in the municipal waste stream. Rather, it is collected and disposed of by PV system installers.
Resident's responsibility.
N/A.

The following questions were asked to the participants who were representing local government in WA to collect data for Research Question 2: what are the key barriers to decommissioning and recycling EOL PV solar panels in WA?

3.2.3. Question 3

When asked about what kind of key barriers they faced while decommissioning and recycling EOL PV solar panels in their LGA, all seven respondents (100%) skipped this question.

The following questions were asked to the participants who were representing local government in WA to collect data for Research Question 3: what are the key factors that could enable the decommissioning and recycling of EOL PV solar panels in WA?

3.2.4. Question 4

When asked what factors could enable the decommissioning and recycling of EOL PV solar panels in their LGA, one respondent (14.29%) answered that EOL PV solar panel decommissioning and recycling service demand needs to come from the local residents. Another respondent (14.29%) answered that the current waste management policy within the local government needs to be changed. Five out of seven respondents gave the following answer, as shown in Table 3 below.

Table 3. Factors that enable the decommissioning and recycling of EOL PV solar panels.

Local Government Response
We do not know of any business that is actively recycling PV systems in WA.
A low cost recycling option.
Free and local drop off for residents—then would be happy to promote.
Product stewardship, ensuring no cost to the LGA.
We are happy to support a collection for a third party decommissioning.

The following questions were asked to the participants who were representing local government in WA to collect data for Research Question 4: how do we overcome barriers in optimizing resource recovery from EOL PV solar panels and promote a circular economy?

3.2.5. Question 5

When asked if the local government for which the respondent is working has a plan to manage EOL PV solar panel waste in the future, seven respondents gave the following answer, as shown in Table 4 below.

Table 4. Does your local government plan to manage EOL PV solar panel waste in future?

Local Government Response
Not yet. The Federal Government is developing a product stewardship policy and released a discussion paper entitled 'Wired for change: Regulation for small Electrical Products and Solar Photovoltaic System Waste' a few months ago.
No.
No.
Not that I am aware of.
No.
No.
If there is a federal/state govt mandated product stewardship program, then we provide a drop off location for residents at our recycling centre, for the decommissioning company to collect them for processing.

3.3. Local Government in WA (Interview)

Out of 33 respondents for this study, four participants provided data through an interview. Two out of the four participants were working for the local government in WA. The results and findings from the interview are presented below.

The following questions were asked to the participants who were representing local government in WA to collect data for Research Question 1: what is the current state of EOL PV solar panels decommissioning and recycling practices in WA?

3.3.1. Question 1: Is Your Local Government Taking Responsibility for the Management of the End-of-Life (EOL) photovoltaic (PV) Solar Panel Wastes in Your Local Government Area (LGA)?

Interview participant 1 responded, "This isn't something that's come up yet for our own facilities. We haven't reached EOL for any of our PV solar systems as of yet, so we haven't come up to that point where we need to decide how we're going to sort of manage them at the EOL. That's not something that I believe was included as part of any of the contracts to get them put in. But in terms of a local government, we don't currently provide any additional comments to residents on how they can support EOL of solar panel recycling or what happens to it afterwards".

Interview participant 2 responded, "No, not at this stage, but it's something we'd like to get into".

3.3.2. Question 2: How Do You Currently Manage Your EOL PV Solar Panel Waste in Your LGA?

Interview participant 1 responded, "As it comes through, we take it because it's not included as a hazardous waste item as of yet, so if it's brought in on the back of the trailer, it just comes through, and it's processed and sent to landfill at the moment, unfortunately".

Interview participant 2 responded, "To be honest with you, I haven't heard of any coming to us unless it's been broken up, and the only thing that would happen if it does come through is it would go into the landfill".

The following questions were asked to the participants who were representing local government in WA to collect data for Research Question 2: what are the key barriers to decommissioning and recycling EOL PV solar panels in WA?

3.3.3. Question 3: What Are the Barriers to Resource Recovery from EOL PV Solar Panel Waste in Your Local Government Area?

Interview participant 1 responded, "Access to recyclers would be something for us. That's not within local governments capability to be a recycler of material". When asked the follow-up question, "So basically what you mean is like even if you guys want to recycle them, there are no recyclers who can recycle it, is it correct?". The Interview participant

1 responded, "Yeah, or at least limited to a monopoly from what I can see at the moment". Also, interview participant 1 added, "We've got other things that are more pressing to focus on first before we get to that stage. So it's on everyone's mind as the thing to do, but it hasn't got to that point yet".

Interview participant 2 responded, "So the barriers are probably going to be things like getting an understanding of how many end-of-life solar panels exist out there in the community so that we can kind of track some progression projection about you know how many are reaching their end of life now and how many are coming to reach the end of life in the next few years so that we can map and plan for that". Also, interview participant 2 added, "The biggest barrier is to get funding to actually be able to do something with the decommissioning of the panels and you know, dissecting all of the various elements".

The following questions were asked to the participants who were representing local government in WA to collect data for Research Question 3: what are the key factors that could enable the decommissioning and recycling of EOL PV solar panels in WA?

3.3.4. Question 4: What Could Be the Factors That Enable the Decommissioning and Recycling of EOL PV Solar Panels in Your Local Government Area?

Interview participant 1 responded, "Top one comes to mind would probably be costs involved". Also, interview participant 1 added, "Supporting recycling of solar panels through grant programs, I think would be important, but then again you need the drive from companies to sort of step up and take that role".

Interview participant 2 responded, "I think getting some surety around volumes is probably, you know, a big thing". Also, interview participant 2 added, "A positive factor to enable decommissioning is that we have a resource recovery site where we could do the work". Interview participant 2 also pointed out the following enabling factor, "understanding how best to deconstruct them and to keep the parts quarantined so that there wasn't contamination between the deconstruction process".

Additionally, interview participant 2 also added, "Extended producer responsibility is going to have to come into play, and it has to start with the manufacturer, and they're going to have to start to make the products that are easily disassembled, easy to repair and that there's a cost upfront when you purchase, it makes sure that the manufacturer takes that product back and disassembles it to remanufacture or repurpose it".

The following questions were asked to the participants who were representing local government in WA to collect data for Research Question 4: how do we overcome barriers in optimizing resource recovery from EOL PV solar panels and promote a circular economy?

3.3.5. Question 5: How Can the Local Government Participate or Contribute to Overcome Barriers in Optimizing Resource Recovery from the EOL PV Solar Panel Waste in WA?

Interview participant 1 responded, "I guess, our main point would be to help provide services and information around recovery of solar PV, particularly in promotion of our own research and the promotion of what we've done with our own solar PV, when we get to that point, I think is important".

Interview participant 2 responded, "I think one of the things could be to lobby state government, particularly the waste authority". Also, participant 2 added, "The government put funding up to the residents to put them on their roofs, and they have to come to the part now when it comes to disposal of these things in the future".

3.4. Recycler (Online Survey)

Among the 29 participants who filled out an online survey form, two participants were existing users of PV solar panels. This indicates that 6.90% of the respondents were recyclers in WA.

The following questions were asked to the participants who were representing recycling companies in WA.

3.4.1. Question 1

When asked if it is profitable to recycle EOL PV solar panels, one respondent (50%) answered that it might or might not be profitable, and one respondent (50%) answered that it probably is profitable to recycle EOL PV solar panels.

3.4.2. Question 2

When asked if there is an economic incentive for them to decommission and recycle EOL PV solar panels, one respondent (50%) somewhat agreed, and one respondent (50%) somewhat disagreed.

3.4.3. Question 3

When asked if they had ever received any grants or financial support from the government to decommission and recycle EOL PV solar panels, two respondents (100%) answered that they had never received any grants or financial support from the government to decommission and recycle EOL PV solar panels.

3.4.4. Question 4

When asked the above question, two respondents (100%) answered that they never received any communication or information from the producer of the PV solar panels on how to decommission and recycle their solar panels.

3.4.5. Question 5

One respondent (100%) answered that up to 20% of the EOL PV solar panels they receive are still in working condition. Please note: from this question onwards, only one respondent has taken part in the online survey.

3.4.6. Question 6

One respondent (100%) answered that they sometimes receive PV solar panels decommissioned before their design lifespan of 20 years.

3.4.7. Question 7

One respondent (100%) answered that up to 20% of the EOL PV solar panels received could be used as it is.

3.4.8. Question 8

One respondent (100%) answered that up to 20% of the EOL PV solar panels received could be refurbished and reused after minor maintenance/repair.

3.4.9. Question 9

One respondent (100%) answered that between 61% to 80% of the solar panels received need major maintenance/repair before they could be refurbished and reused.

3.4.10. Question 10

One respondent (100%) answered that between 41% to 60% of the solar panels received cannot be reused and needs to be recycled for resource recovery.

3.4.11. Question 11

All the respondents skipped this question without providing any data.

3.4.12. Question 12

One respondent (100%) answered that there is definitely no communication process in place to share knowledge, experience, and feedback with the producer of the PV solar panels.

3.4.13. Question 13

One respondent gave the following answer, as shown in Table 5 below.

Table 5. Are there any government regulations or policies that provide legal protocols?

Recycler
Not that we are aware of

3.5. Recycler (Interview)

Out of 33 respondents for this study, four participants provided data through an interview. One out of the four participants was working for an e-waste recycling company in WA. However, it is important to note that the questions were designed for the EOL PV solar panel recycling company, but due to the monopoly of the EOL PV solar panel recycling company in WA and their decision not to participate in this study, the researcher was left with no other choice but to interview an expert in an e-waste recycling company in WA to get insights into EOL PV solar panel recycling in WA. Hence, the questions were modified to suit the situation. The results and findings from the interview are presented below:

The following questions were asked to the participant who was representing an e-waste recycling company in WA.

3.5.1. Question 1: Do You Receive Solar Panels for Recycling in This Facility?

The interview participant answered, "Not at this facility, but we do receive them in the facility in Welshpool in WA and the facility in Dandenong in Victoria". The interview participant also added, "Ours is a general E-waste facility, so we will take computers, household electronics, televisions, basically anything that's electronic waste and solar panels is electronic waste, batteries as well. So, we take a whole range of different materials".

3.5.2. Question 2: How Many EOL PV Solar Panels Can This Recycling Facility Process per Year?

The interview participant answered, "Currently, we don't really have an advanced solar recycling solution, but we're in the process of putting one in and we got recently approved for a grant project, but that project's not confirmed yet".

3.5.3. Question 3: How Many EOL PV Solar Panels Are Received for Recycling per Year?

The interview participant answered, "So we don't get a large volume, there is a lot of it out there. Probably only like 5 tons a year". The interview participant also added, "We can't scale that up without significant investment in the infrastructure, which is why we put in the grant application. So, we have only really taken sample level, we've taken delivery of panels on numerous occasions and done manual dismantling of those panels to explore the sort of process development and concept development of the recycling process. So, we've done a study on it to figure out how much aluminium is there, what's the labor costs, and how much room you would need to run a facility. So, we've done that sort of initial testing but haven't moved it to a commercial scale yet".

3.6. Seller of PV Solar Panels (Online Survey)

Among the 29 participants who filled out an online survey form, 0 participants were sellers of PV solar panels.

3.7. Seller of PV Solar Panels (Interview)

Out of 33 respondents for this study, four participants provided data through an interview. One out of the four participants was working for a solar-panel-selling company in WA. The results and findings from the interview are presented below:

The following questions were asked to the participant who was representing a solar-panel-selling company in WA.

3.7.1. Question 1: Do You Offer a Service to Decommission and Recycle EOL PV Solar Panels to Your Customers?

The interview participant responded, "We advise on the decommissioning, but we do also offer our own services and decommissioning our own equipment. We tend not to offer services decommissioning other people's equipment because it's a bit of a minefield".

3.7.2. Question 2: If a Customer Buys a New PV Solar Panel System from You, Do You Decommission and Recycle the Old PV Solar Panel System Even If They Had Not Purchased the Old PV Solar System from Your Store?

The interview participant responded, "At times, we will do that, yeah".

3.7.3. Question 3: How Do You Currently Manage Your EOL PV Solar Panel Waste?

The interview participant responded, "Currently, a lot of stuff just goes to landfill". The participant also added, "Quite often, the person who we engaged to do the installation removes the old panels and install the new one and will recycle them themselves. In all honesty, it gets crushed up, and the problem is it costs to dispose of a solar panel, and it can be anything up to $20 to $25 to actually get someone to take a solar panel away and dispose of it there in terms of them disclosing how they dispose of that solar panel, they don't".

3.7.4. Question 4: Is the Cost of Decommissioning and Recycling Included in the Market Price That You Set for Your Products?

The interview participant responded, "No, it wouldn't. No, not really. We tend to have a margin built in to basically cover most contingencies, but in terms of recycling cost, that's very hard to predict because it can be incredibly volatile. It depends, what will happen is some place will have too much to recycle. So they say, yep, OK, it's no longer $20 a panel and we now want $45 or you know it's $35 whatever it is because they're just trying to keep you away".

3.7.5. Question 5: If the Cost of Decommissioning and Recycling Is Not Included in the Market Price of Your Product, Then Who Pays for This Service?

The interview participant responded, "Yeah. If we've got them here and we've brought them in, then we do. Yeah. Basically. So then it's up to us to find a way of actually recycling them most cost-effectively".

3.7.6. Question 6: What Are the Barriers to Recovering Resources from EOL PV Solar Panel Waste in Your Experience?

The interview participant responded, "Labor intensity. Labor intensive is the big one, basically, you won't, and no one place will take the whole solar panel and if one place does take whole solar panel, they charge you accordingly, because then they're gonna have to break it down to the glass to the cells, to the backing sheet and to the framework. So how desirable the framework would be would depend basically on what kind of metal it is made of, whether it's aluminium, corroding aluminium, aircraft aluminium, for example, or could be steel could be in a number of things, so and then you'll have different glass qualities as well. Some will be like almost like a Perspex and some will be thicker glass, and some just basic stronger glasses and things like that. The stronger the glass higher it costs to recycle it. Certain glass will have particular additives into it which will make it a nightmare for recycling. That's basically where it comes down. What it comes down".

3.7.7. Question 7: How Do You Recommend Overcoming Barriers to Recovering Resources from EOL PV Solar Panel Waste?

The interview participant responded, "I think they can, if they can produce panels that can be recycled easily, more easily, and materials that can be recycled more easily or come up with methods of recycling the existing materials themselves because they're aware of what they've used. But what we have in manufacturing, it's slowly changing. We have a tendency—I've produced this, I know how to produce. I don't know how to recycle

it". The interview participant also added, "Legislation through information rather than through lobbying".

3.7.8. Question 8: Is Your Team or Company Planning to Introduce this EOL PV Solar Panel Decommissioning and Recycling Service to Your Customers in Near Future?

The interview participant responded, "Probably yes. As a policy, I don't know, but it's the kind of thing you don't really have any choice in and specially in a position where we are as a responsible company".

3.7.9. Question 9: How Do You Plan to Roll out This Service to Your Customers?

The interview participant responded, "We probably would just announce it and then those existing customers who come to us, we would just tell them. We would ideally have a strategy in. And then yeah, like I said, just announce it through social media and web depending on how ground-breaking it was. If it was a truly ground-breaking program in the way it was done, then yeah, we'd pull out some of the contacts and go big media and all the rest of it through various government departments".

4. Results

The results and findings of this study are based on the information provided by 33 participants out of 296 stakeholders contacted for interviews or online surveys. As shown in Table 6 below, 29 out of 33 participants provided data through an online survey, and the remaining four provided data through interviews. Among the 29 participants who filled out an online survey form, 18 were existing users of PV solar panels, two were working in a recycling company, and nine were working in a local government. Among the four participants who provided data through the interview, two worked for local governments, one worked for an e-waste recycling company, and one worked for a PV solar panel seller.

Table 6. Online survey participants segmentation.

Stakeholder	No of Respondents	% of Respondents
Users	18	62.07%
Recyclers	2	6.90%
Sellers	0	0%
Local Government	9	31.03%
Total	29	100%

As shown in Table 7 below, among the four participants who provided data through the interview, two worked for local governments, one worked for an e-waste recycling company, and one worked for a PV solar panel seller.

Table 7. Interview participants segmentation.

Stakeholder	No of Respondents	% of Respondents
Users	0	0%
Recyclers	1	25%
Sellers	1	25%
Local Government	2	50%
Total	4	100%

4.1. The Current State of EOL PV Solar Panels Decommissioning and Recycling Practices in WA

Only 13.33% of the users of PV solar panels who participated in this study had replaced their existing solar panels. This indicates a low generation of PV waste at present. Also, the users had replaced their existing solar panels between 10–15 years after installation. This suggests a discrepancy between the theoretical design life and the actual use life of

PV solar panels. The users did not send the EOL PV to a recycling facility. Instead, the installer of new PV solar panels removed the old PV from the site. This indicates that the third-party companies that decommission the old PV solar panels and install new ones are the fifth stakeholders in this area of study. Another result/finding from this study reveals that the users of PV solar panels did not report any barriers to disposing of their EOL PV. This indicates the lack of awareness among the users of PV solar panels in WA.

The sellers of PV solar panels in WA revealed that they offer EOL PV solar panel decommissioning and recycling services to their customers but contract the task to a third party identified in this study as the installer of new PV solar panels. Furthermore, the low participation rate of the sellers in this study indicates a lack of interest among sellers in the area of decommissioning and recycling the EOL PV solar panels since it is not their core business.

Only one recycling company claims to recycle EOL PV solar panel waste to the Australian e-waste standard in WA. This reveals that there is a monopoly in the EOL PV solar panel recycling in WA. However, the only recycling company in WA did not participate in this study to share the resource recovery rates, technologies in use, and the processes they are using to recycle the EOL PV solar panel waste in WA. Also, this study identified that an existing e-waste recycling company in WA is in its early stages of testing the EOL PV solar recycling market. However, whether they will extend their business to cover EOL PV solar panels is not confirmed.

The entirety (100%) of the participants working in a local government in WA revealed that they are not taking any responsibility for managing EOL PV solar panels in their LGA. This suggests that local governments are unaware of the importance of their role in decommissioning and recycling EOL PV solar panel waste generated in their LGA. Similarly, 100% of the participants working in a local government in WA disclosed that they do not have any plans to manage EOL PV solar panel waste in their LGA in the near future. This indicates the lack of preparation within the local government in WA for the predicted bulk disposal of EOL PV solar panels in the near future.

4.2. The Key Barriers to Decommissioning and Recycling EOL PV Solar Panels in WA

The key barriers to managing EOL PV solar panels in WA identified through data collected from users of PV solar panels are as follows. The first barrier is that the new PV installers are currently taking responsibility for decommissioning the EOL PV solar panel and users are unaware of what they do with it. The second barrier is that 86.67% of the users have no idea what to do with the PV solar panels when they reach EOL.

The key barriers to managing EOL PV solar panels in WA identified through data collected from sellers of PV solar panels are as follows. The first barrier is that no government regulations or policies provide a legal protocol to guide the decommissioning and recycling of PV solar panels in WA. The second barrier is that decommissioning solar panels is labor-intensive and costly. The third barrier is that there is no communication between the sellers and the manufacturer. The fourth barrier is that the third-party contractor has a high degree of control in deciding how to deal with the EOL PV solar panels. The fifth barrier is that users of PV solar panels in WA have a "What's in it for me" attitude when it comes to decommissioning and recycling. The sixth barrier is that the sellers are aware that the EOL PV solar panels are ending up in the landfill, but they are not interested in acting on it. The seventh barrier is that there is a lack of transparency in relation to how sellers deal with EOL PV that ends up at their door. The eighth barrier is that there is a monopoly market in recycling EOL PV solar panels in WA; as a result, the recycling fee fluctuates depending on the quantity of EOL PV solar panels being disposed of.

The key barriers to managing EOL PV solar panels in WA identified through data collected from recyclers are as follows. The first barrier is that a significant financial investment is required for the plants and machinery to establish an EOL PV solar panel decommissioning and recycling facility. The second barrier is that it is a labor-intensive process. The third barrier is that COVID-19 caused a disturbance in the economy. The

fourth barrier is that product design does not favor recycling or recovering material from the EOL PV solar panels. The fifth barrier is that, due to the large size of solar panels, a significantly large processing area is required to collect and store EOL PV solar panel waste compared to other e-waste. Sixth is that the circular economy is underdeveloped and immature. Seventh is the absence of government policies and regulations to determine the Australian Standard for product quality while importing PV solar panels.

The key barriers to managing EOL PV solar panels in WA identified through data collected from local government are as follows. The first barrier is that local governments are accepting landfills as a solution to EOL PV solar panel waste. Secondly, local governments suggest that it is the responsibility of residents to manage their EOL PV solar panel waste, and it is not the responsibility of the local government. Third is that the EOL PV solar panel waste do not appear in the municipality waste stream as it is taken by new PV installers.

4.3. The Key Factors That Could Enable the Decommissioning and Recycling of EOL PV Solar Panels in WA

The key enabling factors for the management of EOL PV solar panels in WA identified through data collected from users of PV solar panels are as follows. The first enabling factor is the development of a second-hand market for used PV solar panels. The second enabling factor is the reduction of the cost of decommissioning and recycling of EOL PV.

The key enabling factors for the management of EOL PV solar panels in WA identified through data collected from sellers of PV solar panels are as follows. The first enabling factor is the development of legitimate PV solar panel recycling companies in WA. The second enabling factor is the increase in demand from the users to recycle their EOL PV solar panels. The third enabling factor is the improvement of product design at the manufacturer's end. Fourth is the increase in awareness and behavior change among the consumers/users. Fifth is the support from the government in terms of grants and policies.

The key enabling factors for the management of EOL PV solar panels in WA identified through data collected from recyclers are as follows. The first enabling factor is the availability of grants and financial support from the government. The second enabling factor is the improvement of product design. The third enabling factor is the partnership among business, government, and consumers. The fourth enabling factor is the introduction and implementation of the Extended Producer Responsibility (EPR) scheme. Fifth is the certainty of the amount of EOL PV solar panel waste that will be received for processing in a given time frame. The sixth enabling factor is the awareness among different stakeholders and a weaker focus on their own interests.

The key enabling factors for the management of EOL PV solar panels in WA identified through data collected from local government are as follows. The first enabling factor is the change in waste management policies within local government. Second is the increase in service demand from the residents to trigger a change in local government policies. Third is the increase in EOL PV solar panel waste management service providers in WA. Fourth is the availability of a free and local drop-off service for residents to manage their EOL PV solar panel waste. Lastly, introducing and implementing an EPR policy for EOL PV solar panel waste could be an effective enabler.

4.4. Sustainable Solutions Recommended for the Decommissioning and Recycling of EOL PV Solar Panels in WA

Currently, there are no policies or regulations that guide the decommissioning and recycling of EOL PV solar panels in WA. The e-waste ban in WA, which is rolling out in 2024, should include PV solar panels, as the ban does not include PVs at this stage [21]. Similarly, the government discussion paper titled 'Wired for Change: Regulation for Small Electrical Products and Solar Photovoltaic System Waste' needs to be prioritized [22]. Moreover, the current government should ensure that 'Wired for Change' does not end as the Minister's Priority List published in 2016–2017, which recommended that a nationwide policy be finalized by June 2022 and be operational by June 2023 but was not achieved [23]. Likewise, the federal and state governments could increase funding or grants to attract

more businesses to establish and operate more EOL PV solar panel recycling facilities and infrastructure in WA in response to the monopoly that exists in WA.

Also, considering the theoretical design life, which is greater than the actual life of PV solar panels, investment in technology and infrastructure should be prioritized as soon as possible. Similarly, a partnership/coalition among the various stakeholders should be formed to share/communicate knowledge and experience in EOL PV solar panel waste management. Likewise, manufacturers of PV solar panels need to take responsibility for the management of EOL PV solar panel waste, which needs to be mandated through policy implementation as the EPR policy. Similarly, manufacturers also need to change/improve their product design and make it more recycle/resource-recovery friendly. Finally, sustainability issues related to poor management of EOL PV solar panel waste could be communicated to the various stakeholders through an awareness/educational campaign.

5. Discussion

As discussed above, it is clear that there is a lack of academic papers related to the management of EOL PV solar panel waste in WA. Hence, more academic research is required in this area of study in the context of Australia to prevent the issues that would arise from failure to prepare for the predicted bulk of EOL PV solar panel waste in the near future. Therefore, this study was carried out to find sustainable solutions for the decommissioning and recycling of EOL PV solar panel waste in Western Australia (WA) to answer the broader research question of how EOL PV solar panel waste can be managed sustainably in WA.

As previously mentioned, to identify sustainable solutions, four main research questions were devised for this study. The data acquired from the research were compared against the academic theory mentioned in the introduction, and some of the findings are discussed below.

5.1. The Current State of EOL PV Solar Panels Decommissioning and Recycling in WA

5.1.1. Bulk Disposal of EOL PV Solar Panels

This study indicates a low generation of PV solar panel waste in WA at present. Therefore, results and findings from this study in the context of bulk disposal of EOL PV solar panels vary slightly from the academic theory discussed in the introduction section above. However, there is still a concern that the local government has no immediate action plan in place for even the small amount of PV solar waste being generated currently.

5.1.2. Role of PV Solar Panel Installers

The installers of new PV solar panels or the third-party company that installs solar panels are underrated in this area of study. Also, the installers of new PV solar panels are taking the responsibility of disposing of the EOL PV solar panels after they are decommissioned from the user's home. According to Xu et al. [10], most recent research focuses on increasing the effectiveness of PV solar panel manufacturing processes, and there are currently very few studies relating to the dismantling and recycling of solar panels at their EOL, and the absence of solar panel recycling facilities globally supports this claim. Similarly, there are not many academic papers on the management of EOL PV solar panels in Australia [6].

Moreover, the results and findings suggest that the third-party company that installs the new PV solar panels offers to decommission the existing EOL PV solar panels. However, it is unclear how they recycle the EOL PV solar panels. Therefore, the results and findings from this study affirm the academic theory that suggests there is a lack of academic studies and data on the topic of EOL PV solar panel decommissioning and recycling.

5.1.3. Design Life of PV Solar Panels

The design life of PV solar panels, which is claimed to be an average of 25 years, might only be a theoretical value. Islam et al. [6] claim that the average usage life of photovoltaic

solar panels is between 20 to 30 years. Also, Xu et al. [10] explain that, as photovoltaic solar panels represent a new technology with a long average usage life, during the first 25 years of their development phase, recycling of waste solar panel was not a major concern.

However, results and findings from this study suggest that the users had replaced their existing solar panels between 10–15 years after installation. This suggests a discrepancy between the theoretical design life and the actual use life of PV solar panels. Therefore, the results and findings from this study vary slightly from the academic theory in this area of study.

5.1.4. Monopoly of Recycler

Only one recycling company claims to recycle EOL PV solar panel waste to the Australian e-waste standard in WA. Choi and Fthenakis [24] clarify that there are only a few big PV solar manufacturers operating a few PV solar panel recycling systems at the process level around the world. Furthermore, Xu et al. [10] agree that there is a global shortage of solar panel recycling facilities, with only a few nations actively recycling end-of-life PV solar panels outside the EU. Therefore, the results and findings from this study agrees with the academic theory that suggests there is a lack of solar panel recycling facilities.

Additionally, according to Deng et al. [4], significant progress has been made in the practical recycling yield of silicon PV modules. The recovery yield for aluminium frames and glass is 100%, 95% for silicon, 94% for silver (Ag), 99% for copper (Cu), and 93% for lead (Pb) [4]. However, the only recycling company in WA did not participate in this study to share the resource recovery rates, technologies in use, and the processes they are using to recycle the EOL PV solar panel waste in WA. Therefore, the results and findings from this study could not confirm or disprove the academic theory that suggests there is a resource recovery possibility from EOL PV solar panel waste.

5.2. The Key Barriers to Managing EOL PV Solar Panels in WA

5.2.1. Economic Barrier

The findings from this study suggest that the low volume of EOL PV solar panel waste is creating a barrier to managing EOL PV solar panels in WA. Similarly, EOL PV solar panel recycling on an industrial scale is uncommon due to economic barriers [4]. The cost of recycling EOL PV solar panels is high, and the quantity of material that could be recovered by recycling EOL PV solar panels is low; this renders the EOL PV solar panel recycling process unprofitable [25]. Another reason for the lack of economic sustainability for the recycling of first-generation EOL PV solar panels is the low waste volume and lack of recycling infrastructure [4]. Deng et al. [4] claim that this is why first-generation EOL PV solar panels are being landfilled.

Similarly, the results and findings from this study indicate that decommissioning and recycling EOL PV solar panels is a labor-intensive and costly process, often requiring significant financial investment in labor, machinery, and space. Therefore, the results and findings from this study confirm the academic theory that suggests there is a low volume of EOL PV solar panel waste being generated in the market, and a lack of financial profitability creating an economic barrier to the management of EOL PV solar panel waste.

5.2.2. Lack of Secondary Market for Recovered Materials and Lack of Infrastructure

The only recycling company in WA that claims to recycle EOL PV solar panel waste in WA to the Australian e-waste standard did not participate in this study. Therefore, the results and findings from this study could not confirm or disprove the academic theory suggesting that a lack of a secondary market for resources recovered from the EOL PV solar panel waste is a key barrier to managing EOL PV solar panels. Additionally, without them participating in the study, it was not possible to confirm the capacity required for the decommissioning and recycling of EOL PV solar panel waste. Therefore, it could not be confirmed whether the lack of infrastructure is a key barrier to managing EOL PV solar panels in WA.

5.2.3. Lack of Policies and Regulation

The data from this study suggest that there is a lack of policies and regulations to guide efficient management of EOL PV solar panel waste in WA. Member states of the EU have been held accountable for the collection, transport, and treatment of EOL PV solar panels since 14 February 2014 as per the revised WEEE Directive, which provides the framework for the management of EOL PV solar panels under the extended producer responsibility (EPR) scheme [6]. In comparison, Australia has no federal-/national-level regulations and state-level regulations in WA for the management of EOL solar PV waste [6]. Therefore, the results and findings from this study confirm the academic theory that suggests that the lack of policies and regulations represent a key barrier to managing EOL PV solar panel waste.

5.3. The Key Enablers to Managing EOL PV Solar Panels in WA

5.3.1. Banning Landfill

The stakeholders in this study, local government, seller of PV solar panels, and recycler, pointed out that banning EOL PV solar panels from landfills will be the key enabling factor for efficient decommissioning and recycling of EOL PV solar panels in WA. Similarly, the most popular method for the disposal of PV modules is in landfills, with modules lawfully disposed of alongside normal household waste in most areas [4].

Likewise, recycling will become a more cost-effective solution if the cost to landfill EOL PV solar panels is increased significantly or prohibited [26]. According to Deng et al. [4], recycling the glass from EOL PV solar panels is practical in nations and states where landfill costs are very high or prohibited. E-waste and solar panels have been prohibited from landfills in Victoria State in Australia since 2019 [27]. This means that Victorians cannot dispose of their EOL PV solar panel waste in the landfill, leaving them with the alternative to either reuse them or recycle them since 2019. Therefore, recycling will become the next best option for EOL PV solar panels if the government introduces a ban on the disposal of EOL PV solar panels in landfills. Therefore, the results and findings from this study affirm the academic theory that suggests banning EOL PV solar panels from landfills will be the key enabling factor for efficient decommissioning and recycling of EOL PV solar panels.

5.3.2. Product Design

The current product design does not favor recycling or recovering material from the EOL PV solar panels. However, the results and findings from this study suggest that improving the design of PV solar panels to make them more reusable and recycle-friendly would be a significant factor in enabling the decommissioning and recycling of EOL PV solar panels in WA. According to Deng et al. [4], PV module manufacturers should consider how to employ recycled materials in their production processes, while maintaining the feasibility of recycling in module design. New PV solar panels should be designed efficiently, so that the processing cost during the recycling of EOL PV solar panels is reduced [4]. Similarly, the product should be designed in a way that allows the recycling companies to recover silver and intact Si wafers from the EOL PV solar panels [4].

According to Deng, Zhuo, and Shen [27], the majority of procedures still use manual sorting at the recycling plant, which ought to be substituted with an automated process that can produce the same degree of selectivity. For this scenario to be practical, manufacturers have to play a crucial role, as they can design their products to be automation-compatible. Therefore, the results and findings from this study affirm the academic theory that suggests that the improvement of the design of PV solar panels to make them more reusable and recycle-friendly would play a significant role in enabling the decommissioning and recycling of EOL PV solar panels.

5.3.3. Extended Producer Responsibility

The responsibility of decommissioning and recycling EOL PV solar panels in WA is a collective effort. However, without the implementation of EPR, decommissioning and recycling of EOL PV solar panels has been inefficient. Given that some of the materials

used to make PV panels are hazardous, making it nearly impossible to recycle or dispose of individually, it is important to have appropriate policies in place that encourage manufacturers to recycle EOL PV solar panels [28]. Similarly, there are few manufacturers who willingly recycle EOL PV solar panels, but the lack of economic incentives and support from the government could mean that this is highly unlikely to continue [28].

Therefore, the results and findings from this study affirm the academic theory that suggests the implementation of EPR is the main enabling factor for efficient decommissioning and recycling of EOL PV solar panels.

5.4. Opportunities to Overcome Barriers

5.4.1. Awareness among PV Users

The results and findings from this study indicate that users of PV solar panels in WA are unaware that most EOL PV solar panels end up in landfill sites once they reach EOL and are removed from their roofs. Also, the results and findings from the study suggest that 86.67% of the users have no idea what to do with PV solar panels when they reach their EOL. Similarly, the new PV installers are currently responsible for decommissioning the EOL PV solar panels from the user's home, but the users are unaware of what installers do to them after decommissioning.

This indicates that raising awareness among the users of PV solar panels in WA could be an opportunity to overcome the barriers to decommissioning and recycling EOL PV solar panels in WA. As mentioned above in the economic barrier section of this study, a low volume of EOL PV solar panel waste is being generated in the market, which is making the recycling of EOL PV solar panel waste unprofitable. If users of PV solar panels could be made aware of the current practice where most of the EOL PV solar panels end up in landfill sites after the new PV installers decommission them from the user's home, then this would raise awareness among the users of PV solar panels in WA. As a result, the environmentally conscious users of PV would look for more sustainable alternatives to dispose of their EOL PV solar panels rather than letting the installers of new PV solar panels dispose of them in landfill sites. Therefore, raising awareness among PV users about the current state of EOL PV solar panel decommissioning and recycling in WA has been identified as an opportunity to overcome the barrier to managing EOL PV solar panels in WA.

5.4.2. Financial Support from the Government

The results and findings from this study affirm that decommissioning and recycling EOL PV solar panels is a complex, costly, and labor-intensive process. There is a significant need for quality research and development in this area of research. Similarly, there is a lack of dedicated recycling facilities, plant and machinery, and logistics networks in WA, which are necessities for the efficient decommissioning and recycling of EOL PV solar panels. Also, there is a need to raise awareness among the stakeholders related to this study about the negative environmental, economic, and social consequences of sending EOL PV solar panels to landfill sites. To achieve the abovementioned objectives, there is a need for large financial resources. Therefore, grants and financial support from the government for the development of decommissioning and recycling infrastructure for EOL PV solar panels have been identified as an opportunity to overcome the barrier to managing EOL PV solar panels in WA.

5.4.3. Ending Monopoly in the Market

The most significant result/finding of this study is that only one recycling company claims to recycle EOL PV solar panels to Australian e-waste standards in WA. However, the recycling company did not participate in this study, so this study could not confirm many different aspects of EOL PV decommissioning and recycling in WA, including the price they charge their customers, their recycling process, and the type/capacity of the infrastructure they use for decommissioning and recycling EOL PV solar panel waste in WA. This clearly indicates that there is a strong monopoly of the recycling company in WA.

Therefore, ending the monopoly of the recycler of EOL PV solar panels in WA has been identified as an opportunity to overcome barriers to managing EOL PV solar panels in WA.

5.5. Proposed Sustainable Solution

The decommissioning and recycling of EOL PV solar panels is a complicated area of study, and it does not have one single solution that addresses all the issues that exist at present. However, the results and findings from this study suggest that decommissioning and recycling of EOL PV solar panels could be sustainable, but require a synergistic effort from multiple stakeholders involved in this area of study. By triangulating the data collected for this study, a sustainable solution for decommissioning and recycling EOL PV solar panels in WA has been identified as follows.

The first step of the proposed solution is the introduction and implementation of EPR by the state government of WA. This means that any solar panels that are sold in WA would be the responsibility of the manufacturer or international/domestic importer of the product for collection, reuse, resource recovery, and recycling when the product reaches its EOL.

Then, the second step would be to ban EOL PV solar panels from being disposed of in landfill sites across WA. This means that any stakeholder in this area of study, if found to be disposing of their EOL PV solar panel in the landfill sites in WA, would first be issued with a warning letter and asked to remove the disposed EOL PV solar panels from the landfill site. Successively, if they are found to be disposing of their EOL PV solar panel in the landfill sites again or if they refuse to remove the EOL PV solar panels from the landfill site, they would be issued with heavy fines and penalties by the state government of WA.

The final step of the proposed solution is to increase financial investment by the state government of WA in this area of study through grants, subsidies, and loans. This would support continuous improvement in the decommissioning and recycling of EOL PV solar panels in WA by increasing the amount of quality research in this area of study. Also, such investment would allow WA to build infrastructures such as dedicated recycling facilities, plant and machinery, and logistics network for EOL PV solar panels. The building of such infrastructure would ensure that the proposed sustainable solutions are practical for the manufacturer of the product or international/domestic importer of the product as they could collect and process their EOL product within WA. The financial investment from the state government should also be used toward raising awareness about the negative environmental, economic, and social consequences of sending EOL PV solar panels to landfill sites.

Overall, the implementation of the proposed solution entailing the introduction and implementation of EPR, the ban of EOL PV solar panels from being disposed of in landfill sites, and the increase in grants and financial support from the government would ensure the protection of the environment by reducing the stress on virgin raw material extraction and by preventing environmental pollution due to landfilling of EOL PV solar panels. It would also create more jobs in the economy and increase the employment rate in the society.

5.6. Implications for Further Research

Three main questions have arisen from this study, which could be explored in the future to take this study forward. These three questions could be applied to local area-specific, state/province-specific, and nation-specific scenarios. The three questions are as follows:

Question 1: what is the estimated number of PV solar panels that will reach their EOL between 2025 and 2050 (each year) in the given local area, state, or nation? The estimated number will provide stakeholders with valuable information to make important decisions such as choosing a strategic location to establish a recycling facility, deciding on the processing capacity requirement of the recycling facility, and identifying the best mechanism to transport and store EOL PV solar panels for recycling.

Question 2: what is the cost–benefit analysis of establishing and operating an EOL PV solar panel decommissioning and recycling facility in the given local area, state, or

nation? The cost–benefit analysis will provide stakeholders with valuable information such as capital investment requirements, investment return, identification of economic break-even points, and identification of environmental and economic benefits.

Question 3: if an EOL PV solar panel decommissioning and recycling facility is to be established and operated, then which plant and machinery would be the most efficient and suitable? Various treatment procedures are currently available to recover the materials from EOL PV solar panels, even if the majority of these have not yet been industrialized [29]. Researching this question will help find the most efficient technology for the recycling of different types of PV solar panels in the local area, state, or nation.

6. Conclusions

The abundance of abandoned EOL PV solar panel waste will soon become a problem due to the significant rise in the production and use of PV solar panels since the late 20th century [10]. Compared to any other waste stream, photovoltaic solar panel waste also has the potential to cause environmental, economic, and social issues if they are not managed properly in time. However, according to Xu et al. [10], most recent research focuses on increasing the effectiveness of PV solar panel manufacturing processes, and there are currently very few studies relating to the dismantling and recycling of solar panels at their EOL, with the absence of solar panel recycling facilities globally seemingly supporting this claim. Similarly, there are not many academic papers on the management of EOL PV solar panels in Australia [6]. Therefore, this study is the first academic research paper considering the decommissioning and recycling of EOL PV solar panels in Western Australia.

This research aims to find sustainable solutions to the decommissioning and recycling of EOL PV solar panel waste in Western Australia (WA) to answer the broader research question of how EOL PV solar panel waste can be managed sustainably in WA. Using a mixed-methods approach, this study took into account both qualitative and quantitative research techniques. Next, to gather information for this study, a questionnaire for an online survey and an interview were created and used.

The key research findings are as follows. Currently, a significant portion of EOL PV solar panel waste ends up in landfills in WA. Also, there is no policy or regulation from the government to control and manage the PV solar panel industry. Moreover, there is only one recycler who claims to recycle EOL PV solar panel waste in WA, but it is not willing to share any information via any mode of communication. Next, there is a discrepancy between the theoretical design life and the actual life of PV solar panels in WA. Furthermore, the third-party companies that decommission the old PV solar panels and install new ones are the fifth stakeholders in this industry who are taking responsibility for the disposal of EOL PV solar panels in WA. This study also found that the users of PV solar panels are unaware of the importance of proper decommissioning and recycling of EOL PV solar panels. Similarly, there is no communication among the different stakeholders. Finally, decommissioning and recycling EOL PV solar panels is a costly and labor-intensive process due to its product design.

The fourth objective of this study is to propose possible sustainable solutions for the decommissioning and recycling of EOL PV solar panel waste in WA. Hence, a possible sustainable solution has been derived by triangulating the findings from the first research objective, entailing the exploration of the current state of EOL PV solar panel decommissioning and recycling practices in the context of WA, the second research objective, entailing the identification of the key barriers and enabling factors for PV solar panel decommissioning and recycling in WA, and the third objective, entailing the identification of how to overcome barriers with respect to the optimization of resource recovery from EOL PV solar panels in WA. The proposed possible sustainable solutions are as follows. The first step of the proposed solution entails the introduction and implementation of EPR by the state government of WA. Then, the second step would be to ban EOL PV solar panels from being disposed of in landfill sites in WA. The final step of the proposed solution is to increase

financial investment by the state government of WA in this area of study through grants, subsidies, and loans.

Therefore, the implementation of the proposed solution consisting of the introduction and implementation of EPR, banning of EOL PV solar panels from being disposed of in landfill sites, and increase in grants and financial support from the government would ensure the protection of the environment by reducing the stress on virgin raw material extraction and by preventing environmental pollution due to landfilling of EOL PV solar panels. Similarly, it will also create more jobs in the economy and increase the employment rate in the society.

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Institutional Review Board Statement: The study was conducted following the National Health and Medical Research Council's (NHMRC) National Statement on Ethical Conduct in Human Research (2007) and approved by the Ethics Committee of Curtin University (Ethics Approval Number HRE2023-0443 and date of approval 14 August 2023).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data supporting reported results can be found using the following link, https://drive.google.com/drive/folders/1PADqDbgYXo8R8Evmi4F-H-7kSOTIKew5?usp=sharing (accessed on 25 October 2023) (shared via google drive).

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