D3.2 Labelling and certification protocols for second life PV modules

Overview

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Contents

Glossary of terms

Backsheet	Polymer foil at the back side of a PV module protecting the internal components. Backsheet is usually white, can be black or transparent (for bifacial applications).
Bifacial PV module	PV module generating extra electricity thanks to a transparent back side (glass or backsheet). It contains c-Si cells with only partial metal coverage at the back.
BIPV module	Building Integrated PV module: a PV module that has been designed to replace a normal outer skin building material/element such as ventilated facade or roof tile.
BOS	Balance Of System: all components of a PV system other than the PV modules, like cabling, mounting, inverter(s), batteries, etc.
Bypass diode	Diode that is placed across typically 20-24 solar cells in series. It reduces module power losses by bypassing the cells in case of partial shading.
CdTe module	A thin-film PV module containing cadmium (Cd) telluride (Te) as active material.
CI(G)S module	A thin-film PV module containing copper indium (gallium) selenide as active material. Gallium is optional as CIS modules also exist.
c-Si module	A PV module containing crystalline silicon (c-Si) as active material. The silicon can be either monocrystalline or multicrystalline (also called polycrystalline).
Direct re-use	The deployment of decommissioned modules without prior intervention such as repair or testing.
EL (-testing)	Electroluminescence (EL) shows module defects like cracks by infrared imaging while current is injected into the module with a power supply
Encapsulant	Polymer material inside a PV module to glue the cells against the front and back cover of the module, and to protect the cells.
IEA	International Energy Agency
Inverter	Electronic device converting DC electricity generated by PV modules into AC electricity for the public grid.
IRENA	International Renewable Energy Agency, an organisation for the promotion of renewable energy with 160 member states.
Junction box	Box at the module's back side or edge, in which the solder strips exiting the module are connected to the external cables. It contains 1-3 bypass diodes.
PID	Potential Induced Degradation, which is the decrease in module power over time (weeks/months) due to the presence of a large potential difference between cells inside the module and the frame. Some modules

	are quite sensitive, while others are not (depends on cell process, encapsulant, …)
Preparing for re-use	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.
PV module string	Several PV modules (can be up to 20) that have been connected in series and are connected to one inverter or battery charger.
PV power plant	A PV system that is large enough to be called a power plant, typically > 1 MW_p in total module peak power. Usually ground-mounted utility-scale PV systems.
PV system	Several PV modules that are interconnected, plus all other components completing the installation (mounting, inverters, etc.). Either connected to the public grid or as off-grid system with battery storage
Recovery	Any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a specific function.
Recycling	Any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes.
Refurbish	The term is often used for valuable goods such as expensive electronics or furniture that are prepared for second use with all necessary measures, comprising cleaning, repairing, and repackaging.
Repair	"to restore something (damaged, faulty or worn) to a good condition" (Oxford Online Language Dictionary).
Re-use	Any operation by which products or components that are not waste are used again for the same purpose for which they were conceived.
Second-life (PV) module	A PV module that has been decommissioned and prepared for re-use (the latter should be the case, but this is not always true in practice)
Thin-film PV module	PV modules with active layers of only a few micrometer thick. Modules can be flexible and semi-transparent, usually with lower efficiency than c-Si PV modules.
Waste	Any substance or object which the holder discards or intends or is required to discard.

1 Introduction

1.1 Circular solutions needed for decommissioned PV modules

The cumulative installed PV capacity reached (globally) 623 GW at the end of 2019 and is expected to reach over 1 TW by 2025 according to the IEA PVPS (Photovoltaic Power System Programme) [1]. The rapid steady increase of global PV power will lead to large amounts of PV module waste in the future. 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, from preparing for re-use to disposal as schematically shown in the waste hierarchy used in the European Waste Framework Directive[3] (Figure 1). Moving down in the triangle means moving to a less favourable option from an environmental perspective. By preparing PV modules for re-use, PV module waste can be turned into a product again, moving up through the red line that separates product and waste.

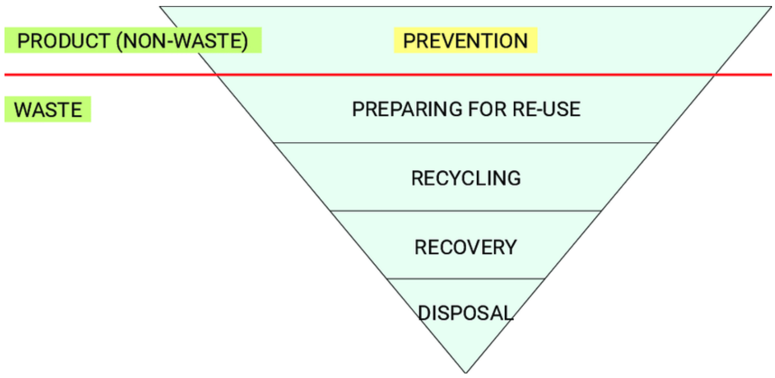


Figure 1: Waste hierarchy triangle.

In the European waste legislation, there is a strong focus on avoiding waste disposal as much as possible, and to stimulate the re-use of discarded products. However, from a technical, economic, and legislative point of view, the re-use of these decommissioned modules is not straightforward at all. **The main goal of this deliverable is to provide guidelines for the preparing for re-use that ensure sufficient PV module quality while still being economic. This involves the application of several testing/inspection methods and a correct re-labelling of the modules.** In the next section, first the requirements will be given for a decommissioned module to be fit for re-use. Then, the standard qualification procedure for new PV modules will be presented as a starting point. It will be discussed how applicable (or not applicable) these tests are as quality checks for decommissioned modules.

1.2 First considerations for testing of decommissioned PV modules

In the first place, it is important to list the main technical requirements for a decommissioned PV module to be fit for re-use. These 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 long enough to make re-use worthwhile.

As a starting point, it is interesting to look at the requirements for new modules. For these ones, international certification standards do already exist for a long time, namely IEC 61215 for general quality (for crystalline silicon PV modules) and IEC 61730 for safety. These standards describe a number of tests that can be performed on a batch of new test modules, assuming that these have all been produced using exactly the same materials and in stable and controlled processes (typical for mass production). The IEC 61215 test sequence is illustrated in the scheme in **Error! Reference source not found.**.

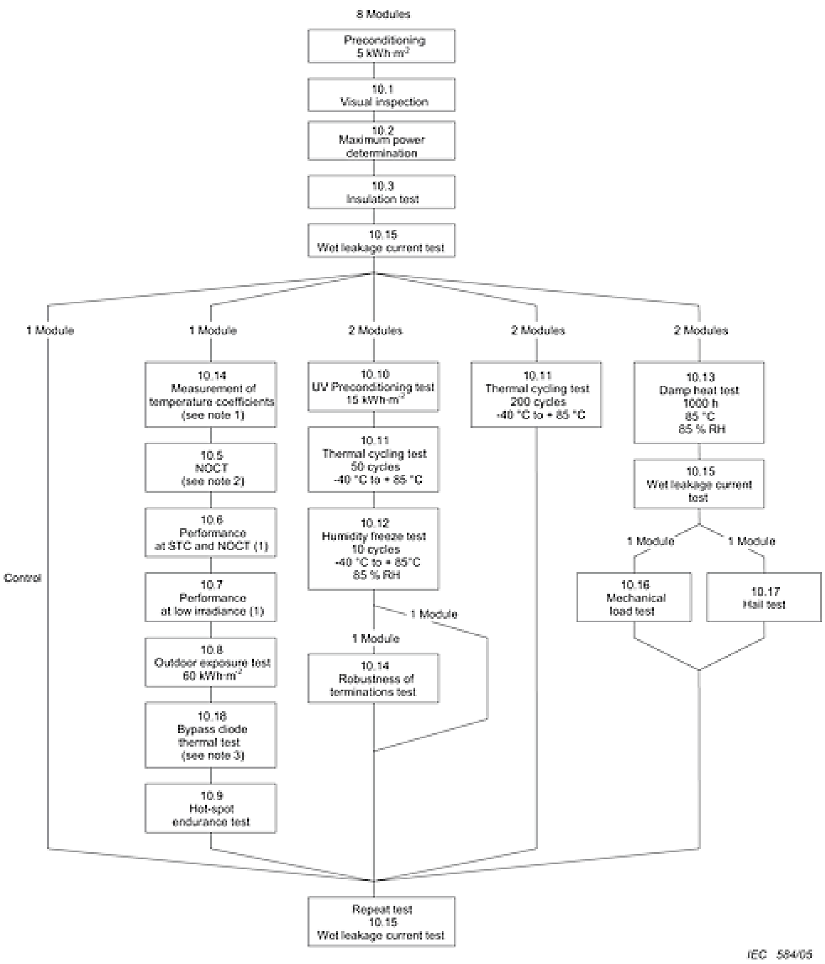


Figure 2: Test sequence for new modules according to IEC61215 (quality certification for c-silicon modules).

Some of the listed environmental stress tests take 6 weeks. It is therefore practically impossible to perform such tests on each of the decommissioned modules. Fortunately, this is also not necessary, for two reasons. First, since PV modules have been certified according to the IEC standards, they are known to pass these tests (in brand-new state at least), so there is no need to repeat them all to qualify the used materials. Secondly, 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.

Although it is neither possible nor necessary to do all tests as described in IEC 61215 on decommissioned modules, there are also tests of short duration among them that could be useful. In particular these are:

- the visual inspection (10.1),
- maximum power determination (10.2)
- and the insulation test (10.3).

When selecting the most suitable quality checks, it is important to consider that the prices for new PV modules have strongly decreased over the last 10 years. Therefore, it is necessary to **limit testing of used PV modules to a minimum** to ensure the **economic feasibility of PV module re-use**. Nevertheless, potential customers do expect to buy 2nd life modules of sufficient **quality and performance**, for which **testing will be required to guarantee this**. In addition, it should be avoided that decommissioned modules of bad quality are transported as second-life modules to other world regions where they will then be soon -if not immediately- discarded as waste. Apart from modules that can be tested without the need for repair, there are also modules that should first be repaired. In that case, the question is if additional tests must be performed, and, if so, which ones.

From these preliminary considerations, it becomes clear that sufficient testing and sorting of decommissioned solar modules is a difficult balancing exercise. In this deliverable, an attempt to come to such a testing and sorting procedure will be made. To obtain a better idea about the tests that are relevant and practical in this respect, common types, origins and possible applications for re-use of decommissioned modules will be first discussed in the next chapter.

2 Decommissioned modules: availability & re-use options

2.1 Availability of decommissioned modules

It is instructive to know where decommissioned modules come from, and what properties we can expect from these modules. Concerning the module technology, Figure 3 shows the cumulative power by module type produced, on a global scale for the period between 2000 and 2020.

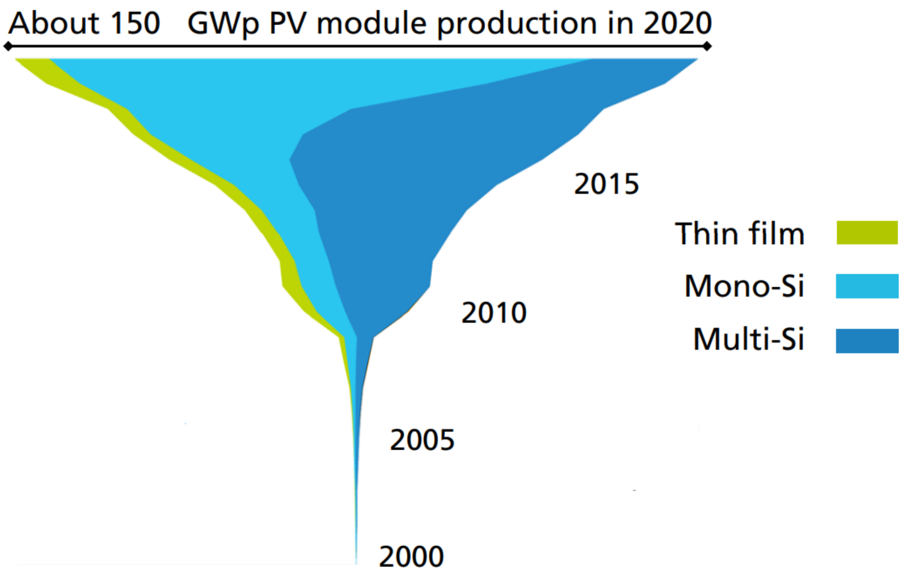


Figure 3: Annual worldwide PV production 2000-2020 (in GWp) by technology[4]

The majority of the installed modules are of **mono- or multicrystalline silicon technology.** Thin film contributes only ~ 5% of the installed capacity. The graph also shows that module production expanded significantly after 2010, which means that huge numbers of decommissioned modules 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 **back sheet** as rear cover, since glass-glass standard modules became more popular only since ~2015. 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.

In practice, almost all decommissioned PV modules available for preparation for re-use are removed from **utility-scale power plants** (> 1 MWp). There are three main reasons for premature module removal: Firstly, damages from severe **weather events,** mainly hail, storm or lightning strikes, which destroyed only part of the modules while other modules are still acceptable for potential re-use. A second reason can be the occurrence of **defect modules** that are repairable: these PV modules are removed and replaced by new ones. A third reason for the removal of PV modules from an existing system can be its **repowering,** which is the practice of replacing the older solar modules in a system for newer ones to gain higher economic returns of the power plant. As will be explained in section 3.2, this repowering is delayed in countries which did introduce guaranteed feed-in tariffs. In the scenario without feed-in tariff it is expected to take place after a period of around 10 years.

2.2 Options & economics for re-use of decommissioned modules

Only technically suitable and economically viable applications for re-use of decommissioned modules can make the preparing for re-use an interesting case to explore and standardise further.

Today, the market of second-life 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-life PV modules.

Firstly, the system of feed-in tariffs has created a lucrative business in the trading of **rare PV modules.** These are **needed to replace defect modules in a solar plant with identical ones** to avoid losing the guaranteed feed-in tariff. The most wanted second-life PV modules are sold for prices of 4-5 €/Wp, which is ~20 times the price per Wp of today's brand-new panels. Clearly, this replacement is financially attractive since it avoids the loss of subsidies. For the companies in Germany which started to trade in second-life PV modules, the selling of rare modules generates a very large part of their profit. This way, the feed-in tariff system has also stimulated and supported the start and growth of companies trading in second-life PV modules.

Secondly, installations which still receive the guaranteed feed-in tariff will usually not be repowered 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 becoming available in the next years. In addition, these **20-year-old modules** with low efficiency will be **close to their expected technical lifetime** of around 25 years, so these modules may not be considered as being relevant for re-use, mostly for economic reasons.

The influence of the feed-in tariff systems 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.

To make module re-use viable in the long run, other applications than module replacement in subsidised systems are required. A detailed economic analysis of module re-use is mandatory and should address two different issues. Firstly, under which conditions the preparation for re-use could be viable. Secondly, for which applications these modules could be used, while increasing profitability in comparison to new modules.

To illustrate some of the economic considerations to make when assessing the cost competitiveness of module re-use, we assume that the second-life modules are sold for a price of ~0.10 €/Wp (typical price on internet trading platforms for second-life modules in 2021). This is **up to 20 times cheaper than their original price** per Wp. But since new PV modules also became cheaper by a factor of 10 over the last 2 decades (2001 – 2021) a second-life module still costs almost **50% of the price of a new module today** (average wholesale price of c-Si modules in EU in 2021 is ~0.25 €/Wp). However, the lower power output per area as well as the lower remaining lifetime of the second-life modules influence the cost per kWh produced significantly. Therefore, second-life PV modules are not economically preferable to new modules in every scenario. This effect is even enhanced by the fact that the module costs are only a fraction of the total system cost, namely to around 30% in a utility scale plant[5]. This means that the total costs for a system with second-life PV modules would only be reduced by ~15%, assuming 50% lower module costs, while the power generation and remaining module lifetime might be significantly lower, depending on the module age.

For several possible applications to re-use decommissioned PV modules, the advantages and disadvantages are listed in Table 1.

The lower relative power density and considerations regarding the cost of land use, narrow the quantity of available second-life modules which would be cost competitive with new modules in solar plants of various scale within Europe. Wendzich[6] found that the module age is the single most influential factor to determine the cost competitiveness of a second-life module in comparison to a new module. Both authors find that in terms of levelised cost of electricity (LCOE) as financial benchmark the maximum viable module age is between 10 and 12 yeas. As technology and price curves change the outcome of these analyses may also change.

The following main applications for large scale re-use of PV modules are currently:

(1) the **repair** of systems receiving feed-in tariffs (replacing some defect modules by second-life ones)
(2) the **export** of second-life PV modules to developing regions for installation in new small to medium size PV systems (often **off-grid**)
(3) **replacing** (all) old modules in a plant with second-life PV modules to extend the lifetime of a PV power plant at low costs or because these old modules are all severely underperforming

Besides these 3 applications, another case in which modules are re-used, is the **on-site repair of defect modules** in an existing PV plant (also listed in Table 1). Although some of the steps required to prepare modules for re-use are also applied here, it is not re-use in the original sense as the modules remain in their original function, place and situation of ownership.

Table 1: List of applications for re-use of decommissioned 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. – 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 and module dimensions adapted to existing racking 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. – Not all repair options are easily applicable on-site (like junction box replacement).
Installing modules in a new PV plant which can be commercial- or utility-scale.	+ Lower module costs. – Much lower module efficiency, lower remaining lifetime, and less warranty versus using new modules. Cost savings are limited since modules contribute only ~1/3 of total 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 limited since modules contribute only ~1/4 of total system costs.
Exporting modules to developing regions for installation in new small/medium sized PV systems (often off-grid).	+ Lower module costs (more relevant in this case considering higher cost of capital). – Much lower module efficiency, lower remaining lifetime, and less warranty versus using new modules.

An important issue in high-income countries is that there are currently no **environmental incentives** to re-use decommissioned modules instead of installing new ones. It has been shown in another part of the Circusol project that the re-use of a decommissioned PV module is always positive from an environmental point of view[7], also when issues like its lower efficiency and the energy required for module transport are considered. So, if new incentives based on environmental impact would be introduced, the re-use of decommissioned modules in high-income countries could be stimulated.

3 Recommendations for quality inspection and labelling of decommissioned modules

3.1 Outline of the approach

This chapter starts with a description of the types of modules and systems which can be considered as relevant for re-use, based on the previous chapter. The next section discusses the general evaluation of the PV modules in a PV plant, which should take place before decommissioning to decide if the modules can be considered for re-use.

After that, different tests that could be used for evaluation of decommissioned modules will be listed and discussed in more detail concerning their relevance and applicability for decommissioned modules. The next sections will cover the potential repair options and most importantly, recommendations for inspection and sorting of these modules.

Finally, the chapter will conclude with the labelling of the modules, as it is an important aspect of the traceability when re-using modules and the last step of the preparing for re-use.

3.2 Types of PV modules and systems relevant for re-use

Since there are so many decommissioned module types and PV systems around, it is important to narrow down on the exact scope of the recommendations that will be given in this deliverable. The first question is whether the rare modules to replace damaged ones in feed-in tariff systems that can be sold at high prices should also be considered. Since this is a rather small market (in MW) that will also disappear over time, these modules will be excluded.

But there are also other choices that have been made. In the following, the discussion will be limited to the following decommissioned modules (which represent by far the majority of the installed capacity in the EU):

- Only modules of **mono- or multi-crystalline silicon** type (which represent approximately 95% of all installed modules);
- Only modules that are **intact** or have **limited repairable defects**;
- Only modules originating from **large systems**;
- Modules can be of **any age** (anyway the age is not always known);
- **NO "rare modules"** that are meant for **replacing** modules in feed-in tariff systems
- **NO modules of BIPV type** (since they are typically hard to re-use in other systems, and also represent only a very small fraction of the market, around 1%)

As a general remark, it is important to dismantle a PV system in an appropriate way to avoid damage to the modules. However, this subject will not be discussed in detail in this deliverable, but the creation of a guideline for decommissioning agents concerning the “decommissioning for re-use" is recommended.

3.3 Evaluation of module re-use before PV plant decommissioning

It is recommended to decide about possible re-use of the PV modules before the decommissioning, so that measures can be taken to keep them in good condition. To check if re-use of (part of) the modules makes sense, in the first place a **visual inspection** of the modules should take place, to check if there are no general problems like delamination or back sheet cracking, for example. The visual inspection list should be rather detailed since a thorough visual check is required to enable taking a correct decision about potential re-use of all the modules in the plant. If the modules have passed the visual inspection, the **energy production data** of inverters can be studied, and **I-V curves** can be measured for several modules distributed over the PV plant (this can be done with an **on-site** indoor I-V tester). In such an on-site tool also **electroluminescence (EL) images** should be made to evaluate the general state of the modules and to find the reason for a possible power degradation of the modules. If available, **drone IR images** can also provide additional information about the general state of the plant.

In the foregoing, it has been assumed that the decommissioning has been planned (usually because of repowering), so is not due to a sudden event like a storm that has impacted the PV plant. In the case of a **sudden event**, it does not make sense to look at production data obtained before the event. Still, a sampling of (the visually intact) modules from the plant for I-V and EL inspection can give a good idea about the state of these modules and the possibility to re-use them.

If it has been decided that (at least a part of) the modules could be fit for re-use, the **decommissioning** can start. In this case, care must be taken to **handle the modules as if they were new**, avoiding practices like walking on the modules, cutting cables instead of correct cable disconnection, and bad packaging methods. The **testing and sorting** can in principle be done **on-site,** which can save on transport. Alternatively, it can be done in a **specialised centre** for preparing the modules for re-use, which may provide better equipment and economies of scale.

In Figure 4, a high-level schematic is shown for the procedure of quality checking and sorting, which will be further specified later on. During the quality inspection, the modules can be sorted into 3 different classes:

- **Class 1:** Re-use is possible without repair and/or extra checks (on top of basic checks)
- **Class 2:** Repair and/or extra checks are needed
- **Class 3:** Only fit for recycling

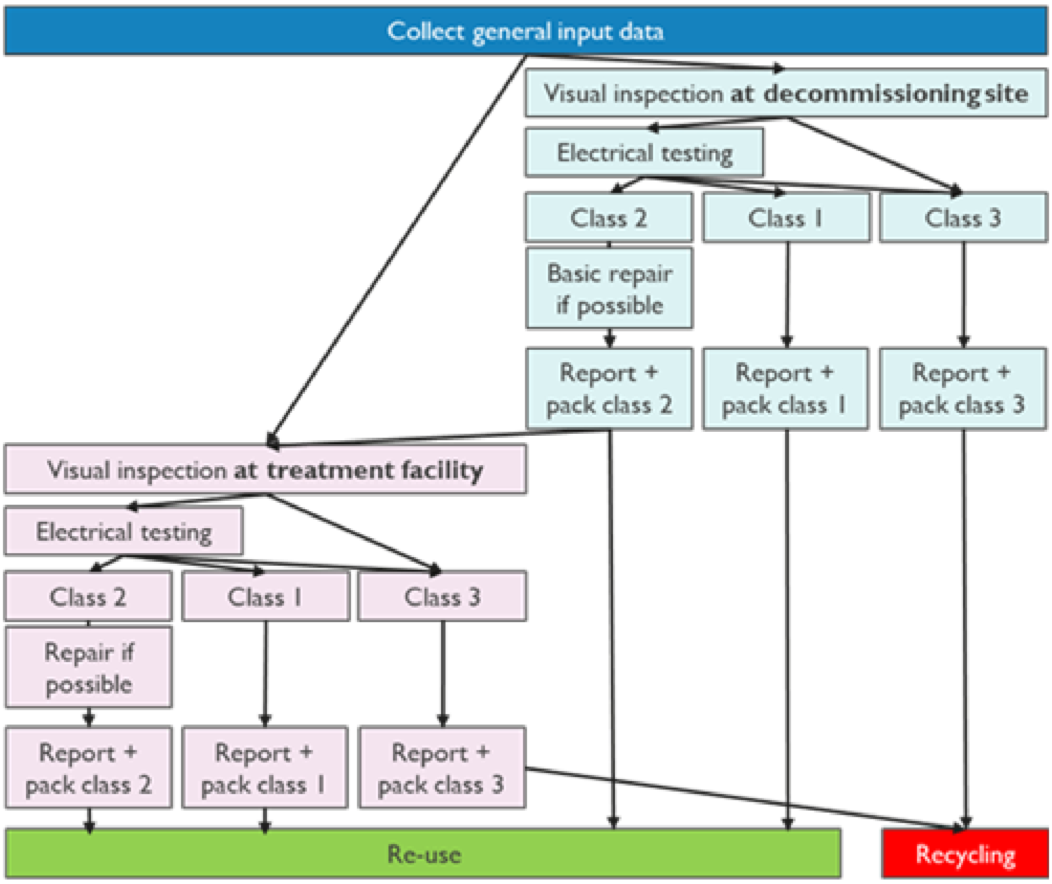


Figure 4: Quality inspection sequence to prepare PV modules for re-use performed at decommissioning site (light blue) or at a treatment facility (pink).

In the next section, the visual inspection and possible test methods for decommissioned modules mentioned in the figure above will be discussed in more detail. As mentioned before, the tests need to be technically and economically feasible and viable, but also give sufficient guarantee about the remaining module performance and safety.

3.4 Visual inspection & test methods for decommissioned modules

3.4.1 Visual inspection of PV modules

To ensure efficiency of the procedure to prepare for re-use, it is best to do a first visual check on the modules before any electrical testing will be done. Some visual defects are only minor, while others are a reason to send the module directly to recycling:

- **fracture** or split in the **front glass**;
- **burn spots** on the front cells, the solder joints, conducting paths, busbars, close to or directly on the junction box;
- **deformation** or **bloating** of the junction box.

If the frame is dented or deformed, it depends on the severity. Usually, the frame can be repaired by gluing it back on with silicone, the target is to ensure no humidity can enter at the point of damage. If the technician is not sure whether the frame can be repaired with this method, the module should be put to recycling.

Many faults which occur on the backside of the module can be repaired, meaning the module can be re-used. If the foil is bloated, the bloating bubble needs to be cut open, smoothed out and repaired by adding EVA repair foil with heat resistance up to 95°C. The same is the case if there are scratches or cracks in the foil. This is important so that no humidity can reach the cells. If "yellowing" is visible on the backside, meaning a discoloration of the foil, the cells are not affected, so the module can still be used.

Concerning the **cables**, if they are damaged, replace them with standard solar cables and MC4 plugs using the pliers. Even if they are not damaged, it would increase compatibility to exchange plugs on all modules which are supposed to go back into operation, yet it is not a necessity.

A very critical point is the **junction box**. As stated before, if it is dented, deformed, bloated, burned or in any other way damaged, it is a recycling case. But if the junction box seems intact from the outside and can be opened, it can be checked for damages inside. If the solder strips are burned, the module should be recycled, because the repair is not economical, as it takes about a day's labour. If the diodes are in any way damaged, exchange them for the standard Schottky-diodes. Without the original diodes the module will also be sent to the ELV class.

Based on the foregoing, a basic visual inspection decision tree is shown in Figure 5. There can be many visual defects to a module, but the inspection should not be too detailed, to avoid that much time is needed to go through it. A more detailed visual inspection of the modules should have been performed already before decommissioning, where the general state of the modules has been assessed.

This decision tree is only meant as a quick visual check of clearly unacceptable issues (and to select the modules that need repair).

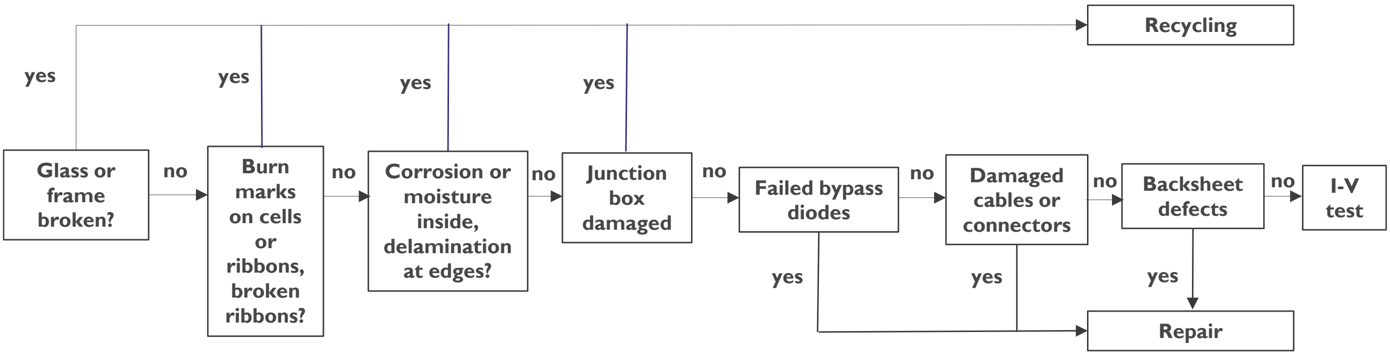


Figure 5: Visual inspection decision tree.

3.4.2 I-V curve measurement

To obtain information about the module performance, its **I-V curve** has to be measured. This can be done either **outdoor** at a sufficient irradiance level (> 800 W/m^2) with a hand-held meter and correcting to STC, or **indoor** (indoor can also be in a trailer that contains a solar simulator that can be used on-site). The number of modules that can be measured on a day with such an on-site solar simulator is limited to several hundreds, so that measuring each module on large PV systems is quite a challenge (for a 20 MW plant this could take up to 4 months if only one simulator is used). A very important issue is whether an I-V measurement should be performed on every PV module that is intended for re-use. One could argue that the general evaluation on PV plant level based on inverter data, drone images and I-V measurement of part of the modules can give enough confidence about the performance of the modules. However, if measurement of the modules can be done in a quick and efficient way it is still preferable to measure the I-V curve of every module, so this will be assumed in the rest of this deliverable.

Although the shape of the I-V curve can give more information about possible issues with a PV module, for clarity and simplicity it is recommended to use only the **remaining maximum power divided by the original maximum power** as criterion. This ratio can and should also be used as criterion for the functionality of the module. The functionality is of key importance, since this determines if the module should be considered as waste or as a product. For usual energy consuming electronics, the check for functionality is much easier since it is either functioning or not. For an energy generating device like a PV module this is not the case, and a **criterion for the minimum remaining power** has to be chosen, which will always be somewhat arbitrary. The proposal is **to use**

a lower limit of 80% for the remaining power compared to the original one. This value is chosen since this is also the standard guaranteed lower limit for module power after 20 years, so it gives some uniformity. It should be noted that a typical module that is still fit for re-use will be around **10 years old** so that the remaining power after 20 years could further decrease to a value below 80%. However, for a module that is not sold in new state, this can still be acceptable.

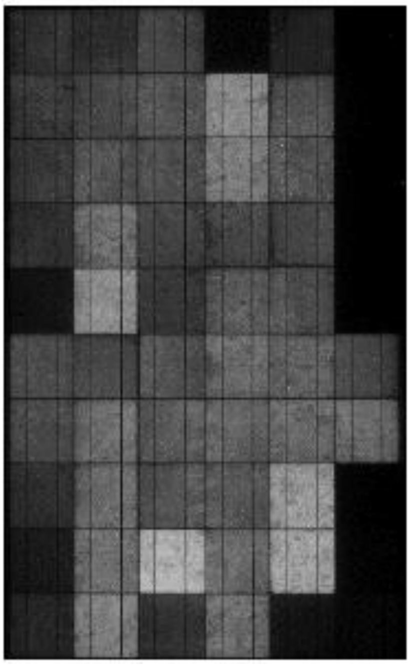
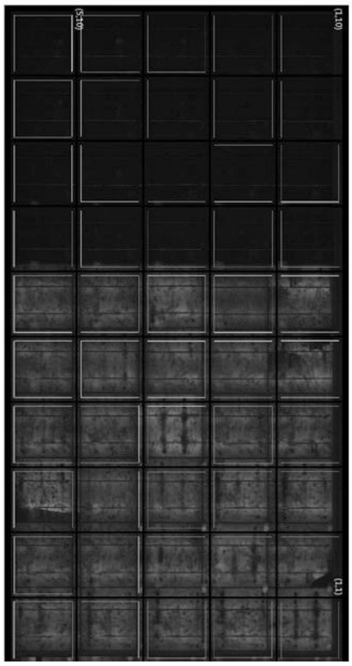
3.4.3 EL imaging

The **electroluminescence (EL)** technique (already recommended in 4.3 for general plant evaluation) can give important information about **internal defects** in a module, like cell cracks, locally increased series resistance or potential induced degradation (**PID**). In this way, it can be a very valuable tool to make an evaluation for the general "health state" of the modules and the typical failure mechanisms that are present in the decommissioned modules of a particular system. However, it is not possible to use quantitative measures based on these pictures. For example, setting a maximum for the number of cracked cells is not useful, since the importance of a crack depends on its length, its location within the cell, and the probable crack propagation direction. The effect of cracks on the performance will anyway be present in I-V curve, so the lower limit of 80% remaining maximum power is also a safeguard against the presence of a huge number of cell cracks in a module.

Since the EL measurement involves connection to the module and measurement in the dark, it could be done after an indoor I-V measurement. However, since the information cannot be used as a pass/fail criterion for every module, it is recommended to use EL only for analysis of the **general state and failure mode(s) in a plant**, and NOT to decide if a particular module is fit for re-use. It is recommended to check randomly selected modules from a batch with EL before starting the selection and sorting of all modules, for example 1% of the total number of modules. This to obtain a good view about the general state of the batch and the types of defects that are present in them. Of course, the I-V curve should ideally be measured at the same time to avoid unnecessary handling.

In the following table, some examples of EL images of PV modules with some typical issues are given:

Table 2: Visual appearance of some module defects in EL imaging.

		
Module affected by Potential Induced Degradation (PID): the strongest affected cells (dark) are located near the module edges	Module containing many cell cracks: many cell parts are black since no current flow is possible	Module with one of the bypass diodes short-circuited: part of module not working

A particular point of interest is the detection of modules that are prone to Potential Induced Degradation (PID), like the one shown in the left picture in the table above. This is typically visible in EL by darker cells in a more or less random pattern across the module, but more of them are located near the module edge. In the case of PID-prone modules, the strongest affected modules are located at the module string end with negative polarity, while the ones at the positive part of the string are not affected at all. For this reason, **it must be assumed that all modules in a system are PID-prone if some modules in a PV system are PID-prone,** even if they have not been affected by PID themselves. One option to avoid PID is to ground the negative pole of the module string, but this is only possible for inverters with transformer (while most inverters have no transformer). To "repair" PID, electronics have been developed that reverse the potential difference with the frame during the night. Another option is to use an DC/DC optimiser for each module, which keeps the potential difference with the frame low, but this is considered too costly for a utility scale plant.

To deal with the issue of PID-prone modules, it is recommended to provide this information on the new label. If there are any modules in the system that have degraded by more than **20%** by PID, or if anti-PID measures have been taken in the plant because of PID affected modules, all new module labels should include information that they are **PID-prone**.

3.4.4 Insulation test

For safety reasons, it is important to measure the **insulation resistance** as is required for any electrical equipment. In the IEC 61215 standard that describes the tests for module type certification, 2 tests have been described. One has to be done in dry conditions ('insulation test'), and is to be done before any environmental tests have taken place on the modules while the other one ('wet leakage current') takes place in a water bath, and the voltage is 1/3 of the setting for the insulation test (only the maximum rated system voltage). It is clear that the **wet leakage current test** is **not practical** to apply on large numbers of modules. Instead, the **insulation resistance test** of **IEC 61215** can be done. In short, this test requires a voltage between frame and cabling of 3 times the maximum rated system voltage, requiring a total measurement duration of 2 minutes and setting the lower limit for the product of module area and resistance to 40 $M\Omega m^2$. For a typical decommissioned module of around 1.6 m^2, this will mean a required resistance of > 25 MΩ.

Insulation measurements that have been done on decommissioned modules by project partner Futech have shown that many of these modules typically have lower insulation resistance values than they must have had in brand new condition. The values ranged from 6-85 MΩ, with many of the values being below the limit of 25 MΩ. This was attributed to a probably higher amount of moisture in the encapsulant and the sealing of the module edges. It is also not completely fair to expect that the insulation values are still the same than that could be obtained in brand new condition. For normal double insulated electrical equipment, the required minimum resistance is only **2 MΩ**, so the **recommendation is to use this value as well for decommissioned PV modules**.

Concerning the duration of the test, the 2 minutes that have been described in the IEC61215 test are too long for practical purposes. Since the current flow typically anyway reduces as a function of time (due to capacitive effects), the recommendation is to determine the resistance **after 5 seconds**.

3.5 Repair options for decommissioned modules

There can be something wrong with the decommissioned modules, some defects can be repaired easily and without much doubt about the future reliability (like replacement of a broken connector) but other ones are more difficult. In the table below, different repair options are listed with their estimated costs.

Table 3: Module defects, repair solutions and total cost estimates (including labour costs, 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	Not clear yet

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

) 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 often still economically feasible. When distributing the costs among all the modules, the costs per module are reduced to a few € only. In practice there are also operators that do not want to take the effort for the few percent repairable modules and just send them for recycling.

For the repair of **cracked back sheet**, the situation is different since all modules in a PV plant are affected when an inferior back sheet 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 back sheet 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 back sheet repair solution that is both reliable and economically viable. Material costs for this coating solution are only ~3 euro per module, 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 back sheet with a strong adhesive layer that has the size of the full module, and is to be glued on top of the old back sheet. Given the large effort that is currently put into these back sheet 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.

3.6 Testing and sorting of decommissioned PV modules

In this section, it will be assumed that the modules that enter the process of qualification and sorting have received a positive evaluation for potential re-use. This means that there are no doubts about the general state of the modules, and that the modules can now individually be checked, repaired (when necessary) and labelled to finish the preparing for re-use. Since it is assumed that the modules originate from one plant, they are assumed to be of the same type and original power.

For reasons of clarity, it is not recommended to have too many classes of modules meant for re-use. Still, it would be good to have a separation in two classes based on the maximum system voltage for the future application of these modules. This gives the possibility to put modules that have a certain issue (like a certain repair history or back sheet cracks) in the class with reduced maximum system voltage. The proposal is to have one class that is called the **"original system voltage" (OSV) class**, while the other one is the **"extra low voltage" (ELV) class**.

Description of the **OSV modules**:

These modules can still be used for system voltages up to their original maximum value (usually 1000 V DC, or 1500 V DC at most). They can be returned into the usual PV power generation with grid-connected string inverters.

Description of the **ELV modules**:

These modules are restricted to extra low voltage (< 120 V DC) power generation. Systems built with this module category can generate power for extra low voltage applications, independent of the power grid. Alternatively, they can be grid-connected in combination with optimisers, since such an approach also avoids high system voltages (but comes at a higher cost due to the addition of the optimisers).

The distinction between voltage classes aims to increase the profitability and overall value of the re-use process through the following mechanisms:

- Including the ELV modules opens up the range of eligible quality, so that more modules can be recovered. This impacts positively on the cost drivers of volume and re-use percentage.
- The cost structure in ELV systems might be particularly suitable for re-use of decommissioned modules, as these systems are generally compact and area usage might be less relevant.
- The potential to create social and environmental value could be particularly high in ELV module applications. These modules often substitute dirty energy sources such as diesel generators, kerosene lamps or car batteries and sometimes create energy access, enabling sustainable development in energy poor regions.

In Figure 6, the **decision tree for checking and sorting of decommissioned PV modules** is shown in its basic form, based on the foregoing sections and the introduction of the two voltage classes that have just been mentioned.

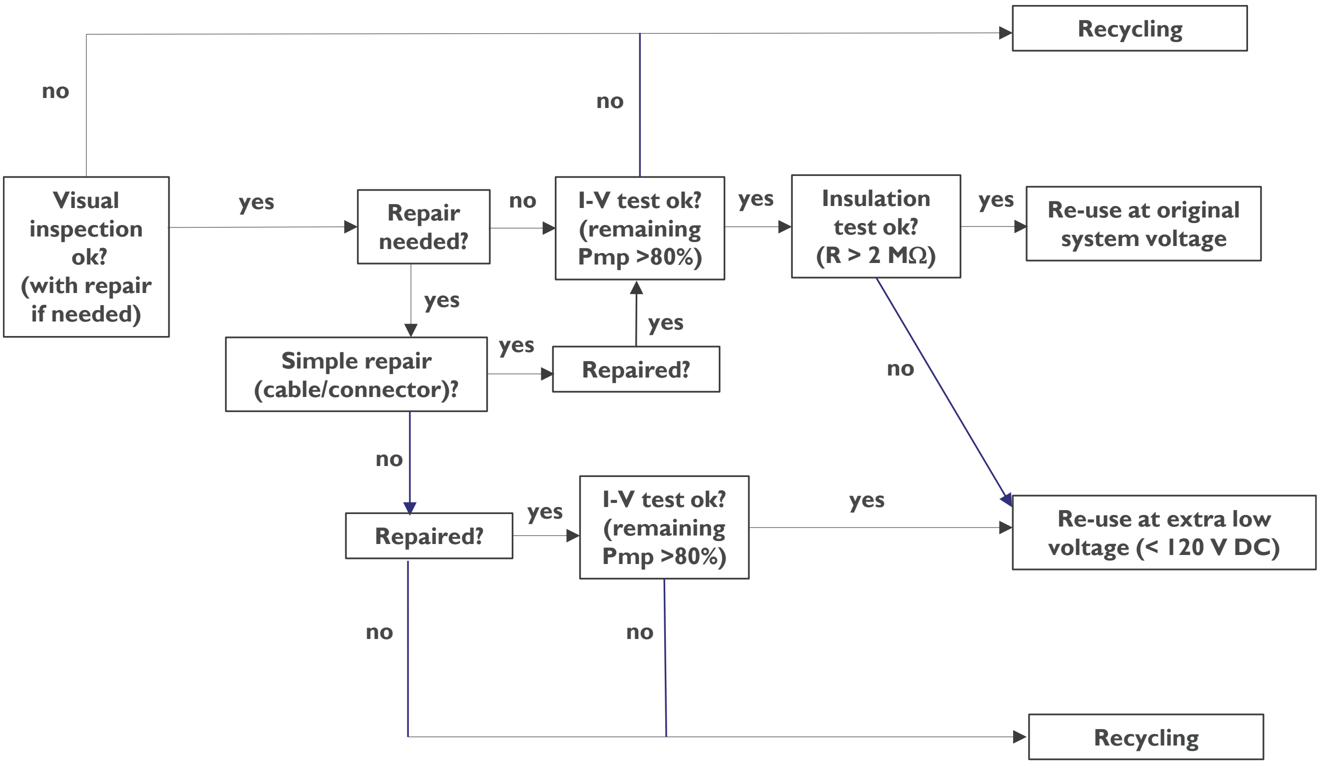


Figure 6: Decision tree for checking and sorting of decommissioned PV modules (coming from a plant that has already been positively evaluated for potential re-use of the modules).

After the **visual inspection** (described earlier in 3.4.1) has been passed and the module has been repaired where appropriate, the next step is the **I-V measurement** (see 3.4.2) to see if the module still delivers enough power (at least 80% of the original power). For the measurement to be precise, the front side needs to be clean from dirt, dust, moss or other pollutants.

For the modules to be used at the original system voltage, also the **insulation test** has to be passed, that has been described in more detail in 3.4.4. If the insulation test has been passed, the module can proceed to the OSV class, otherwise it has to be put in the ELV class.

Finally, after the testing has been finished, the modules fit for re-use should be **labelled** with the measured electrical parameters and sorted in power classes with a 5% width. The labelling will be discussed in more detail in the next section.

3.7 Labelling of decommissioned modules

After the module has been checked, a **label** with the major results is printed and placed on the back of the module, **in addition to the original label**. All module data shall be stored in a central database and the full documentation shall be attached including measurement number and date. If the serial number of the module was still identifiable it should be included into the documentation. If there were any modules in the original plant that have degraded by more than 20% by PID, or if anti-PID measures have been taken in the plant because of PID affected modules, this should be indicated on the new label of all modules. The labels shall comply with EN50380:2003 and put to on the backside of the module. An example of a label is presented in **Error! Reference source not found.**.

Table 4: Information to be included in labels for second-life PV modules.

Company Name S. Ample Module Road 11 Zip City	PV module for re-use	Barcode
General Information		
Test Number	XXXXXXXXX	Date
PID-prone	YES/NO	
Electrical Data Standard Test Conditions E=1000 W/m^2, Tc=25° C, AM 1.5G		
Pmax	XXX	W
Imax	XX.X	A
Umax	XX.X	V
Isc	XX.X	A
Uoc	XX.X	V
Maximum System Voltage	**XXX**	**V DC**

Additional information on protection class II or other tests or warnings may be included.

References

1 Masson G., Kaizuka I. (2020) “Trends in Photovoltaics Applications 2020”, Report IEA PVPS Task 1, International Energy Agency (IEA) Photovoltaic Power Systems (PVPS) Programme.

2 IRENA report “End-of-Life Management Solar Photovoltaic Panels” (2016).

3 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), alco called the Waste Framework Directive.

4 Phillips, S., and Warmuth, W. (2021) Photovoltaics Report, Fraunhofer ISE/PSE Projects.

5 IRENA report “Renewable power generation costs 2020” (2021).

6 Wendzich L., “The Value of 2nd life solar PV modules, an economic assessment of the competitiveness of rehabilitated solar modules including an environmental impact indicator”, Master thesis, Berlin (Germany), 2020.

7 N. Rajagopalan N., Smeets A., Peeters K., De Regel S., Rommens T., Wang K., Stolz P., Frischknecht R., Heath G., and Ravikumar D. 2021. Preliminary Environmental and Financial Viability Analysis of Circular Economy Scenarios for Satisfying PV System Service Lifetime. International Energy Agency (IEA) PVPS Task 12, Report T12-21:2021. ISBN 978-3-907281- 23-9.