Received: 2 July 2021 | Revised: 28 August 2021 | Accepted: 29 September 2021
DOI: 10.1002/pip.3490

SPECIAL ISSUE ARTICLE

PROGRESS IN PHOTOVOLTAICS WILEY

Towards a successful re-use of decommissioned photovoltaic modules

Arvid van der Heide[1] | Loic Tous[1] | Karsten Wambach[2] | Jef Poortmans[1,3,4] | Jan Clyncke[5] | Eszter Voroshazi[6]

[1]imec (Energyville campus), Genk, Belgium
[2]bifa Umweltinstitut GmbH, Augsburg, Germany
[3]Department ESAT – ELECTA, KU Leuven, Leuven, Belgium
[4]UHasselt, Hasselt, Belgium
[5]PV CYCLE, Brussels, Belgium
[6]CEA-INES, Le Bourget-du-Lac, France

Correspondence
Arvid van der Heide, imec (Energyville campus), Thor Park 8320, 3600 Genk, Belgium.
Email: arvid.vanderheide@imec.be

Funding information
European Union's Horizon 2020 research and innovation program, Grant/Award Number: 776680

Abstract

Since massive numbers of photovoltaic (PV) modules are expected to be discarded in the next decades, it is important to think about end-of-life management for those PV modules and to include re-use next to recycling. However, the re-use of decommissioned PV modules is a quite complex subject since there are requirements from technical, economic, environmental and legislative point of view. An evaluation of possible applications for second-hand PV modules showed that currently, the use of these PV modules in high-income countries is only interesting for specific applications. These are the replacement of some defect modules to repair PV systems (that usually still receive feed-in tariff) or the replacement of all PV modules for either a low-cost extension of system lifetime or the repowering of severely underperforming systems. For low-income countries, second-hand PV modules are interesting to build new small to medium size PV systems (often off-grid). The typical decommissioned PV module is a crystalline silicon glass-backsheet module from a utility power plant. Most PV modules originate from plants that have been partly damaged by severe weather or from repowered plants that did not receive feed-in tariff (anymore). Currently, technical requirements to qualify potentially re-usable PV modules for re-use are lacking. In the legislation also, a clear criterion for a PV module to be considered functional is needed, since it is not an easy yes/no situation like for a typical electronic device. In this paper, guidelines for a low-cost quality inspection and cost-effective PV module repair are given. It is proposed to set a clear performance threshold at 70% of the original power for a PV module to be not considered as waste. With this paper, we aim to open the dialogue on a commonly accepted re-certification protocol and threshold values. Currently, the worldwide re-use market size is estimated to be around 1 GWp/year, of which 0.3 GWp/year is originating from Europe (mainly Germany, with Italy rapidly coming up). Many second-hand PV modules are shipped to developing countries without recycling facilities which might create the risk of disposal on the longer term. To create a healthy and sustainable market for second-hand PV modules, it will be important that evaluation standards for potentially re-usable PV modules become available and that the existing electronic waste legislation will be adapted for energy-generating products like PV modules.

KEYWORDS
PV module re-use, qualification and testing, sustainability

1 | INTRODUCTION

The global cumulative installed photovoltaic (PV) capacity reached 623 GWp at the end of 2019 and is expected to reach over 1 TWp by 2025 according to the International Energy Agency (IEA) Photovoltaic Power Systems (PVPS).[1] The rapid steady increase of global PV power will lead to large amounts of PV module waste in the future. International Renewable Energy Agency (IRENA) published an estimated cumulative waste of 1.7–8 million tons by 2030,[2] making clear that adequate solutions for end-of-life management of PV modules will be needed. There are several options to treat waste in general, from preparing for re-use to disposal as schematically listed in the waste hierarchy triangle used in the European Waste Framework Directive* (WFD), shown in Figure 1.

Moving upwards in this triangle means moving to a more favourable option from an environmental perspective. By preparing PV modules for re-use, a PV module that became waste can be turned into a product again, moving up through the red line that separates product and waste. In article 3 of the WFD, the preparing for re-use is defined as ‘checking, cleaning or repairing operations, by which products or components of products that have become waste are prepared so that they can be re-used without any other pre-processing’. In the European waste legislation, there is a strong focus on avoiding waste disposal as much as possible and on stimulating the re-use of discarded products.

In this paper, guidelines for preparing of PV modules for re-use will be given. These guidelines are meant as a first step on the path to adapt existing international standards, and create new ones if necessary, to facilitate the re-use of PV modules. But before discussing these guidelines, the requirements for a successful re-use of PV modules on a large scale will be discussed. Although it might seem obvious that functional and safe PV modules that have been decommissioned should be re-used in installations, there are quite some requirements to make this successful in practice. These requirements are of different nature: technical, economic, environmental and legislative.

The paper will further present a brief overview of the current practices and actors in the market of second-hand PV modules, that already started to grow over the last years. It is to be expected that the re-use market will still change strongly in the future since there will be an increased number of decommissioned PV modules (that will also include other module generations). In addition, the current influence of the feed-in tariff system on the market of second-hand PV modules will disappear, and environmental guidelines are expected to emerge. Although it is difficult to predict these changes correctly, an attempt to do this will be given in an outlook into the future at the end of this paper.

2 | REQUIREMENTS FOR A SUCCESFUL PREPARATION FOR RE-USE AND RE-USE OF PV MODULES

2.1 | Technical requirements for a succesful preparation for re-use and re-use of PV modules

The technical requirements for a PV module to be re-used are the following: the module should still have a reasonable performance compared to its original performance, there should be no safety concerns and the expected remaining technical lifetime should be

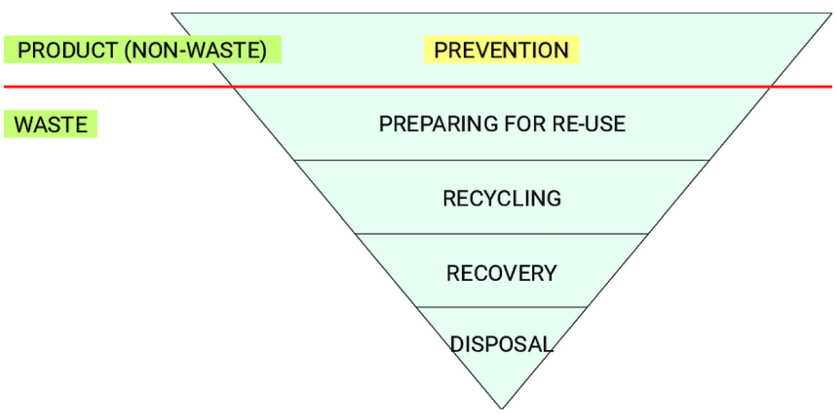

FIGURE 1 Waste hierarchy triangle of the European Waste Framework Directive [Colour figure can be viewed at wileyonlinelibrary.com]

enough to make re-use worthwhile. To ensure this, it is necessary to develop quality checks and sorting procedures for decommissioned PV modules (for some modules, simple repair operations will also be required). It will be clear that it is not possible to do expensive and time-consuming environmental stress tests on each of these PV modules. However, this is also not necessary for two reasons. In the first place, since PV modules have usually been certified according to IEC standards, they are known to pass these tests (in brand-new state at least), so there is no need to repeat them. In the second place, the years of outdoor operation can be regarded as an additional and valuable real-life reliability test, that can even reveal failure mechanisms that had not been detected in the qualification tests of the IEC standard. A clear example of this has been the case of silicon PV modules made with a full polyamide backsheet that did pass certification according to IEC 61215, but that started to suffer from severe backsheet crack formation after only 4–7 years of outdoor operation.[3,4] The mechanisms of this backsheet degradation have been studied over the last years.[5,6] In Figure 2, a picture of such a backsheet is shown.[7]

The point is to perform necessary and sufficient tests for the future re-use of PV modules, with the critical consideration that safety is ensured. Repair of such PV modules should be done wherever needed, and any repair procedure should at least have passed the qualification tests with respect to the expected remaining lifetime. A careful assessment of safety aspects must be considered in combination with a basic performance test as required to fulfil the end-of-waste criteria of the European WFD. In this respect, it can also be worthwhile to sort PV modules for re-use in two system voltage classes, one class for PV modules that keep their original maximum system voltage rating of typically 1000 or 1500 V and another class for PV modules with a decreased maximum system voltage of only 60 V, for which the high voltage isolation test can be skipped. Such a module can be used in a small off-grid system or in a larger grid-connected system, provided that one optimiser per module is used. In Section 3, guidelines for the decommissioning of PV plants and testing of PV modules for future re-use will be given.

2.2 | Economic requirements for a succesful preparation for re-use and re-use of PV modules

The main economic requirement is that the application of second-hand PV modules should be financially attractive, even though the second-hand PV modules will have a lower efficiency and shorter lifetime than new ones. Also, investors should have enough trust in the future reliability of the PV modules although there is usually limited or no product warranty on second-hand PV modules.

Today, the market of second-hand PV modules in Europe is still strongly influenced by the system of feed-in tariffs that has been introduced in many countries in the period around 2005. These feed-in tariffs were introduced to stimulate the installation of PV modules, with a guaranteed price per generated kWh for a period of typically 20 years. This system has two important effects on the market of second-hand PV modules.

In the first place, installations that still receive the guaranteed feed-in tariff will usually not be repowered (replacing of all modules by new ones with higher efficiency) until the period of 20 years is over, to avoid losing the guaranteed feed-in tariff. This causes a delay in the repowering compared to a situation without subsidies, which will also limit the number of decommissioned modules that will become available in the next years. In addition, these 20-year-old modules with rather low efficiency (even the original one) will be close to their expected technical lifetime of around 25 years, so these modules will not be relevant for re-use.

In the second place, the system of feed-in tariffs has created a lucrative business in the trading of rare PV modules which are needed to repair systems having defect modules with identical or similar

FIGURE 2 Full polyamide backsheet showing cracks after several years of outdoor operation [Colour figure can be viewed at wileyonlinelibrary.com]

modules in order to avoid losing the guaranteed feed-in tariff. The most wanted second-hand PV modules are sold for prices of 4–5 €/Wp, which is ~20 times the price per Wp of today's brand-new panels. It will be clear that this replacement will be financially attractive since it avoids the loss of subsidies. For the companies in Germany that started to trade in second-hand PV modules, the selling of rare modules generates the largest part of their profit. In this way, the feed-in tariff system has also stimulated and supported the start and growth of companies trading in second-hand PV modules.

The influence of the feed-in tariff system on the market will gradually decrease in the future, but since this system has been abandoned in most countries only 5 years ago, it will still take around 15 years before it will eventually disappear.

It should be noted that even for PV systems without feed-in tariff, it is very interesting if original modules can be obtained on the second-hand market when some defect modules need to be replaced. The reason is that it is very inconvenient to replace the defect modules by other module types (certainly new ones): because of their different module dimensions and electrical parameters, one or more module strings need to be re-arranged.

For the longer term, also other applications are needed than the usage of second-hand modules to replace the defect modules in old PV systems. Mainstream second-hand PV modules are typically sold at a price of ~0.10 €/Wp, which is 10–20 times less than their original price per Wp. However, since new PV modules became so cheap over the last 10–20 years, these mainstream second-hand PV modules still cost around 50% of the current price of new modules. Given the lower power per area and the lower remaining lifetime, it will be clear that second-hand PV modules will not be preferable above new ones for all applications. Even more so when it is considered that the module costs are only a part of the total system costs (for a utility-scale plant around 30%, varying somewhat per country[8]). This means that the total costs for a system with second-hand PV modules would be only slightly reduced, while the power generation and remaining module lifetime are significantly less.

For several possible applications for second-hand PV modules, the advantages and disadvantages are listed in Table 1.

The disadvantages of installing second-hand PV modules in new residential, commercial/industrial or utility-scale PV plants in Europe are currently considered to outweigh any potential benefit. This means that the main applications for second-hand PV modules are as follows: (1) the repair of old systems, typically still receiving feed-in tariff, which has been mentioned previously; (2) exporting second-hand PV modules to developing regions for installation in new small- to medium-sized PV systems (often off-grid); and (3) replacing all modules of a PV power plant with second-hand PV modules to extend its lifetime at low costs or because the old modules are severely underperforming. These applications could be expanded if environmental incentives would be introduced in high-income countries. A bit differing from the three applications just mentioned above is the on-site repair of defect modules in an existing PV plant that has been included in Table 1. In that case, there is no change of ownership, but still a repair is performed to avoid that the product is discarded.

TABLE 1 List of applications for re-use of PV modules with main advantages and disadvantages

Applications for re-use of PV modules	Main advantages (+) and disadvantages (−) for the potential customer
Replacing modules that have damage, usually due to severe weather. In case of subsidised PV plants, operators are often required to replace the damaged modules by (nearly) identical ones to avoid losing subsidies.	• No loss of (high) subsidies • Possibility to complete the installation again in an easy way. This is also valid for systems without feed-in tariff. • Finding modules (nearly) identical to the damaged ones can be very difficult leading to high module costs.
Replacing all old modules of a PV plant to extend its operation beyond the initial design life of 20–25 years or because the system is severely underperforming.	• Lower module costs • Module dimensions are adapted to existing racks and mounting systems. • Much lower module efficiency, lower remaining lifetime, and less warranty versus using new modules.
Re-use of the defect modules in an existing PV plant after on-site repair to prolong the lifetime of the total plant. A special example is the 'repair' of PID affected panels using electronics that apply a high reverse bias across modules during the night.	• No need to search for replacement modules that are hard to find and that are expensive. • No additional costs for dismantling and transport. • On-site module repair can be hindered by weather conditions. • It can be difficult to reach a particular defect module within a system, or the rear side of modules in general.
Installing modules in a new PV plant which can be of commercial- or utility-scale.	• Lower module costs. • Much lower module efficiency, lower remaining lifetime, and less warranty versus using new modules. Cost savings are also limited since PV modules contribute only ~1/3 of total PV system costs.
Installing modules in a new residential PV system.	• Lower module costs. • Much lower module efficiency, lower remaining lifetime, worse aesthetics and less warranty versus using new modules. Cost savings are also limited since PV modules contribute only ~1/4 of total PV system costs.
Exporting modules to developing regions for installation in new small/ medium-sized PV systems (often off-grid).	• Lower module costs. • Much lower module efficiency, lower remaining lifetime, and less warranty versus using new modules.

Abbreviation: PV, photovoltaic.

2.3 | Environmental requirements for a successful preparation for re-use and re-use of PV modules

From an environmental perspective, the requirements are that both the preparation for re-use (which includes repair if needed) and the re-use of the original PV modules do not have a negative impact on the environment.

There are no negative effects on the environment when the operation period of a PV module is prolonged (in contrast to the prolonged use of old cars, for example). Since recycling methods are still expected to improve in terms of the material recovery, the re-use of the PV module could also provide more time to explore improvements of waste treatment methods. When second-hand PV modules are applied at locations where there is no electricity grid and where these modules replace generators running on fossil fuels, this would reduce both carbon dioxide emissions and air pollution.

The feasible methods for repair of PV modules mainly involve replacement of parts that are needed to transport the current from the inside of the module to the external world (cables, connectors and junction boxes) and do not involve operations that create hazardous emissions and/or waste streams.

Although preparing PV modules for re-use and the re-use itself is no reason for concerns about the environment, the relocation of modules to countries without collection and PV module recycling facilities is a reason for concern.

In such a case, chances are high that the valuable metal parts like the aluminium frame and the copper cables will still be removed, but that the laminated glass-sheets with the solar cells inside will not be recycled. Especially for systems in remote locations, the collection probability will be close to zero. The biggest concern for the environmental pollution by uncontrolled disposal of PV modules is the leaching of metals, for example, in the case of silicon modules, this might be the leaching of lead (Pb) contained in the solar cell metallisation and the solder tin on the interconnection strips. For modules with intact glass, this risk is virtually zero, but upon frame removal or afterwards, the tempered glass plate will very likely become shattered, which enables leaching of toxic materials. This is an important issue, as has been shown by researchers that investigated the rate of leaching from solar modules for different module technologies.[9,10]

Of course, the absence of local recycling facilities is also a concern for the installation of new PV modules in these regions, although for these modules there would be more time left to still create local waste treatment facilities. Apart from local recycling, another solution could be to first collect a huge number of modules locally before shipping these modules to a recycling facility elsewhere in a large batch to be more efficient. However, in both cases, the economical assessment will be predominant and since developing countries usually do not even have a waste treatment infrastructure for the classical waste flows, it is very unlikely that for a special waste flow, such as PV modules, one or more treatment facilities will be constructed.

2.4 | Legislative requirements for a succesful preparation for re-use and re-use of PV modules

The legislative requirement for a successful preparation for re-use and re-use of PV modules is that there should be a clear set of requirements for the preparation for re-use and re-use of PV modules—products that generate electricity (!)—in order to avoid the abuse or misuse of the concepts of preparation for re-use and re-use itself. An important example of such misuse is the exporting of real waste PV modules while stating on the paper trail that these modules are 'second-hand' PV modules, a classic illegal route for electrical and electronic waste.

On the highest (global) level, the Basel Convention[11] from 1989 has set rules for the shipment of all kinds of waste, electronic waste is also one of the waste categories within this Convention. In the European Union (EU), the Waste Shipment Regulation† of 2006 (originally dating from 1993) sets the rules for the transboundary shipment in, within and outside the EU and thus is the European implementation of the Basel convention. In the 2012 revision of the EU directive on Waste from Electrical and Electronic Equipment (WEEE),‡ PV modules have been included for the first time under its scope. The WEEE Directive is a classic example of the application of the so-called Extended Producer Responsibility principle, whereby the first one placing a product on the territory of one single country must organise the take-back, the waste treatment and the financing of these operations.

In general, within the Basel Convention, the Waste Shipment Regulation and the WEEE Directive, there is a clear set of rules to define when a product is waste or when it can be considered as a product fit for preparation for re-use and its accompanying shipment. What is missing is regular inspection on these rules by each single country of the EU. For PV modules, an important shortcoming of the current legislation is that the rules to discriminate between waste and a potential product that is fit to prepare for re-use have been designed with only energy consuming devices in mind. For these devices, the functionality is easy to verify: It is still working, or not. For a PV module, this is not the case: Since its power output will gradually decrease, it is necessary to set a minimum limit for the fraction of the original power to be able to discriminate between a potentially re-usable product and waste. Even if such a limit would be introduced in the accompanying Correspondents' Guidelines§ under the Waste Shipment legislation, its verification is not straightforward, since it requires special equipment to measure the remaining power output. It should be mentioned that in the context of the Basel Convention there are also other requirements for used EEE not to be WEEE. These are, among others, the absence of external damage and sufficient packaging to avoid transport damage, and the availability of the invoice/contract related to the selling of the EEE to a third party in which it is stated that the materials are for direct re-use.

In the rest of the world, PV modules are usually not considered as WEEE, but just as general waste. This enables easier operating for traders in second-hand PV modules since there are less demanding rules and there is less administrative burden related to the Extended

Producer Responsibility, but it also implies that there is a far higher risk on unwanted practices.

3 | PREPARING DECOMMISSIONED PV MODULES FOR RE-USE

3.1 | Available decommissioned PV modules

Before discussing the guidelines for preparing for re-use, it is instructive to know where the decommissioned modules come from, and what properties we can expect from these modules. Concerning the module technology, Figure 3 shows the module power that has been produced worldwide per year for the period between 2000 and 2020, broken down by technology.[12]

It will be clear that almost all modules installed are from crystalline silicon (c-Si) technology, thin film contributes only ~5%. The graph also shows that module production became much larger after 2010, which means that huge amounts of discarded panels can be expected in the near future.

Concerning the module construction, it is important to note that the decommissioned c-Si modules currently available have still been made with a backsheet as rear cover, since glass–glass standard modules became more popular only in the last couple of years. Building-integrated photovoltaic (BIPV) modules are of negligible importance for re-use since their installation share is only ~1%, while they are often custom made and installed in small- to medium-sized systems so that re-use is rather unlikely.

In practice, almost all decommissioned PV modules for preparation for re-use are removed from utility-scale power plants (>1 MWp) since removal from smaller systems is inefficient. A first reason for removal can be a severe weather event (hail, storm, lightning strikes, …) that destroyed only part of the modules while other modules are still acceptable for potential re-use. A second reason can be the occurrence of modules that got defect in any other way: These PV modules are removed and replaced by new ones. Finally, a third reason for the removal of PV modules from an existing system can be its repowering. As has been explained in Section 2.2, this repowering is delayed in countries that did introduce guaranteed feed-in tariffs but is normally expected to take place after a period of around 10 years. It should be mentioned here that next to power loss, another important reason for the decommissioning of a plant can be the safety problems, in the majority of cases caused by deep cracks in the back sheet material, like the ones that can be observed in Figure 2.

3.2 | Guidelines for decommissioning PV plants

Since the preparing for re-use can profit from a correct decommissioning of PV plants, some guidelines for decommissioning large PV plants will be given in the following paragraphs. Ideally, this starts with collecting the PV plant general input data (PV module types, dimensions, nominal electrical data, number of modules per string, …). The owner or operator of the decommissioning site may be able to supply information about the PV modules (current age, predominant defect types, current typical electrical module data, …). To obtain general information about the condition of the modules in a PV plant in a quick way, test results from string measurements in the field and monitoring results of the plant can be studied. This can be complemented by drone flights with infrared camera measurements to identify potential defects. The collected information about the PV plant can be used to decide if the evaluation of the modules can best be performed at the decommissioning site or at a treatment facility. Other important factors in this decision are the time and budget available for the decommissioning process. If the modules in the PV plant are known to be prone to potential induced degradation[13] (PID), it is important to realise that all modules in the system are PID prone, also the ones that were not degraded since they were internally at a positive polarity with respect to the frame. The information shall be used in the decision tree on any reuse/repair refurbishment and economic considerations. Based on the detailed analysis of the PV plant, it could also

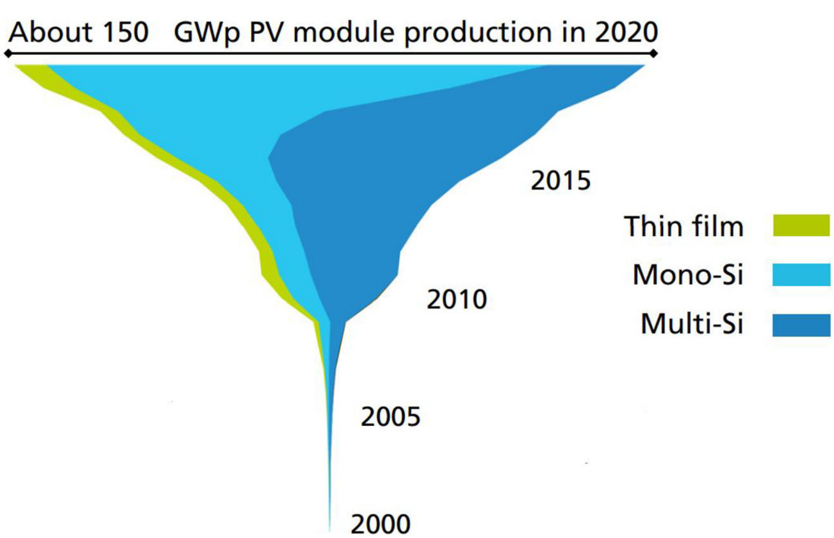

FIGURE 3 Annual worldwide PV production 2000–2020 (in GWp) by technology [Colour figure can be viewed at wileyonlinelibrary.com]

still be decided that an on-site repair of defect modules is preferable above decommissioning of the plant.

Although it might sound logical, it is important to stress that the PV modules should not be damaged externally or internally during dismantling, transport and storage. Since the dismantling concerns old modules and time is money, workers are typically less careful than with new ones. This could result in external damage to glass, backsheet, connectors or cables, and internal damage to the cells and interconnections by bending modules or even walking on them. Also, correct packaging is important to avoid transport damage, although this is usually not high on the priority list for modules that have been dismantled. Guidelines and dedicated actors could change these current practices.

3.3 | Guidelines for preparing modules for re-use

For the development of the guidelines below, it has been assumed that the potential second-hand modules will only be (low value) mainstream modules. This choice has been made since the expensive 'rare' modules will later disappear from the market anyway, and even now they only represent a small amount of cumulative power. Since the value of the mainstream second-hand PV modules is only around 0.10 €/W, it will be clear that little time and money can be invested in the preparing for re-use. Still, it will be necessary to perform some minimal verification of the module quality, performance and safety.

In this section, some main concepts about such a verification and sorting procedure will be presented, but it should be stressed that this is not intended as a final and complete set of guidelines covering all details. Within the European R&D project CIRCUSOL, that handles about circularity concerning PV modules and batteries, several partners are still working together on this subject and are now in contact with the IEC Technical Committee 82 (Solar Photovoltaic Energy Systems) to initiate standardisation on the preparation for re-use and re-use of PV modules. The final goal is to adapt existing standards and/or develop new ones to facilitate a successful preparation for re-use and re-use of PV modules on a large scale, but the first target is to write an IEC 'Technical Report' on the standardisation requirements for second-hand PV modules.

The quality inspection and possible repair can be done either at the decommissioning site (avoids extra handling of modules) or at a treatment location with more verification and repairing facilities. As mentioned in the previous section, this location choice can be based on the general condition of the modules as derived from plant monitoring data and drone imaging of the modules (if available).

During the quality inspection, the modules will be sorted into three different classes:

- Class 1: Re-use without further treatment is possible
- Class 2: Further measurement and/or repair required
- Class 3: Recycling

The process of inspection and sorting of modules for both location types is shown in Figure 4.

As shown in Figure 4, any electrical testing should be performed only after passing a quick visual inspection, since it would be a waste of time and money to do this for modules with severe visible defects. A very detailed checklist for visual inspection of fielded modules has been published by National Renewable Energy Laboratory (NREL).[14] Figure 5 shows an example of a simplified version of such a visual inspection checklist that is more practical to inspect many PV modules within a reasonable amount of time.

Only modules with damaged junction box, cables, local backsheet scratches or connectors should still be submitted to electrical testing (after repair if this is required to measure) while the presence of other visual defects (broken glass, broken ribbon, burn marks, large area edge delamination, broken frame, etc.) should lead to modules being put directly to the recycling class.

The most basic electrical testing of module performance is the measurement of short circuit current (I_{sc}) and open circuit voltage (V_{oc}) in daylight using a hand-held multi-metre. These I_{sc} and V_{oc} values can then be compared to the original module datasheet values. Since differences in I_{sc} and V_{oc} will only reveal very severe defects, these measurements can only be used to reject really bad modules, so they are of limited use. For this reason, it is strongly recommended to measure a full *I-V* curve for each module. Nowadays, portable *I-V* curve recorders are available that include irradiation and temperature sensors to correct to standard test conditions. Even though the irradiation is corrected for, it is recommended to do these outdoor measurements when the module is illuminated with direct solar irradiation for the best accuracy. Investing in a mobile solar simulator can be worthwhile when one is frequently measuring many modules on-site. Compared to a portable *I-V* curve recorder, the measurements are more precise and can be done independent of the outdoor irradiation conditions.

A difficult point concerning the evaluation of the *I-V* curve is to decide when the module is not (sufficiently) functional anymore. For a usual energy consuming appliance, it is easy to test on functionality: It either works or not. However, for a PV module, the only way to judge its functionality is to set a lower limit for the remaining power, and this value will always be somewhat arbitrary. A reasonable value for the lower limit could be for example 70% of the original power, which represents already a power below the expected value after 20 years, according to the usual annual degradation rate of PV modules. It would be good if such a limit would also be included in the future waste legislation to solve the current issue of unclarity about functionality for energy-generating devices. Still there would be the issue that it is not possible to check modules on their performance without a solar simulator (or alternatively an *I-V* tracer provided that solar irradiation is available), but it is important to have at least some value to enable the discrimination between functional product and waste if needed.

As mentioned in Section 2.1, it can be practical to make a further subdivision into two maximum system voltage classes: the original value (typically 1000 or 1500 V), or a reduced value of only 60 V. For

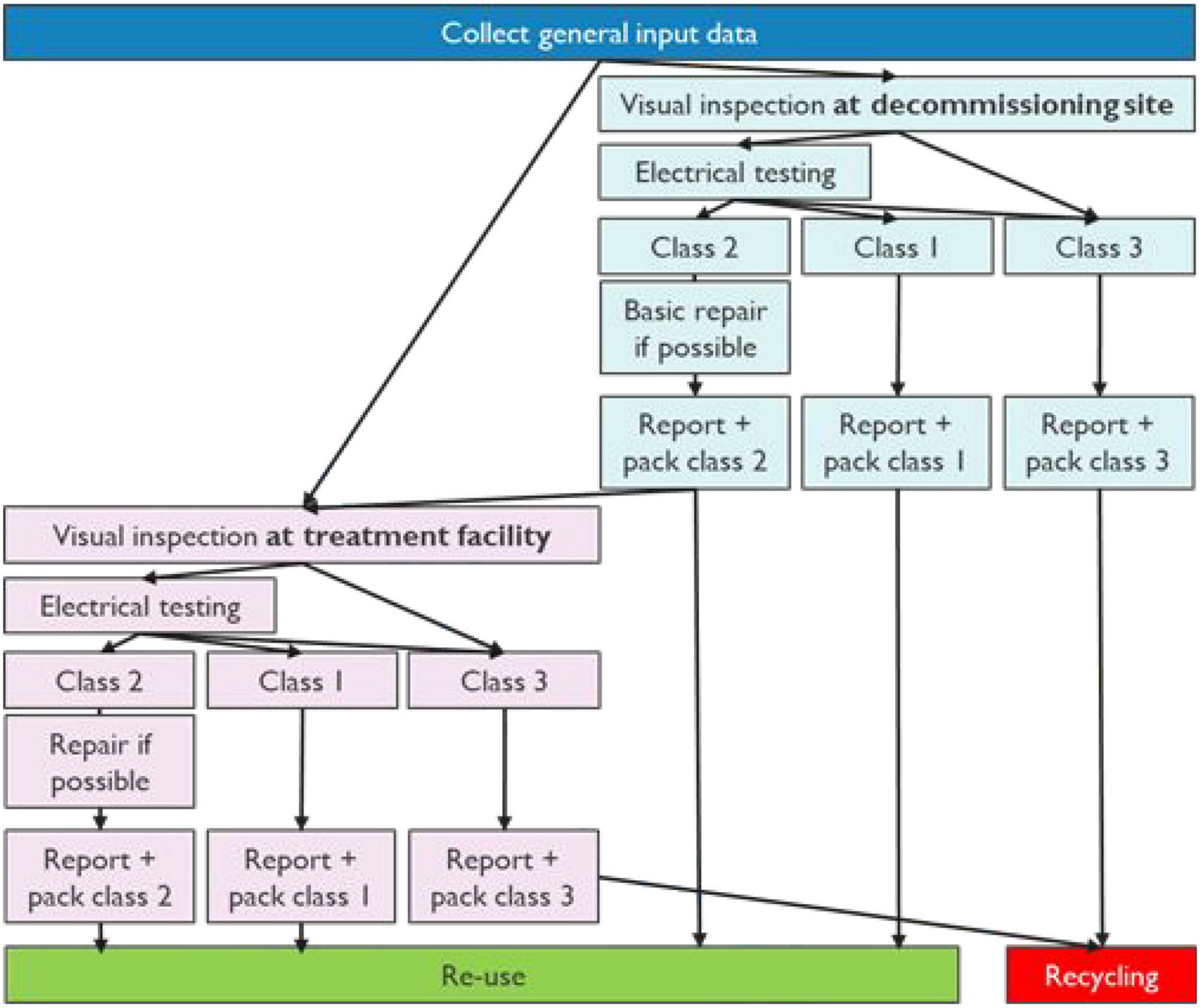

FIGURE 4 Inspection sequence for preparing PV modules for re-use at the decommissioning site (light blue) or at a treatment facility (pink) [Colour figure can be viewed at wileyonlinelibrary.com]

this 60-V class, no further electrical tests are required, and small defects like backsheet scratches can be accepted. An option could be to send also modules known to be PID prone to this 60-V class (even if they did not degrade in the system since they were closer to the non-degraded part of the string). In this way, it can be prevented that the modules will suffer from PID in the future. Another option could be to clearly mark these modules to be PID prone, but this would assume that future users of these modules know how to avoid further degradation of PID modules.

For modules that are intended to keep the original maximum system voltage rating, the following minimum electrical safety tests should be performed:

- Ground continuity tests of all frame parts
- Isolation resistance

Modules failing these safety tests could still be sent to the 60-V class. The test types just mentioned have been specified for new modules in IEC61730-2, MST13 (ground continuity, to check if all frame parts are electrically connected) and MST16 (isolation resistance, determination if the module is sufficiently well-insulated between current-carrying parts and the frame). In practice, it has been found that it is rather difficult for modules that have been operated for many years outdoor to pass the isolation resistance test of the IEC61730-2 standard (that are normally applied on new modules that have never been installed outdoor). This could be due to moisture ingress into the module and/or decreased isolation by the encapsulant. For this reason, it seems reasonable to perform an isolation test that is somewhat less strict for these modules. However, it still has to be determined what would be a safe and reasonable upper limit for the leakage current for second-hand PV modules.

Concerning the use of electroluminescence (EL) for examination or sorting of modules, in view of the costs and also the difficulties to judge the severity of defects in these images, it seems not feasible to do this for every module. However, the technique can be helpful to get a view on the type of defects that are present in the modules, by

Glass plate broken	Backsheet scratches	Moisture/corrosion in module	Broken interconnection strip(s)
☐	☐	☐	☐
>10% of cells broken	Delamination at edges	Burn mark on cells or ribbons	Air bubbles at module edge, on/between cells
☐	☐	☐	☐
Frame warped/broken	Junction box damaged	Cable damaged or loose	Cable connector(s) damaged
☐	☐	☐	☐

FIGURE 5 Example of checklist for visual inspection

sampling several modules originating from different positions in module strings.

Finally, the repair options for modules that were sent to Class 2 will be briefly discussed now. A list of defects with repair solutions and repair costs is presented in Table 2.

Failed bypass diodes, damaged junction boxes, connectors and cables typically occur randomly among PV modules in a plant, with an occurrence of a few percent of the total number of modules. The costs for some of these repairs (mentioned in Table 2) would be too high if every module had to be repaired, but since only a few percent of the potentially re-usable PV modules need to be repaired for these failure types, repairing is still economically feasible. When distributing the costs among all the modules, the costs per module are reduced to a few € only.

For the repair of cracked backsheet, the situation is different since all modules in a PV plant are affected when an inferior backsheet material has been used. The best technical solution to solve this issue is by applying a coating on-site to avoid transport costs and minimise downtime. Since the number of modules with backsheet issues is large (in Europe alone, the affected solar capacity is estimated to be 6 GW), currently several institutes and companies put a lot of effort in finding a backsheet repair solution that is both reliable and economically viable. Material costs for this coating solution are only ~3 euro per module,[15] but the repair time of 8–10 min per module seems rather long for a practical solution (according to a developer of such a repair solution the target should be at most 2 min per module). Recently, also a product has been introduced that is a piece of backsheet with a strong adhesive layer that has the size of the full module, and is to be glued on top of the old backsheet. Given the large effort that is currently put into these backsheet repair solutions, there is a considerable chance that a solution will be developed that meets the requirement of being reliable and economic at the same time.

TABLE 2 Module defects, repair solutions and total cost estimates (for W-Europe in 2020) based on experience of field operators

Defect	Repair solution	Estimated costs/module (€)
Failed bypass diode(s) in junction box, typically short-circuited	Replace bypass diode(s) by comparable ones. In the future this solution will often not be possible anymore, due to the current trend to fill more and more junction boxes with potting material	20
Failed bypass diode(s) with potting in junction box	Remove the junction box and replace by new one (including diodes) that does not require potting	60
Junction box with internal or external damage	Remove junction box and replace by comparable new one	60
Damaged cables	Replace cables (including connectors)	20
Damaged or missing cable connector(s)	Mount new connector(s) on cables	5–10
Cracked backsheet over entire surface	Clean backsheet and apply a coating on top of the original backsheet	Still under development

4 | OVERVIEW OF THE SECOND-HAND PV MARKET AND CURRENT PREPARING FOR RE-USE

The second-hand PV market has grown over the last years, leading to worldwide 15 companies trading in re-usable and second-hand PV modules by now. These companies are trading an estimated 1 GWp/year in total, of which around 0.3 GWp/year originates from Europe. These estimates are based on discussions with actors in the field of preparing PV modules for re-use, since neither site decommissioning nor PV reselling is being registered. In Europe, five German companies are active in this sector, which is logical since Germany was the earliest adopter of PV, and has the largest installed power of Europe as well. Most of the other big players are registered in China. Second-hand PV modules are mostly in demand in low-income markets. These include African countries but also certain regions of the Middle East and South East Asia which seek extreme low-cost PV systems with less quality/aesthetic requirements. The (usually rare) modules that are used to replace defect modules in feed-in tariff systems by identical or similar ones amounts to around 10 MWp/year in (Western) Europe. Overall, second-hand PV modules are not competitive for new residential, commercial and utility-scale PV installations in high-income countries. Preparing for re-use and re-use of a PV module in these countries is today only viable for niche applications and its uptake will depend on the issue if/how CO_2 footprint will be integrated in electronic product cost.

5 | CONCLUSIONS AND OUTLOOK

The evaluation of possible applications for second-hand PV modules showed that the use of these modules in high-income countries is only interesting to repair PV systems that usually still receive feed-in tariff, to replace all modules of a plant to extend the lifetime of it at low costs or to repower severely underperforming systems. In lower income countries, second-hand PV modules are interesting to build new small- to medium-sized PV systems that are often off-grid. The typical decommissioned module is a crystalline silicon glass-backsheet module from a utility plant. Most PV modules originate from plants that have been partly damaged by severe weather or from repowered plants. Guidelines for a low-cost quality inspection and cost-effective module repair have been given. To start with, a visual inspection excludes modules with shattered glass, bended frames, hot spot damage and so on for which it does not make sense to do any further inspection. The cost pressures on second-hand PV modules demands to limit the qualification to an outdoor/indoor I-V measurement and basic safety tests.

An important difficulty is the criterion for a module to be still functional, since it is not a clear easy yes/no criterion like for a typical electronic device. In this contribution, a value of 70% of the original power is proposed to open the discussion with the different actors. We believe a common set of testing requirements and performance threshold in a standard is critical to ensure quality, that can trigger acceptance from users and create a clear boundary with modules that should be considered as waste. Currently, the worldwide re-use market size is estimated to be ∼1 GWp/year, of which 0.3 GWp/year originating from Europe (mainly Germany). Many second-hand PV modules are shipped to low-income countries without recycling facilities which might finally result in module disposal, which is an important concern.

It is important to create international standards for the quality inspection of re-usable PV modules. Developments in this direction are currently made within the European project CIRCUSOL, a group of partners of this project has contacted IEC TC82 to start the standardisation, with the writing of an IEC Technical Report as the first target.

Concerning waste legislation, it is important to note that the EU is currently the only region that has categorised PV module waste, namely, in the category of electronic waste. But even in the EU, the legislation should still be more adapted to PV modules (as it was originally written for classic electronic equipment consuming electricity instead of electricity-generating equipment). It will be clear that it is important to create also adequate waste legislation for PV modules in non-EU countries, to enable a sustainable second-hand market.

Looking into the further future (10–20 years), there will be important positive changes for the potential of preparing PV modules for re-use, since these decommissioned modules:

- Will be mostly of glass–glass type: less risks for re-use (less cell cracks, lower degradation and no backsheet issues).
- Will be mostly of multi-wire type: power less sensitive to cell cracks.
- Will come from systems without feed-in tariff: no need to wait 20 years before repowering.
- Will be probably cheaper compared to new ones than now, due to more availability and limited possibility for future price lowering for new modules.

While the better quality and reliability of decommissioned modules mentioned in the first two points are positive for 're-users', they might delay repowering. An increasing number of national and European incentives consider the environmental footprint of PV modules which can further encourage re-use of PV modules. In summary, re-use of PV is expected to increase considerably in the future, and an adapted technical, legislative, economic and environmental framework can support this emerging sector and contribute to the creation of a circular PV sector.

ACKNOWLEDGEMENTS

The authors would like to thank Mónica Alemán, Ivan Gordon, Bart Vermang, Sebastien Lizin, Boris Mertvoy and Kerstin Baumann for their valuable contributions to this work. This work has been funded in part by the CIRCUSOL project that has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement 776680.

DATA AVAILABILITY STATEMENT

Research data are not shared.

ORCID

Arvid van der Heide https://orcid.org/0000-0002-7589-4526

Loic Tous https://orcid.org/0000-0001-9928-7774

Karsten Wambach https://orcid.org/0000-0003-0422-4557

Jef Poortmans https://orcid.org/0000-0003-2077-2545

Eszter Voroshazi https://orcid.org/0000-0002-7412-8467

ENDNOTES

* Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance), also called the Waste Framework Directive.

† Regulation (EC) No 1013/2006 of the European Parliament and of the Council of 14 June 2006 on shipments of waste.

‡ Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on WEEE.

§ Correspondents' Guidelines No 1 on Shipments of WEEE and of used Electrical and Electronic Equipment (EEE) suspected to be WEEE.

REFERENCES

1. Masson G, Kaizuka I "Trends in photovoltaics applications 2020", Report IEA PVPS Task 1, International Energy Agency (IEA) Photovoltaic Power Systems (PVPS) Programme. 2020.
2. IRENA report. "End-of-life management solar photovoltaic panels" 2016.
3. Han H, Ji X, Hu H, et al. Aging behavior and degradation of different backsheets used in the field under various climates in China. *Sol Energy Mater Sol Cells*. 2021;225:111023. https://doi.org/10.1016/j.solmat.2021.111023
4. Tracy, J, Gambogi, W & Felder, T, et al. Survey of material degradation in globally fielded PV modules. Proc. of the 46th IEEE Photovoltaic Specialists Conference, Chicago, USA; 2019. https://doi.org/10.1109/pvsc40753.2019.8981140
5. Lyu Y, Fairbrother A, Gong M, et al. Drivers for the cracking of multilayer polyamide-based backsheets in field photovoltaic modules: in-depth degradation mapping. *Prog Photovolt*. 2020;28(7):704-716. https://doi.org/10.1002/pip.3260
6. Lyu Y, Kim JH, Fairbrother A, Gu X. Degradation and cracking behavior of polyamide-based backsheet subjected to sequential fragmentation test. *IEEE J Photovolt*. 2018;8(6):1748-1753. https://doi.org/10.1109/jphotov.2018.2863789
7. Eder GC, Voronko Y, Oreski G, et al. Error analysis of aged modules with cracked polyamide backsheets. *Sol Energy Mater Sol Cells*. 2019;203:110194. https://doi.org/10.1016/j.solmat.2019.110194
8. IRENA report. "Renewable power generation costs 2020" 2021.
9. Nover J, Zapf-Gottwick R, Feifel C, Koch M, Metzger JW, Werner JH. Long-term leaching of photovoltaic modules. *Jpn J Appl Phys*. 2017;56(8S2):08MD02. https://doi.org/10.7567/jjap.56.08MD02
10. Nover J, Zapf-Gottwick R, Feifel C, Koch M, Werner JH. Leaching via weak spots in photovoltaic modules. *Energies*. 2021;14(3):692. https://doi.org/10.3390/en14030692
11. Basel convention on the control of transboundary movements of hazardous wastes and their disposal. 1989.
12. Phillips S, Warmuth W. Photovoltaics report, Fraunhofer ISE/PSE Projects. 2021.
13. Pingel S, Frank O, Winkler M, Potential induced degradation of solar cells and panels. Proc. of the 35th IEEE Photovoltaic Specialists Conference, Honolulu, USA; 2010:2817–2822. https://doi.org/10.1109/pvsc.2010.5616823
14. Packard CE, Wohlgemuth JH, Kurtz SR. "Development of a visual inspection data collection tool for evaluation of fielded PV module condition", National Renewable Energy Laboratory (NREL), Golden, USA, NREL/TP-5200-56154. 2012.
15. Voronko Y, Eder GC, Breitwieser C, et al. Repair options for PV modules with cracked backsheets. *Energy Sci Eng*. 2021;9(9):1583-1595. https://doi.org/10.1002/ese3.936

How to cite this article: van der Heide A, Tous L, Wambach K, Poortmans J, Clyncke J, Voroshazi E. Towards a successful re-use of decommissioned photovoltaic modules. *Prog Photovolt Res Appl*. 2021;1-11. doi:10.1002/pip.3490