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Review

Product stewardship considerations for solar photovoltaic panels

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Abstract: While the uptake of solar photovoltaic panels for the generation of clean energy has almost exponentially increased over the past about 10 years, effective end-of-life management legislation is still lacking in many nations. Organizations like the International Renewable Energy Agency have clearly outlined the need and benefit of robust end-of-life management legislations, such as a product stewardship scheme or extended producer responsibility, to avoid a looming significant waste legacy. This article explores a possible design of an end-of-life legislation for solar photovoltaic panels including new and existing panels, necessary legislation for a second-hand economy for solar photovoltaic panels, and options for necessary levies to support an emerging recycling industry for solar panels. The article also tries to make recommendations for a product stewardship scheme for solar photovoltaic panels and its financial support.

Keywords: product stewardship; extended producer responsibility; solar photovoltaic panels; waste management; end-of-life management

1. Introduction

1.1. Solar photovoltaic panel uptake and expected waste volume

The increase in the use of solar photovoltaic panels (solar PV panels) has significantly contributed to the steady increase in the application of renewable energy technologies for the generation of electric power all over the world. While fossil fuels are still the dominant source for electric power generation, it is expected that this situation will change within the next 20 years and renewable energy generation, especially via solar PV panels, will be the main source for the production of electric energy. At the current total cumulated solar PV capacity of about 707,495 MW, the related number of installed solar PV panels is staggering [1]. Taking the average output of a standard solar PV panel into account, Germany and Australia have the highest uptake of solar PV power per capita (Table 1).

Table 1. Solar PV uptake per capita of nations with a significant contribution of solar PV towards their renewable energy mix [1].

Country	Solar PV capacity (MW)	Solar PV uptake (W) per Capita
Australia	17625	705
Germany	53781	648
Japan	67000	529.7
Italy	21594	363.5
South Korea	14575	282.4
Spain	11785	250.7
USA	73814	224.9
UK	13563	203.6
France	11724	175
China	235834	168.4
India	38983	28.5

In 2020, rooftop solar installations increased by 27.5 per cent in Australia and large-scale solar projects also increased by 36.2 per cent, resulting in a market share of renewable energy of 24.4 percent. As a consequence, the market share of renewable energy sources in Australia has overtaken fossil gas generation, which is at about 20%, for the first time [2]. Currently, about 80 million solar PV panels are installed in Australia. Silicon PV panels constitute more than 90% of the installed panels [3].

This large number of solar PV panels is expected to create a significant waste volume not only in Australia, but worldwide, in about 20 years. During the next 10 years, the annual PV panel waste volume in Australia has been calculated by the authors to remain low (less than 10,000 tons/year) before 2025, but to surge after 2030, as the result of the first boom of PV system installation around 2010–2012 entering their end-of-life [3–5]. The calculations are based on the actual PV capacity in Australia [1,2]. Considering an average lifetime of 15 years the annual PV panel waste volume is calculated to be about 75,000 tons by 2030. If calculated based on an average life time of 20 years, the waste volume will only reach about 35,000 tons per year by 2030, but will jump to almost 95,000 tons within only a few years, followed by significant increases in the waste volume of well above 100,000 tons per year from 2035 on. Eventually, the cumulative waste volume from solar panels in Australia will reach about 1.5 million tons by 2036 (Figure 1) and more than 2 million tons by 2040. However, even with a simple recycling step that removes the frame and glass cover, the waste volume can be significantly reduced (Figure 1). With almost three billion solar panels installed wordwide, the waste volume is

estimated to reach more than 60 million tons world wide by 2035. To avoid such an unwanted waste legacy, robust end-of-life management legislation has to be created.

The expected demand for minerals and materials for renewable energy systems, like solar photovoltaic panels, makes it even more necessary to establish the processes and legislations for a circular economy for the materials embedded in solar panels [6].

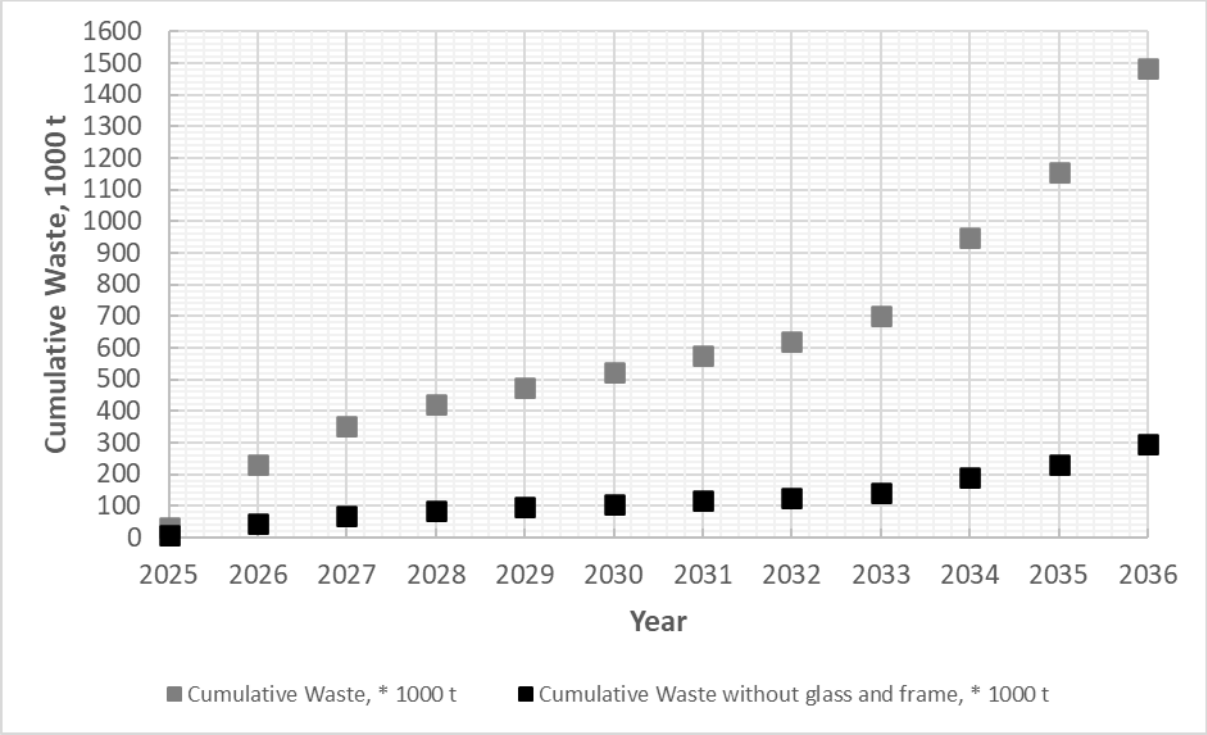

Figure 1. Cumulative and annual waste from solar PV panels and cumulative waste from solar PV panels without glass cover and frame based on 80% of a panel's weight sits in the glass cover and frames based on 15 years of lifetime for a panel.

1.2. Product stewardship

A legislated process like a product stewardship scheme or extended producer responsibility (EPR) can be of benefit for regulating the end-of-life management of solar PV panels [7]. Product stewardship recognizes the responsibility of stakeholders who are involved in designing, manufacturing, and selling products to ensure that their products are managed in a way that reduces their impacts on the environment and human health throughout the life-cycle and across the supply chain.

Various forms of product stewardship schemes exist, which are mainly defined by the level of governmental regulations. Voluntary product stewardship schemes by the industry stakeholders are run by the industry and their outcomes are usually reported to governments to prove their effectiveness. Mandatory product stewardship schemes are introduced by the government and require the industry to adhere to the goals and regulations of the schemes. Co-regulatory schemes are approved by the government and are run by an administrator or product stewardship organization (PSO) on behalf of the involved industry. The PSO must ensure all reasonable steps are taken to meet outcomes specified

in the regulations. Overall, product stewardship schemes provide better control and oversight for the government in regard to end-of-life management processes than an EPR.

The Organization for Economic Co-operation and Development (OECD) outlines that under an EPR a producer of a product has responsibility for a product during its whole life cycle which, therefore, includes the end-of-life management and a producer has to take responsibility for what needs to be done with the product at the end of its useful life. According to the OECD, an EPR policy requests producers to take full or partial environmental and/or economic responsibility for a product over the whole life cycle. An EPR ensures that the producer is not relying on landfilling of the product once it is out of use, because the scheme integrates the environmental characteristics of products throughout the product's life cycle including its manufacturing [8]. An EPR scheme requires polluters to pay for the environmental impact of a product, as the scheme legislates that a price of pollution is embedded in the supply chain. Because EPRs are designed to ensure that the responsibility for recycling and waste disposal rests with the industry and, eventually, the customers, the costs of end-of-life management are part of the prices of the product and not requested in form of the levy at the time of purchase.

Most nations with significant solar PV capacities do not yet have robust legislations in place which govern the end-of-life management of solar PV panels, but include solar panels into general waste legislation like the European WEEE Directive [9] which often do not legislate recycling and outlines that end-of-life management processes for solar panels have to be established and implemented at a member state level [9,10].

It is important to outline what are the responsibilities of the solar PV industry as well as that of consumers in regard to the end-of-life management of solar PV panels. Without this, the essential further increase of solar energy to further reduce greenhouse gas emissions from fossil fuels may be jeopardized due to the possible scenario that consumers are reluctant to replace their solar panels or upgrade their solar systems because of the uncertainty of what to do with the unwanted or damaged panels. In addition, such legislation and associated schemes can provide incentives for producers to develop more easily recyclable solar PV panels and triggers the creation of second-hand markets for the re-use of solar PV panels as demonstrated for other technologies [11].

While recycling appears to be the preferred option for the end-of-life management of solar PV, it is worth exploring whether an intermediate strong second-hand economy for used solar PV panels also seems to be a viable path towards reducing the waste legacy of solar PV panels, e.g. especially for oil-rich nations with a high fossil fuel share in the energy mix, lower per capita income, and a manufacturing sector which is mainly driven by energy sources based on fossil fuel [12,13].

This review article intends to provide a practical approach toward a product stewardship scheme for solar photovoltaic panels, which can deal with the end-of-life management of existing and new panels. The article also outlines a possible product stewardship scheme for new and existing panels and its financial support.

2. Lifetime of solar PV panels

Just a simple recycling process that removes the glass cover and frame of a panel can reduce the amount of cumulative waste volume in Australia down to 100,000 t in 2030 and about 250,000 t in 2035. This is still a significant amount of waste and sends a large amount of high-purity silicon of the solar cells worth tens of millions of dollars to landfill Manufacturers usually warranty a 25-year power

degradation warranty of solar panels, i.e., panels will output at least 80% power after 25 years. However, early decommission prior to technical end-of-life has been observed in Australia [2–5], especially in the residential systems, due to several economic and technical reasons, as well as severe weather events and natural disasters.

Therefore, the increase in waste from solar PV panels can be expected to materialize much earlier than previously thought. Recent studies estimated the average panel lifetime to be 10–12 years [5], and 15–20 years in Australia before they are decommissioned [3].

3. Possible regulatory environment

A review of existing EPRs by the OECD has shown that the majority appear to be mandatory rather than voluntary [8]. Take-back requirements, which can vary in scope and extend, are the most often applied scheme to ensure compliance and are often defined by mandatory targets, and less often by voluntary targets, for collection and recycling of the related product. The report also outlines that to achieve higher collection rates, effective schemes often provide incentives to consumers to return the product at the end of its operational life to a specified collection point, which, of course, can be the selling point or the installer of new panels, as it is usually the case for car tires.

In the long run, EPRs and product stewardship schemes aim at the reduction of waste and, therefore, should encourage and incentive the design of easy-to-recycle products. This can be achieved by taxing difficult to recycle materials or environmentally harmfull production processes for a product. In the case of solar panels, especially in the case of upgrading existing panels, the re-use of their frame, glass panel, and junction box could be encouraged by an easy process to replace the solar cells of panels.

The cost efficiency of landfill use often makes it very difficult for alternative disposal methods to compete. In contrast, some European countries and other jurisdictions like the state of Victoria in Australia have banned solar PV panels from landfills or reduced the landfilling, because of environmental considerations and, therefore, economically and ecologically reasonable recycling and re-use processes of the panels is necessarily under investigation. This development indicates that focused regulatory measures like landfill bans can be a powerful tool to achieve desired developments. However, such regulatory measures need to be accompanied by legislations that inhibits circumventing such measures through e.g., sending the waste to other jurisdictions with less stringent regulations.

Another measure can be the tracking of the panel's serial numbers. This action can provide information about the number of panels installed, including imported panels from international manufacturers, their place of operation and owner, and eventually what happened to the panels at their end-of-life, who dismantled the panels and where the panels are recycled. A Serial number tracking would also be a powerful tool to control the export of waste panels or ensure that they are not exported in case a waste export ban is in place. This measure would also give regulators and governments a powerful tool to monitor recycling rates.

The ownership of the panels also needs regulatory clarification. Once the panels are installed and operating on rooftops of private dwellings, their operator is obviously the owner. However, once the panels are dismantled and on their way to a recycler, it needs to be clarified who the owner is and who is responsible for the proper handling to avoid panels fall into a 'black hole'

with nobody being responsible for the panels in case actions are required. In case the recycler or operator is the dismantler, this consideration is obsolete. However, dismantling is done by a third party, it is necessary to identify the ownership during the period of transport to the recycler and any consequences for the dismantler in case the panels are not handled as expected or illegally dumped.

In the case of commercially used solar PV panels for, e.g., a solar farm, it can be expected that business agreements between solar PV manufacturers and solar farm operators clarify the ownership for the panels and panels do not fall into a 'black hole'.

Some legislation like the End-of-Life Vehicle (ELV) Directive of the European Commission [14] and other countries require manufacturers to ensure that their cars have a guaranteed recyclability. In the case of the EU ELV Directive, it is 85% in weight [15]. A legislation for solar PV panels, which requires a similar guaranteed recyclability for solar PV panels in weight can ensure that future panels are using materials which are more easily to recycle. This is especially important in regards to the weatherproofing polymers, front sheet and back sheet, of the solar cells, which are representing a particular environmental problem in regards to the recycling of solar panels due to the possible formation of hydro-fluorite gas during incineration of the back sheet [16].

4. Ensuring compliance and participation in an end-of-life legislation

One issue with end-of-life legislation is the control of compliance and avoiding so-called free riders [17]. Free riders are businesses or organizations that may benefit from an end-of-life legislation without contributing to the cost of operating the schemes. This can especially be in the case of voluntary schemes or co-regulatory schemes with very little oversight from governments, low recycling and collection targets, or lack of incentives for participation [18]. Free-riders can be a major deterrent to the participation of industry in a scheme and thereby threaten the effectiveness of existing and emerging product stewardship schemes, as they not only cause an element of unfairness into a product stewardship scheme, but also can risk that a product stewardship scheme is overburdened [19]. Therefore, all manufacturers and importers of products that are subject to an end-of-life legislation need to be encouraged or even mandated to take greater responsibility for the product's environmental impact that they place on the market, if necessary, through stringent legislations and appropriate control. This consideration can indicate that a mandatory scheme for solar panels is more appropriate than a voluntary scheme given the ever increasing number of installed panels and the clearly outlined waste volume in the coming decades.

In the case of a voluntary product stewardship scheme, one obvious measure would be that only panels from manufacturers who participate in the product stewardship scheme or extended producer responsibility scheme can be sold or are accepted for import in the case of international manufacturers. Because such restrictions may be in conflict with national competition and consumer rules and international general trade agreements, legal accreditations of such measures from related government bodies and regulators may be necessary.

Market forces can also be exploited to control free riders by involving retailers. Such measures often do not require regulatory approvals. Retailers have the closest interaction with consumers and, therefore, are an important and integral part of an end-of-life legislation, as retailers not only can give preference to product providers, who offer greater environmental performance, but educate the consumer on how to choose environmentally preferable products and whether manufacturers

participate in an end-of-life legislation scheme. Retailers can also enable consumers to return products for recycling or provide information about local collection centers. As all products are designed with a consumer choice in mind, the product must attract consumers who makes the choice between competing products and who must use and dispose of products responsibly. Therefore, products that can only be legally disposed of at the cost of the consumer, as their manufacturers do not participate in a product stewardship scheme or extended producer responsibility scheme, may not attract much consumer attention [20]. Consumers must be encouraged to make responsible buying choices which consider environmental impacts and recyclability of a product, and to act responsibly in regards to support the recycling of a product through proper disposal. Thus, consumer engagement in end-of-life legislation schemes is essential to close the loop.

Therefore, it is necessary to legislate that retailers of panels must provide consumers with information about which manufacturers are participating in end-of-life legislation schemes, whether the panels will eventually be accepted for recycling or not and whether the consumer will be responsible for the panel's end-of-life management and related costs in case the consumer chooses panels from not participating manufacturers. This principle of shared responsibility is essential for a successful end-of-life legislation. To document the participation of a manufacturer in a product stewardship scheme or extended producer responsibility scheme and ensure consumers that panels will participate in recycling and re-use schemes, retailers and manufacturers must provide consumers a certificate of recyclability on the purchase of the panels along with appropriate warranty documentation. Such a certificate, like an electrical certificate of compliance, must be presented to any new owner of the panels.

While legislation can provide the framework for the participation of manufacturers in an end-of-life legislation scheme, especially in the case of a mandatory scheme, enterprise agreements between the Producer Responsibility Organisation (PRO) and manufacturers must legally regulate the participation in a product stewardship scheme or extended producer responsibility scheme and the eligibility of panels to be accepted for recycling.

5. Potential product stewardship scheme

As indicated above, a mandatory product stewardship scheme for solar PV panels or a co-regulatory scheme with strict regulation regarding participation appears to be more appropriate considering the ever-increasing number of panels, increasing the number of solar panel manufacturers, and to avoid free riders. A potential scheme can distinguish between panels from private users and commercial users (Figure 2). In the case of commercially used panels, the EU's WEEE Directive's legislation Business-to-Business (B2B) model could apply. Products for professional use only like medical equipment, industrial machines, large manufacturing equipment, and servers, are allocated as B2B EEE or when it became waste as B2B WEEE. One important aspect of this legislation is that the producer or importer must declare that the producer has the adequate resources available to finance the take back schemes and/or environmentally sound management of the waste which is generated by the product at its end of life. This declaration is made by the producer as part of the submission of Waste Management Plans and Reports. The purpose of the Waste Management Plan is to ensure that B2B producers are managing the waste in an environmentally sound manner. This means that collection, storage, reuse, treatment and recovery, or as appropriate, disposal of the waste is carried out in accordance with all relevant legislation and best practice. The coverage of the related costs, take back

options, or other related end-of-life management actions can be negotiated between the producer and business end user. This B2B model would ensure that legislators have a clear understanding of the end-of-life management of panels outlined in detail by producers and the ability to monitor declared actions by the involved business at the end of the panel's productive life. In addition, with this model operators of commercially used panels, e.g., in solar farms, have a clear understanding of what will happen with the panels at the end of their operational life and the involved processes, responsibilities of the business partners in regards to end-of-life management, and potential cost. The tracing of serial numbers can provide a tool for regulators to track end-of-life panels, even from private users.

Manufacturers, who are expected to take panels back after their operational life, can be encouraged to engage in enterprise agreements with local solar PV recyclers to manage the collection and recycling of panels if the manufacturer is not prepared to take panels back. This may be especially of interest to overseas manufacturers who want and need to ensure that panels undergo end-of-life management processes which are in line with the legislation of the jurisdiction where the panels reside. Export bans of waste on the jurisdiction where the panels reside may also make this model a viable option for overseas manufacturers.

End-of-Life management of panels from private users is also shown in Figure 2. This process can be much straighter forward compared to a B2B model. Unwanted or damaged panels are removed by installers or collectors from private households and transferred to recyclers for proper processing.

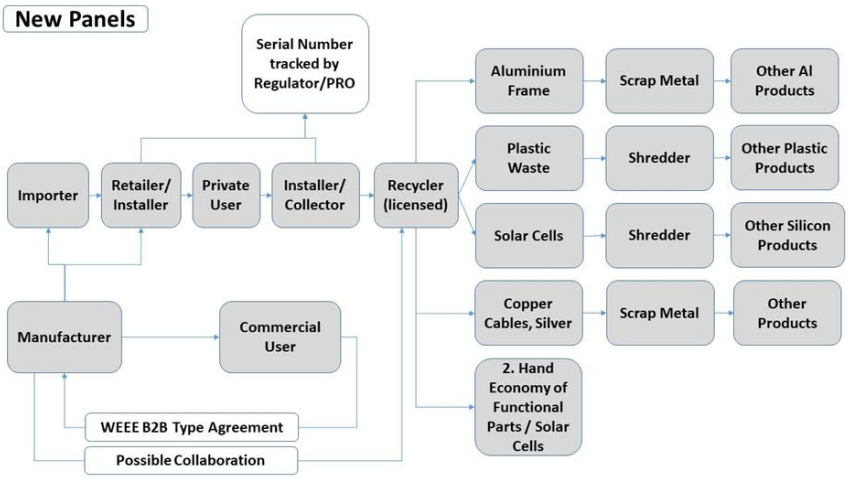

Figure 2. Flow chart of possible product stewardship scheme for new solar PV panels.

Retailers and recyclers provide the serial numbers of panels to the regulator or PRO. This measure allows tracking of panels and proper documentation of recycling rates.

Once they are removed from the private user the ownership of the panels needs to be clarified in order to manage responsibilities for the panels until they are recycled. It would be inappropriate that the ownership resides with the private user, as the private user has no control about the panels once they are removed from the private property. Therefore, ownership needs to go to the installer or collector until the panels are with the recycler. Ideally, the installer or collector and recycler are the same entity.

6. The weight dilemma

Established product steward schemes often work by using weight as the main unit of measurement to track recycling rate and recovery. However, a scheme aimed at solar panels needs to be more specific in this regard. Silicon PV panels, which account for roughly 95% of the PV market are layered devices whose sides are framed by an aluminum profile [21,22]. The mass distribution of these devices is shown in Table 2. It is clear that three components are responsible for most of the weight of the panels, namely the glass, the aluminum frame and the encapsulant. These three components combined account for ~90wt%. Depending on the size of the panel, this number could be even higher. This creates a situation in which creating regulations based only on weight can promote the recycling of these components and leave behind the materials that are more important from a waste management perspective: Pb, Si, Ag, and Cu.

Table 2. Material weight distribution of the main components of silicon PV modules.

Materials	Main substance	General crystalline silicon [23] weight %	455 W mono-crystalline [24] weight %
Solar cell (mono)	Si	2–3	3.3%
Encapsulant	EVA	7[a]	10.1%
Ribbon	Tin-plated copper ribbon	0.6–1[b]	0.5%
Bus bar	Cu	-[b]	0.1%
Backsheet	Tedlar	-[a]	3.9%
Aluminum frame	Al	10–20	10.2%
Coated semi-tempered glass (front side)	Glass	69–75	69.3%
PV component connection & j-box	Cu	2	1.1%
Silica gel	SiO_2	-	1.4%

[a]Encapsulant and backsheet considered in conjunction as "polymers". [b]Ribbon and bus bar considered in conjunction as "copper".

The Pb is used in the solder applied to the modules in the copper ribbons. While efforts are in place to reduce the usage of PV in solar panels, it is currently the material responsible for classifying silicon photovoltaic devices as a hazardous waste under several jurisdictions [25]. Thus, a program that does not specify what should be the fate of the Pb content runs the risk of contaminating the environment, which goes against the very purpose of implementing an end-of-life legislation in the first place. Moreover, the Si, Ag, Cu are less than 5wt% of the solar panel, yet hold >50% of the economic value [26].

Therefore, from the perspective of scarce materials, these materials should be recovered. Perhaps they should be even favoured in respect to the recovery of the polymers present in the solar panels, which have a significant weight (7–14%) but negligible value [27]. However, a recovery target purely based on weight may have the unintended consequence that only some particular materials are recycled and others not to satisfy recovery targets.

7. Existing panels

A common issue with new end-of-life legislations is how to deal with existing products that are subject of the end-of-life legislation. One solution, of course, can be to exclude all products from the related end-of-life legislation, which were sold before the scheme was legislated. This, however, would cut off recyclers from a valuable stream of to be recycled waste until newly sold products reach their end-of-life. It would also be a significant problem to establish a viable secondhand economy for used solar PV panels, as related regulatory frameworks governing aspects like electric and safety certifications, quality assurance, and product service are not established. In addition, in the case of solar PV panels, such a measure would significantly delay the development of proper recycling technologies and processes and, therefore, would be a barrier to establishing a circular economy for solar PV panels. Therefore, it is recommended to include existing panels in an end-of-life legislation and design the scheme in a way that it can also deal with existing panels considering both avenues, recycling and re-use similar to the EU's WEEE Directive [9].

Figure 3 shows a potential framework for including existing panels into an end-of-life legislation scheme.

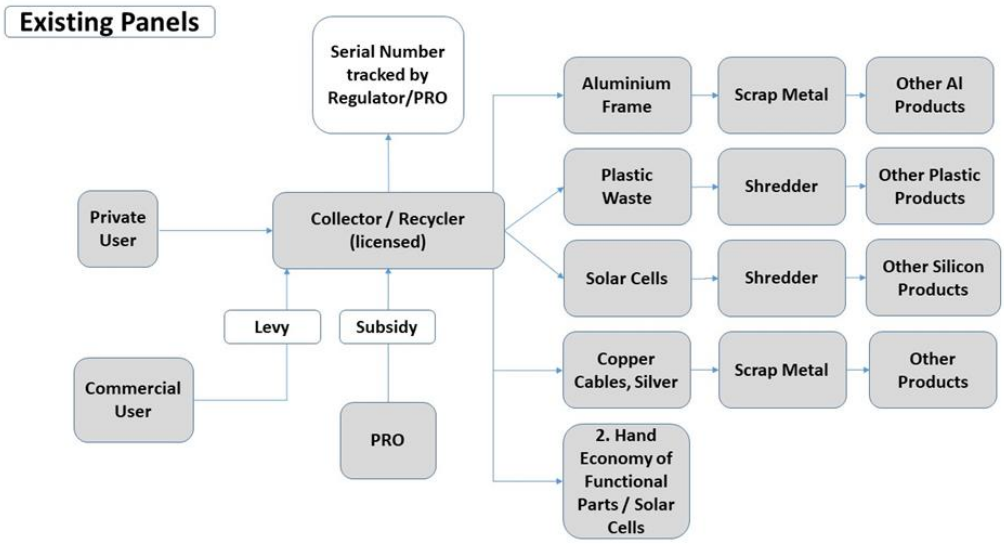

Figure 3. Potential framework for including existing panels into a product stewardship scheme.

8. Re-use of functional panels

The re-use of still functional solar panels may provide a scenario for a viable second hand economy in this sector, comparable to the computer sector [28]. Solar panel reuse offers a variety of social and environmental benefits and is an approach that could easily fit into existing collection and recycling networks and processes. There is a small solar panel reuse market in Australia, however, there is significant scope to scale and further develop solar panel reuse as part of a circular economy for the solar energy sector. Critical to the ongoing success of solar panel reuse, whether for international or domestic markets, is the ability to assure consumers on the safety and quality of second hand solar panels.

Consumers of second hand solar PV panels need to be certain that the second hand panels are working properly and at a certain defined capacity. A certification of some type would be essential, independent of whether second hand panels are imported or come from local sources. Ensuring solar panels meet safety and performance requirements in Australia prior to export, will also prevent non-functioning panels becoming a waste burden at the receivers' end, where adequate waste management infrastructure may not be in place to safely and appropriately handle these solar panels.

A bare minimum would be a certification like the electric safety and compliance certificate or equivalent to ensure safe operation of the panels. An electric safety and compliance certificate or equivalent would need to be provided by a certified electrician or equivalent before the panel enters the secondhand economy.

As the capacity of solar PV panels degrades with time at rate of about 1% per year, consumers need to be assured that the secondhand panel provides a minimum capacity in watts. This is essential to ensure that consumers can calculate the amount of secondhand panels which they need for a certain solar system. Therefore, a certificate would be necessary that provides information about the capacity and age of the secondhand panel. Again, this certificate would need to be provided by a certified individual or organization to ensure legal compliance before the panel enters the secondhand economy. Building on the principles of a circular economy, this type of solar panel certification should interface with a solar panel tracking platform, as part of product assurance processes. It is, therefore, essential to establish second hand solar panel certification standards, which also will be very informative for a solar panel end-of-life legislation.

Figure 4 shows a potential scheme for the re-use of secondhand solar PV panels. The main aspect is that secondhand panels either from private users via a recycler or from manufacturers via a B2B type agreement need to be certified by licensed certifiers before the panels enter the second hand economy. This process should be in place every time when a panel is re-used.

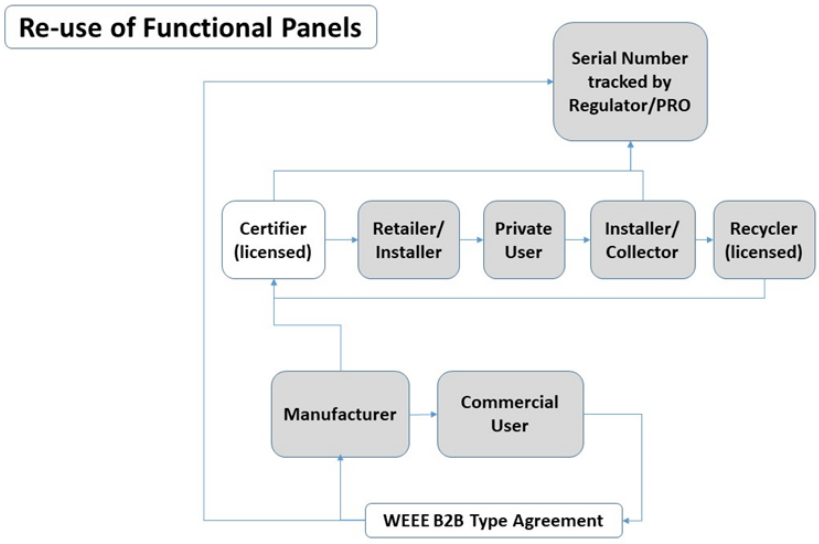

Figure 4. Potential framework for the re-use of PV panels in second hand economy.

9. Levy and flow of funds

Comparison of the level of levy and recycling rates in Europe do not indicate a clear correlation, but can vary significantly between countries. A comparison of the Japanese and Swedish EPR systems for e-waste concluded that while the Japanese requirement for the consumer to pay a substantial recycling fee at end of life could be considered to encourage reuse, it also encouraged illegal disposal. The Swedish system achieved a higher collection rate due to free and convenient collection, whereas the Japanese system obtained greater recycling rates for collected materials due to mandatory targets. This indicates that besides the levy other factors are affecting the recycling rate depending on the jurisdiction. However, among them, the convenience for consumers to ensure the collection of unwanted products without paying a levy at disposal of the product appears to be important to increase the collection rate and decrease illegal disposal [29,30].

If the preferred end-of-life legislation is a product stewardship scheme, it can, therefore, be recommended that an upfront levy like an Advanced Disposal Fee for supporting a product stewardship scheme for solar PV panels is either requested on import or at retail to ensure that private consumers are not requested to pay a significant fee for the disposal of unwanted panels when consumers need to replace damaged panels or want to upgrade existing solar systems. Especially in the case of upgrading existing panels a levy at disposal of the unwanted panels could be detrimental to the solar industry as consumers may delay or cancel the upgrade if the levy is too high.

The study by Monier et al. [29] also shows that high collection rates are achieved where a fully funded product stewardship organization is overseeing the product stewardship scheme and gives effect to obligations for multiple producers in the frame of the scheme. This would require that the levy is set at a level which not only allows to support collection and recycling of the panels, but also provides funds to support the operations of an effective product stewardship organization [29].

It may also be possible to raise the levy at the point of import or distribution from the local manufacturer, as it may present less of an administrative burden due to the smaller number of organizations involved at this point in the supply chain compared to the large number of retailers and/or installers. However, in the case of such an import tax, it is necessary to avoid implications with trade agreements or raising the suspicion of protecting locally produced panels against international competition.

At the current stage, the level of the levy is difficult to define and it may vary significantly between the various jurisdictions, but considering other product stewardship schemes a levy of about 1% of the current sales value of solar PV panels appears to be sufficient. Given the significant number of about 250 million panels installed in 2019 and another about 320 million installed in 2020 worldwide with, of course, significant variations between the various nations, it can be assumed that there is some room to define an effective and sufficient levy, especially in nations with significant uptake of solar power. Whatever levy is applied, previous studies clearly show that it is essential to continuously monitor [23] and, if necessary, adjust the levy to ensure high collection and recycling rates with time.

Commercial consumers of solar panels and manufacturers may engage in B2B agreements which define what will happen with unwanted solar panels and the related cost sharing for collection and recycling or cost-sharing in regards to the levy if the panels enter the regular waste stream. Private consumers can pay the levy of a fraction of it, in case manufacturers agree to cover parts of the levy, on purchase. The collected funds are then provided to the product stewardship organization for its

operation and supporting installers/collectors and recyclers to a level that ensures the viability of the business.

An Advanced Disposal Fee (ADF) levied at the purchase of a solar panel, therefore, appears to be appropriate. Given the large number of already installed solar panels and their expected lifetime, the ADF, however, needs to be calculated to not only cover the costs of the collection and recycling of newly purchased panels, but also the costs of collection and recycling of already installed panels.

Figure 5 shows a potential flow of levy. Key aspects are the tracking of the serial numbers of the panels to control levy payment. As mentioned above, the levy is collected by the product stewardship organization, which also manages the rebates for viable collection and recycling of the panels. Manufacturers and commercial users of panels may negotiate the end-of-life management of panels through a B2B type agreement. However, if panels are not recycled by the manufacturer, but given to a recycler, a levy needs to be paid to the product stewardship organization.

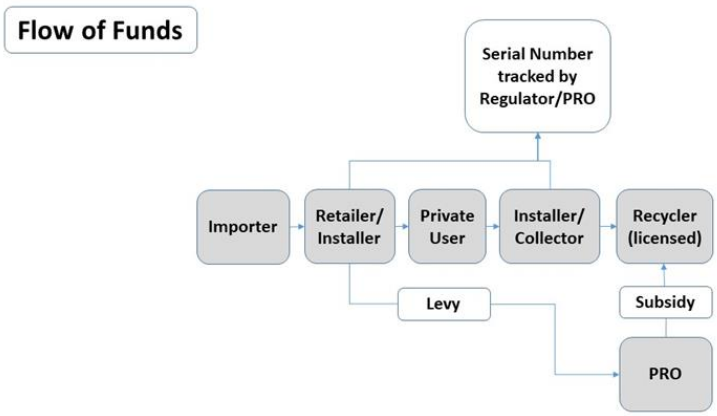

Figure 5. Potential framework for a levy regulation in the frame of a product stewardship scheme for solar PV panels.

10. Conclusions

Various examples of product stewardship schemes and extended producer responsibility schemes in Australia and also other nations for a range of products show that effective and robust end-of-life legislation can be created for the benefit of having a circularity of materials and addressing the problem of increasing amounts of waste and the resulting environmental damage. For solar PV panels, an end-of-life legislation can be designed that addresses existing and new panels and supports the creation of a secondhand economy for the panels. Like for other products, which are subject to end-of-life legislation, it will be necessary to have a levy on the panels to support an emerging recycling industry and finance an effective Producer Responsibility Organization, which regulates the scheme. The widely discussed demand in minerals and materials for renewable energy systems, like solar photovoltaic panels, makes it even more necessary to establish the processes and legislations for a circular economy for especially silicon to reduce the environmental footprint of the manufacturing of solar PV panels. About 3 billion solar PV panels are installed worldwide containing about 1.8 million tons of high-grade silicon, the current value of which is about USD 7.2 billion. Considering this, recycling of solar PV panels has the potential to be commercially successful.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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