A Roadmap to the Second life of Photovoltaic Modules

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A Roadmap to the Second life of Photovoltaic Modules

by

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in partial fulfillment of the requirements for the degree of

Master of Science in Sustainable Energy Technology

To be defended publicly on Monday 17 July 2023 at 4:00 PM

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This thesis is on embargo until 16 July 2024

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Project Duration:	21 October 2022 - 17 July 2023
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Acknowledgement

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I would like to take this opportunity to express my gratitude to the people who have supported, guided, and motivated me over the last eight months through the journey of my Master's thesis. While writing this report there was a particular moment where I was going through the first page after the cover that says "in partial fulfillment of the requirement for the degree of ....." and it was a surreal one. To be finally able to do the master's that I've put on hold for about 5 years after my bachelor's. It has made me appreciate this journey even more. For this, I would like to thank my parents, Venkatesh and Kalpana who have always vouched for me, supported me in the decisions I've made and also kept me grounded in moments when required, and lifted my spirits when they were down and motivated me to keep going and believe in myself and the process.

Second I would like to thank the PVMD group and all its members whom I reached out to during my thesis with doubts and times when I was looking for a way to proceed with my thesis. They were kind enough to provide me with insights and act as sparring partners for my brainstorming sessions. In particular, I would like to thank my supervisor Dr.Malte Ruben Vogt who provided me with the opportunity to work on this topic and gave me the freedom to shape and direct the thesis in the way I see fit. He created an environment where I could express my ideas freely and he would help me shape them and gently nudge me in the right direction. Additionally, I would also like to thank Dr. Chengjian Xu a Post Doc member of the PVMD group who tagged along on my thesis after 3 months. He made me realize that the quality of the report does not lie in the complexity of the content, rather it lies in the simplicity of presenting one's work.

I am also grateful to Dr. Arno H.M Smets for accepting to be the chair of the thesis committee immediately upon my request.

Finally I would like to thank friends, who are home away from home. Few friends I would like to thank, my closest and dearest friend Maria who has been a constant support throughout this journey, José who has constantly motivated me to reinvent myself, Adithya for helping me stay tethered to the lighter and humor-filled side of me. These last two years have been wonderful in terms of growth, learning to be mindful, friends, and memories.

Thank you TU Delft!!!

Harshraj Gali
Delft, July 2023

Abstract

Two words that could epitomize the focal point of today's society are "Energy Transition" and "Sustainability". The PV systems are at the forefront of this energy transition. In PV systems, first-generation Si-based PV modules are the market leaders with a market share of 92.5% in 2020. However, sustainability concerns have emerged in recent years regarding the module technology's post-initial lifespan. In order to make solar panels truly sustainable, it is also important to focus on what happens to these solar panels at the end of their initial intended use. The aim of this thesis is to focus on enhancing the sustainability of the existing PV system by investigating strategies to prolong the lifespan of PV modules through the concept of second life. To accomplish this, the thesis investigates the boundary conditions (the price of the refurbished module) for an economically feasible second use of PV. This research is crucial, particularly given the projected increase in cumulative installed capacity from 1 TWp in 2022 to 5.2 TWp by 2030, in order to meet the Paris Climate Agreement target of limiting global warming to below 1.5°C.

To propose a new market structure, it becomes important to understand the existing policies and practices. Overarching policies in the EU, such as the Waste from Electrical and Electronic Equipment (WEEE) directive sets out the targets for collection, preparation for reuse and recycling, and recovery targets for waste generated from EEE including PV modules. Glass and aluminum are the components of the PV module that are recycled. They make up close to 85% of the weight of a PV module and represent only 35% of the total value of the components in a module. Most of the recycling today is downcycling, meaning that not even the 35% is completely recovered. The remaining materials and sometimes the entire module is dumped in a landfill at €1 per module. Recycling these panels can cost between €15 to €30 per panel and post recycling a minimum value of €6.6 and a maximum of €21 can be derived from the recovered materials. However, these materials cannot be directly utilized to manufacture PV panels without further processing.

The thesis estimates the quantity of materials, such as silver, copper, silicon, glass, and aluminum present in PV systems. This estimation includes the weight of each material within PV modules, as well as the monetary value associated with these materials.In the year 2030, about €86 billion and €58 billion worth of silicon and silver, respectively, are contained in the installed PV panels. If the prevalent EoL processes are followed, at the end of their lifetime, these materials will be unaccounted for.

All processes must be economically viable and operate within well-established financial boundaries. In this study, the concept of the Levelized Cost of Electricity (LCOE) is utilized as a standardized metric for comparing a new PV module versus a refurbished module and setting up boundary conditions. To emulate the market, two scenarios are considered. On the one hand, the first scenario considers the entire system cost, including the second-hand PV module, Balance of Plant (BoP), and soft costs. In this scenario, a minimum second lifetime of 23 years ensures a positive cash flow for the manufacturers/suppliers. On the other hand, the second scenario considers the placement of a second-hand module into an existing system (eliminating the need for additional BoP and soft costs) and shows that no minimum second life of the panel is needed to ensure a cash inflow for the manufacturers/suppliers. The effect of subsidies and policies on LCOE are also analyzed utilizing discount rates. In general, the higher the discount rate, the higher the resultant LCOE.

Finally, a market structure that utilizes the concept of a Product Service System (PSS) and aims to facilitate the utilization of second-life PV modules along with a proposal for the positioning of a Product Service System Provider (PSSP) is presented. Integration of the PSSP into the existing market structure is proposed in a stage-wise manner, utilizing the distribution system operator (DSO) for effective implementation. To achieve this integration, two strategies are recommended, one based on the size and capacity of the installed systems and the other based on geographical boundaries. Additionally, a brief overview of PV subscribe, which is a business model that stimulates the second-life market, is provided.

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1 Motivation and Background

In less than a decade, society has transitioned from its focus on developing and deploying technologies that help accelerate the energy transition to a more balanced approach between the former and the concept of circularity. With climate change finally catching up it has become inexorable to fast-track the energy transition. There have been several initiatives both regional and international that focus on combating climate change. One of the well-recognized International initiatives on this front is the Paris Agreement in 2015. This agreement aims to limit global warming to below 2°C, preferably 1.5°C, compared to pre-industrial levels [1]. The main way to realize this target is to curb CO_2 emissions and phase out fossil fuels. Naturally, alternative energy-harnessing methods are being researched, and the most widely and successfully developed technology is Photovoltaic (PV) technology. In order to meet the aforementioned climate agreement an estimated 5200 GWp or 5.2 TWp of cumulative installed capacity of solar energy is required by 2030 according to the International Renewable Energy Agency (IRENA) [2].

Solar/PV panels are a way to harness energy from the sun, a renewable and sustainable source. However, there has been a lot of debate in recent years surrounding the sustainability of the panel technology after its first life. In order to make solar panels truly sustainable it is also important to focus on what happens to these solar panels at the end of their initial intended use. In order to analyze the handling and processing techniques at the End of Life (EoL) of panels it becomes important to look at the different elements to which they are exposed and the effect they have on panels. This understanding would make it possible to better understand the need for and creation of a sustainable production system for solar panels after the end of their first life. This ecosystem could be the key to making PV technology a truly sustainable energy source and help upscale the installed capacity to 5.2 TWp in 2030 from 1TWp in 2022 [3].

Despite improving material efficiency in the PV industry, rising demand driven by increased installations remains a challenge. Longer lead times are a consequence of production facilities being unable to meet this demand. As a result, material inventory and supply chain constraints may impede the achievement of the IRENA target of 5.2 TWp by 2030. As a result, it is crucial to find solutions that address this challenge and ensure that the PV industry can continue to grow sustainably. China is the largest supplier of polysilicon contributing to 79% of the global capacity. According to the International Energy Agency (IEA), if an 85% material recovery rate is achieved and there is a systematic collection of end-of-life (EoL) modules, the cumulative secondary supplies obtained from recycling all EoL PV modules could fulfill approximately 3%-7% of the PV industry's demand for aluminum, glass, copper, silicon, and silver between 2031-2040, and over 20% between 2041-2050 [4] The material crunch, increase in demand, and longer lead times impede the energy transition. The concept of second life in the form of reuse and refurbishment could be a possible solution to overcome this barrier. In the next sections of this chapter, various solar panel technologies deployed commercially are introduced, followed by the materials used for the technology being analyzed in the report. Further, the various elements a panel is exposed to during its lifetime, and the result of this exposure are enumerated. This would provide an idea of the conditions of the modules at their EoL and help devise better handling and processing. Finally, the thesis objective and structure will be outlined.

1.1. Generation of solar cells

The PV effect was first observed by Edmond Becquerel in 1839, and ever since then, numerous ways have been developed to harness the energy radiated by the sun. Silicon PV panels have been the primary means of doing this since their commercialization in 1954 [5]. The majority of effort and resources have been dedicated to improving the efficiency of solar panels. This improvement has been realized either in the form of new technologies such as thin film or multi-junction solar cells or improved efficiencies of existing technologies such as the mono and poly-crystalline-based solar cells as depicted in 1.1. For example, the efficiency of organic solar cells has increased from 3% in 2006 by about five-fold to 15.2% in 2022 [3], although this might not be the case for all technologies. Along with the increase in efficiencies over the years, various new technologies have been introduced to realize higher efficiencies. These new technologies can be classified into three generations depending on the cost of production, base material, and efficiency as depicted in Figure 1.2.

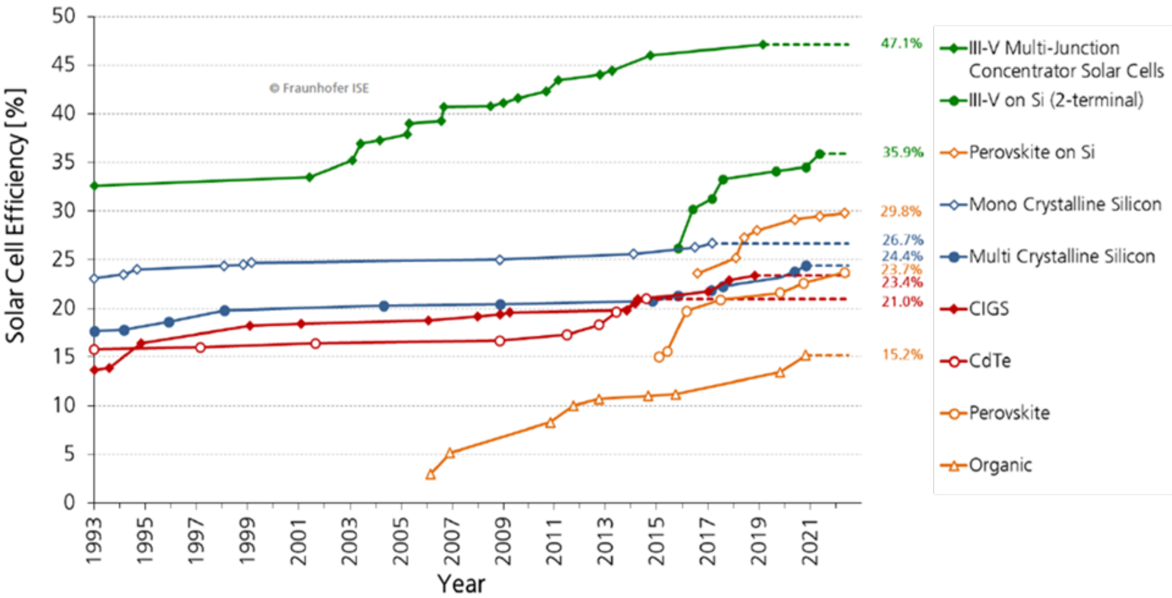


Figure 1.1: Efficiency trends in PV cells (lab environment) [3]

1.1.1. First generation

Based on crystalline Silicon (Si) wafers this generation of solar cells has been occupying a market share of upwards of 90% to date and are expected to be the market leader in the near foreseeable future as well [3]. Due to the high purity of Si used, the associated cost of production for these cells is generally higher as compared to the second generation. Although the cost can be a prohibitive factor, the highly stabilized commercial efficiencies are a driving factor for its market dominance. This generation can further be classified into Mono-crystalline and multi-crystalline depending on the methods used to produce Si cells. Monocrystalline solar cells as the name implies the entire volume of the cell is composed of a single crystal of silicon. The metallurgical grade silicon which consists of unwanted impurities is subjected to refining which involves the manufacturing of $SiHCl_3$ (Trichlorosilane) a liquid compound. At this stage trichlorosilane still contains impurities, but the liquid makes it easier to separate impurities as compared to the solid. After purification, $SiHCl_3$ is heated in the presence of H2 to obtain polysilicon and HCl. The final stage of producing monocrystalline silicon from the polysilicon is done by the Czochralski process. The final result is an ingot which is then sliced into wafers with which monocrystalline cells are manufactured [6]. The highest achieved lab efficiency for this type of solar cell is around 26.8% as depicted in Figure 1.1 As the name suggests, multi-crystalline or poly-crystalline silicon cells are produced by fusing numerous grains of silicon. Solar cells based on poly-crystalline silicon are simpler to produce since they do not require vacuum compared to mono-crystalline silicon solar cells, thus making them less expensive [7]. However, the trade-off for the cost is that the grain boundaries in these cells form an additional source for recombination and result in lower efficiency as

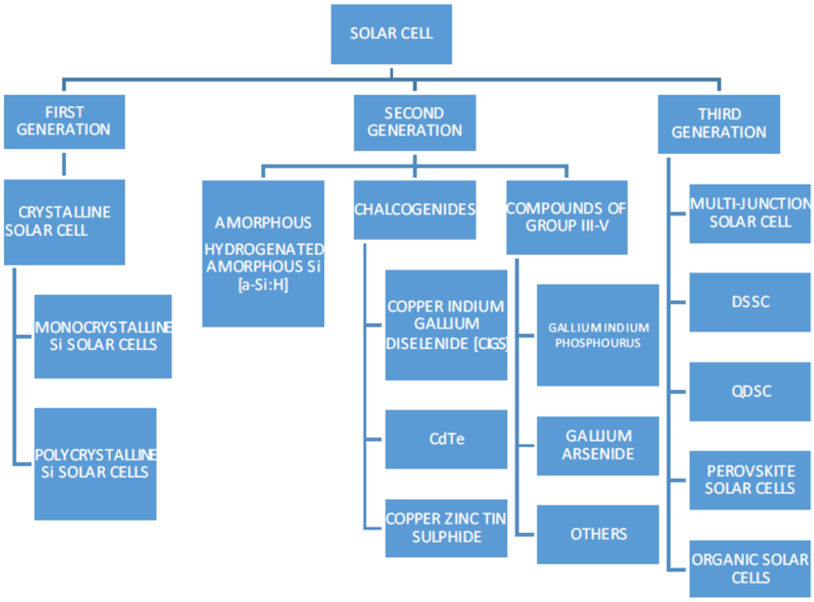


Figure 1.2: Generation of solar cells [8]

compared to mono-crystalline Si cells [6]. The highest recorded lab efficiency for poly-crystalline Si cells as seen in Figure 1.1 is 24.4%.

1.1.2. Second generation

Also referred to as thin film solar cell technology, the development of this generation of solar cells is to reduce the production cost by reducing material cost. These cells generally have a thickness no greater than 4 or 5 microns and are formed by multiple grains and micro-crystals of the material. A common characteristic of materials used in this generation is the ability to absorb sunlight in extremely thin layers in the aforementioned scale as opposed to the hundreds of microns required for crystalline silicon and resulting in low material usage and cost. The material should also be easy to deposit on an inexpensive substrate such as glass, polymer, or metal. Although several materials have been researched over the years only CdTe and CIS have shown great potential along with already established materials like amorphous Si, thin-film poly-crystalline silicon, and CdTe [6]. An interesting property of this generation is that they can be produced into flexible and lightweight structures and can easily be integrated into building components. The highest lab efficiency in thin film technology is 23.4% for CIGS and CdTe at 21.0% [3].

Henceforth the focus is solely on first-generation i.e. crystalline silicon-based solar cells. Therefore, the use of solar panels/cells refers to crystalline silicon-based solar panels/cells until and unless specifically mentioned otherwise.

1.2. Module materials

This section provides insight into the material specification for first-generation solar panels and typical weight distribution. Figure 1.3 depicts a typical weight distribution of the materials in a solar panel. Glass constitutes about $3/4^{th}$ of the weight followed by aluminum at 13% which is used in the frame of a module and plastic (polymers) such as the encapsulant at 9%. Silicon and copper (metal) constitute to 3% each, whereas silver constitutes less than 1% of the total weight [4]

Material specification

1. **Glass**: The use of glass in a solar panel is twofold, one either as a substrate or superstrate for the cell and second as a module front cover and in the case of a bifacial module even as a back cover. The most commonly used glass is low-iron soda lime float glass [9]. The content of iron in the glass is very crucial as it is the biggest absorber. Depending on the oxidation states of iron it exhibits different characteristics, Fe^{2+} is responsible for a broad absorption in the near-infrared

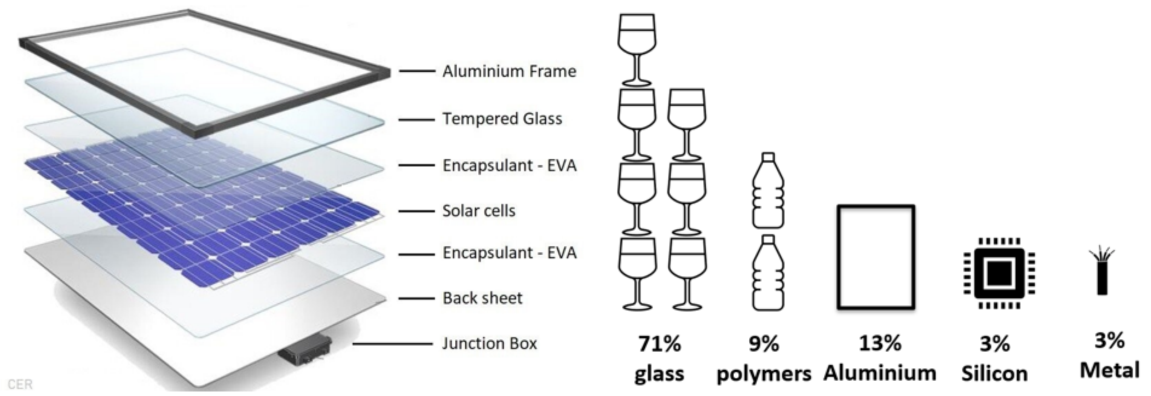


Figure 1.3: Architecture and weight distribution of a typical first-generation PV module

and this gives the glass a green color and reduces the efficiency of the module. The other state in which iron exists is Fe^{3+}, this is responsible for the absorption of UV light and isn't of great significance in terrestrial applications [10]. Due to high transparency, low cost, and mechanical robustness, this glass type is preferred [9]. The low cost can be attributed to the wide range of use of low iron soda lime glass in the civil industry and hence it is produced on a large scale. A tempered version of this glass is used in the front and back cover as it is four times stronger than standard plated glass. Further, the glass is fire-resistant and shatters when broken, reducing the risk of injury [11]. A tempered version of 3.2mm is generally used for the front cover. The glass surface is also an important parameter that ensures the adherence of encapsulants, that is the next component being dealt with.

2. **Encapsulant**: Along with holding the components together, encapsulants used in PV modules provide electrical insulation, reduce moisture ingress, optically couple superstrate materials to PV cells, protect components from mechanical stress, and protection from corrosion. Despite long exposure to UV radiation, temperature, and humidity cycles the encapsulant must adhere to surfaces, and transmit light. Many encapsulants have been researched, during the 1960s and 1970s poly dimethyl siloxane-based encapsulants were dominant [12]. However, the need to reduce the cost of production research on alternative materials lead to the development of ethylene vinyl acetate resins (EVA). To date, EVA continues to dominate the solar panel encapsulant industry with a market share of close to 80% [13]through a combination of low-cost and decent properties. In the upcoming sections, encapsulants refer to EVA-based encapsulants.
3. **Frames**: Protecting the edges of the glass and providing mounting points for the module are the two important features of the frame. The most widely used material for the frame is anodized Aluminium of the 6000 series grade, due to its lightweight, manufacturability, corrosion resistance, and high strength.
4. **Silicon**: It has already been established that 90% and above of the solar panels installed are based on silicon solar cells. Silicon is the second most abundant element in the earth's crust just after oxygen [14]. The silicon used for producing solar cells is known as Solar grade silicon or polysilicon (not to be confused with polycrystalline silicon) with a purity level ranging from 6N to 9N, where 6 represents the number of 9's i.e, 99.9999% pure silicon, and so on. Silicon is mainly extracted from quartz which is a pure form of silica or silicon dioxide (SiO_2). The lowest grade of Silicon is referred to as metallurgical silicon with a purity of 98% to 99% [15]. A powdered form of metallurgical grade silicon is purified to the required level of purity using the Siemens process. Even though there are other semiconductor materials such as Germanium with a lower band gap, the thermal stability, cost of materials, and relative ease of manufacturing have contributed to the widespread use of silicon in solar panels.
5. **Copper**: In crystalline silicon-based solar cells copper is generally used as tabbing ribbons also known as solar ribbons. They are used as cell interconnects i.e, to connect two cells to form a string. Further, they are also used to connect strings of solar cells. These tabbing wires are generally made of solder-coated-coated ribbons, which are soldered onto the busbars of the cell.

The most common solders used are lead (Pb) based like Pb-Sb and Pb-Sn-Ag [9]. Oxygen-free high conductivity (OFHC) copper is generally used to produce tabbing ribbons [16]. OHFC is the highest purity grade of copper at 99.99% where the oxygen level has been reduced to 0.001% or below through electrolytic refinement [17]. Further, the copper is dead soft, i.e. as the name implies it can be easily bent for soldering to the cells and does not cause stress to the cells after connection[16].

6. **Silver**: Being the best metal to conduct electricity and light due to its unique crystal structure and single valence electron, silver in the form of a paste is used in solar cells. In silicon solar cells it is paramount to use a material to use a collector with minimum electrical resistance in order to collect the electricity generated by the cell. In commercial silicon cells, screen printable silver paste is used composed of silver, and glass particles are used to form contacts with the emitter [18]. The PV industry consumes about 8% of the world's annual silver supply [19]. Silver is used predominantly for the busbar and fingers in a silicon cell.

After having looked at the different materials and components in a typical first-generation solar panel, the following section deals with the factors that affect the panel such as solar radiation, moisture, temperature, wind, soiling, etc. Further, the effect of these elements on the individual components and the panel as a whole is discussed.

1.3. Stressors and degradation

The performance/power output of a solar panel depends on the system configuration, which includes the size of the PV array used, the type of module, azimuth, solar panel pitch, tilt angle, cable thickness, charge controller, inverter, and battery efficiency [20]. Further, environmental elements, manufacturing, and handling processes can cause stress to the solar panel, which can affect its instantaneous output and slowly degrade its performance over time. This section provides an overview of the various environmental conditions followed by a discussion of how they affect the performance of a module. Understanding the stresses and the effect they have on a module will provide a better understanding of the condition of a module at the End of life and appropriate handling techniques can be devised. This section provides a basic introduction to the various stressors and degradation modes, acknowledging their vast and deep nature.

1.3.1. Stressors

Stressors are elements that affect the performance and long-term reliability of PV Modules. While the stressors arising from environmental conditions can be grouped under external stressors, the internal stressors are the ones that can be attributed to the processing and bill of materials incompatibility of PV modules [9]. The most predominant external stressors are solar irradiation, ambient temperature, humidity, soiling, and wind velocity [9], [20]–[22].

Solar irradiation

The concept of a solar cell is based on the utilization of photon energy contained in solar irradiation. The wavelength corresponding to the band-gap of crystalline silicon is around 1100 nm [23]. This wavelength represents the bare minimum energy that must be contained in a photon to generate an electron-hole pair. The solar spectrum AM1.5 is considered as a standard test condition in solar cell design [24]. This spectrum corresponds to a wavelength range from 280nm to 4000nm and has an integrated power of 1000 w/m^2. However, the entire spectrum is not utilized by the silicon-based solar cell, the fraction of the spectrum utilization is as depicted in 1.4. The lower end of this spectrum 280-400 nm represents the UV region and only 4.6% of the total power [9]. The lower the wavelength, the higher the energy contained in the photon. The excess energy contained in the UV region after utilization to generate electron-hole pairs is released as thermal energy and is represented by the blue-shaded region in Figure 1.4. Continuous exposure to photons in the UV region leads to the absorption of heat which catalyzes a change in the structure of the encapsulant, which leads to embrittlement and discoloration [25]. The UV region can further be divided into UVA (315-400nm) and UVB(280-315nm), which correspond to approximately 98.5% and 1.5% of the total energy in the UV region respectively. Literature suggests that UVB is more detrimental to polymeric materials [9], the majority of which is blocked/absorbed by the module glass [26]. The amount of incident UV light is a function of the altitude and latitude and time of the year [9], [27], [28]. This means that the effect of UV radiation varies based on the geographic location of the PV module.

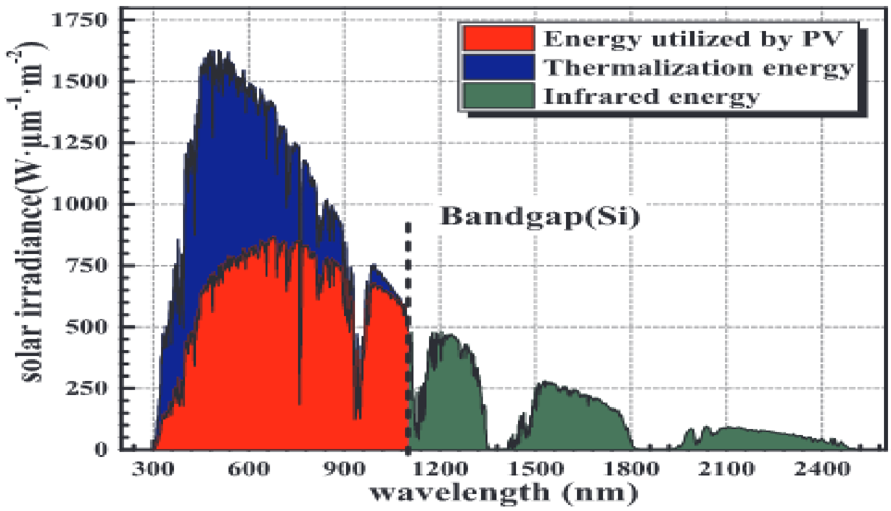


Figure 1.4: Solar spectrum utilization for silicon-based solar cells [23]

Ambient temperature

The term "ambient temperature" is used to represent the temperature of the air/surrounding environment where the equipment is stored or installed [29]. Henceforth, temperature and ambient temperature are used interchangeably. It is an important factor in determining the efficiency and performance of a PV module as they are designed to operate at a certain temperature range. The output power and efficiency are linearly dependent on temperature [20]. The constituents of the solar panel such as the glass, frame, cell interconnects, back sheet, and encapsulant exhibit several thermo-physical and thermo-chemical properties. Thermo-physical properties refer to the physical properties of a substance that are dependent on the temperature such as Specific heat capacity, thermal conductivity, thermal expansion coefficient, density, and melting point. Whereas the latter refers to the chemical properties that are dependent on temperatures such as enthalpy, the heat of formation, entropy, Gibbs free energy, and heat capacity. Due to incident radiation, the temperature of the cell and module varies from the ambient temperature, and the heat dissipation from the cell depends on the geometry and thermal conductivity of the surrounding material, wind speed, and the installation configuration. For PV modules the thermo-chemical properties have an accelerating effect on module degradation, as the temperature is a key trigger to chemical reactions and diffusions that change the structure of the bonds [9]. In literature, these effects are modeled using the Arrhenius equation [30], [31]. The Arrhenius equation can be used to determine the effect of a change in temperature on the rate constant (k), and consequently on the rate of the reaction. Equation 1.1 [32] shows the Arrhenius equation where k represents the degradation rate constant, and A is known as the pre-exponential factor, which is a constant that depends on the frequency of molecular collisions and the orientation of the colliding molecules. The activation energy E_a represents the minimum energy required for a reaction to occur and is expressed in kJ/mol. R is the universal gas constant (0.008314 kJ/mol/°K) and finally, T represents the temperature in Kelvin [32]. The temperature T in the case of a PV module would be the operating temperature T_c. Equation 1.2 can be used to determine the operating temperature of the module at an irradiance G_T (W/m^2) [20]. T_a represents the ambient temperature (°C). NOCT is the temperature of the PV module with no load and operating at the conditions below [33]:

- Solar flux on the cell surface:800 W/m^2,
- Air Temperature: 20 °C,
- Average wind speed: 1 m/s,
- Mounting: Open back side and tilt to solar noon.

$$\ln k = \ln A - \frac{E_a}{RT} \tag{1.1}$$

$$T_c = \left[T_a + \left(\frac{NOCT - 20}{800}\right) \times G_T\right] \tag{1.2}$$

The effect of operating temperature on the performance and efficiency of the panel has been captured in various literature. Outcomes of a few published literature in terms of the relationship between ambient temperature and efficiency of the module have been tabulated and can be found in Appendix A [20].

Humidity

Humidity is a measure of the amount of water vapor that air can hold at a given temperature. Throughout, the literature Relative Humidity is measured and is defined as the ratio of the partial pressure of the water vapor and the water vapor saturation pressure in the ambient atmosphere [34]. Henceforth the term humidity refers to relative humidity. Humidity can affect the module in two ways. First, the water vapors suspended in the air can alter the irradiance level of sunlight reaching the module. Second, prolonged exposure to humid conditions can cause ingress of water into the module packaging [20], [22]. The former affects the performance of the module instantaneously and does not lead to the degradation of the module and therefore is not being analyzed further. However, the mode of water ingress into the module contributes to a slow build-up of degradation and is of interest. Moisture ingress and ambient temperature play an important role in determining the rate of life and performance limiting factors such as corrosion, electrical shorts, and material deterioration of the cell and module material [35]. Polymeric materials, edges of the modules, voids created by manufacturing, handling, and climatic stressors are ways by which water suspended in gaseous form can permeate and accumulate within the module [9], [35]. Hydro-dynamic expansion and contraction can induce mechanical stresses, but these become relevant only when there is the ingress of water in larger quantities [9]. Moisture ingress can be modeled using Fick's diffusion law which describes how particles diffuse from a region of higher concentration to a region of lower concentration [35],[36]. Experimental and empirical investigations carried out showed the effects of moisture on the structural composition of a module. Erosion of low molecular weight species, dissolution of ions, deterioration in electrical insulation of dielectrics causing leakage current, and damage to interfacial adhesive bonds causing delamination resulting in further acceleration of the ingress of moisture and passivation losses are the effects of moisture ingress captured in literature[9], [20], [35]. In the form of ice, it can lead to the delamination of the front glass or frame damage as a result of the volume change during the freeze-thaw cycles. A study carried out to investigate the effect of relative humidity and temperature on efficiency showed that variation of humidity has a higher effect on the panel efficiency [37]. The efficiency of a monocrystalline silicon PV reduces by 0.015 for a percentage increase in relative humidity.

Soiling

Soiling an environmental stimulus refers to the dry accumulation of dirt, dust, water stains (salts), bird droppings, microbial algae growth, etc. It is difficult to model the soiling pattern on the glass on a continual basis in terms of deposition rate, particle size, types, etc [38]. Therefore, the effect of dust is examined by studying the change in performance due to accumulation. Depending on the properties of the soiling particles they are capable of reflecting, and absorbing the irradiance and this alters the amount of irradiance that reaches the cell and ultimately the performance. Further, large soiling particles such as bird droppings can cause partial shading of the module and lead to cell mismatch and eventually hotspot formation unless cleaned [9]. Apart from the properties of the soiling particles, the extent to which the performance of a module is affected depends on the module surface properties, location of installation (temperature and rainfall), and mounting configuration such as tilt angle and height from the ground [9], [39]. Experimental studies have been conducted in different parts of the world to study the effect of dust on solar module performance. These results are location specific and cannot be generalized [38]–[40] a few results to show the diversity of observations are enumerated below [22].

- A study in the USA over a two-month period showed an average reduction of 1% in the performance with a peak of 4.7% [41].
- 40% and 32% degradation in a 6 and 8-month period respectively in Saudi Arabia [42], [43].
- 17%-65% reduction depending on the tilt angle over 38 days in Kuwait [44].

- 33.5%-65.8% reduction in performance of one to six months exposure respectively in Egypt [45].

A wind tunnel experiment and field investigation was carried out to determine the deposition of dust for various wind directions [46]. Mani et al [43] attempt to capture the factors that influence PV performance and dust deposition for various climatic zones, and weather characteristics and also recommend mitigation measures for each.

Internal stress factors

As mentioned earlier internal stresses are a result of module design, processing-related effects, and material incompatibility. Module manufacturing processes such as encapsulation and poor cross-linking of EVA have been linked to PV module failures in the field [9]. During the heating of encapsulant films for lamination, significant shrinkage with subsequent expansion was detected. This behavior results in a dislocation of cells or interconnects inducing additional stresses or distortion, or even deformation of the back sheet [47]. During the post-lamination cooling process from the curing temperature of the encapsulant polymer, thermo-mechanical stresses are induced within the components. This results in the laminate warping and displacement of the cell, as suggested by an analysis using the coarse model[48]. Crosslinking of the EVA polymer chain is necessary to obtain an encapsulant with desired elastomeric and highly transparent properties, as its native form does not meet the required mechanical or optical requirements for laminate formation [49]. Crosslinking of polymers refers to the formation of covalent bonds between polymer chains, resulting in a three-dimensional network of interconnected polymer molecules. Insufficient crosslinking in EVA might occur due to low temperatures or short crosslinking times, but these are generally cured post-installation under operating conditions [50].
Module architecture and bill of materials properties such as the physical properties like water vapor transmission rate, oxygen transmission rate, acetic acid transmission rate, and water solubility, of the component material dictate the influence of the lifetime and degradation rates in the module [51]. Further, design matching of relevant PV components such as the encapsulant and backsheet with the rest of the module components is an important factor in the durability and reliability of a module [9]. A few defects caused due to material incompatibility have been recorded in literature and are illustrated below

- One of the earliest and most prominent cases of material incompatibility was the yellowing of EVA in PV modules installed in California in 1980. The discoloration was found to be a result of interactions between cross-linking peroxides and a few stabilizing additives [52], [53].
- Adhesion issues due to the combination of polyethylene-based encapsulant and polypropylene-based backsheet [54], [55].
- In recent years PV module failure owing to the cracked polyamide backsheets has been reported. These cracks have been observed after several years of field aging, but do not develop in accelerated testing in the laboratory [9].

The grounding of module frames in a typical PV system results in a potential difference between the active circuit (cells and interconnects) and the module frame [56]. This mismatch of voltage in the module components drives a degradation mode in the module known as Potential Induced degradation (PID).
A PV module deployed in the field is exposed to a combination of these stressors which results in the impediment of performance of the module on a both short and long-term basis and also affects the reliability of the module. In the following section, the result of continual exposure to these stressors is analyzed.

1.3.2. Degradation

Degradation refers to the gradual deterioration or loss of performance of a system, material, or component over time. The commonly occurring degradation modes in PV modules are corrosion, glass corrosion, photo-oxidation resulting in discoloration and delamination, Photo Induced Degradation (PID), Light-Induced degradation (LID), deformation of module frame [9]. The delineation between degradation and failure related to PV modules is not always well defined. The stressors discussed in the previous section can lead to various degradation or failures in a PV module. An introduction to these modes of degradations will be provided in Chapter 5.

1.4. Thesis objective

The second life of energy systems can aid the energy transition by maximizing resource use and avoiding premature disposal of systems and resources. This thesis aims to provide insight into creating a circular system around first-generation PV modules. Therefore the main research goal is to develop:

“Roadmap for Second Life of First Generation PV Modules based on Reuse and Refurbish”

In order to devise this roadmap, the following objectives need to be achieved:

Sub-objective 1: Outline the existing policies and processes
Analysing the solar waste handling policies and guidelines in the European Union (EU) will help understand the existing processes and EOL management systems. Waste Electrical and Electronic Equipment (WEEE) Directive and the EU Waste Framework Directive are among the few policies that will be studied. By means of this review, it will be possible to identify the gaps or shortcomings in the current policies. Further, this will help in establishing a few recommendations for creating a roadmap for the second life of solar panels.

Sub-objective 2: Determine the amount of PV waste expected in the next 30 years
Studying the installation trends over three time periods i.e., 2014, 2020, and 2030 provides an idea of the amount of materials and the value of these materials being invested in the deployment of solar panels. Analyzing the current policies and status of EOL management with the installation trends reveals the value of materials being discarded.

Sub-objective 3: Economic boundary conditions for reuse and refurbishment
Economic viability is an important parameter to be considered along with technical feasibility. An economic threshold in terms of the maximum price for a second life module will be determined using the concept of the Levelized Cost of Electricity (LCOE).

Sub-objective 4: Market structure to facilitate second life
An elaborate pathway for the flow of a PV module leading to reuse and refurbishment will be presented. This will help establish a fair idea around better handling of EoL PV modules and lead the way to a circular economy around PV modules.

1.5. Thesis outline

This report is divided into six chapters, each covering a different aspect of the handling and disposal of solar waste. Chapter 2 provides an overview of solar waste management policies in the form of a few important EU directives (applicable in all member states) and a country-specific policy. Chapter 3 presents the cumulative installation trends for three time periods: 2014, 2020, and 2030. The aim is to translate these trends into material quantities and monetary values to gain an understanding of the potential volume of materials and values that will be discarded in the future. In Chapter 4, the study establishes an economic feasibility boundary for second-life solar panels using the concept of Levelized Cost of Energy (LCOE). The aim is to determine whether second-life panels can be economically viable. Chapter 5 proposes a market structure and a process flow for the second life of a PV module i.e reuse and refurbish. Additionally, the chapter proposes a few basic testing and certification standards to improve the trustworthiness of second-life panels. The overall objective is to promote the reuse and refurbishment of solar panels and reduce the volume of waste going to landfills. Finally, in Chapter 6 key observations and recommendations will be provided.

2
EOL Management Today: Policies and Practices

While technology plays a crucial role in managing EoL PV panels, regulatory frameworks provide the legal and institutional support necessary to enforce responsible waste management practices. Combining and integrating of both approaches is required to ensure an effective EoL process that minimizes negative environmental and health impacts.
In this chapter, the overarching and prominent policies and regulations related to the EoL management of PV panels in the EU i.e, the Waste Electrical and Electronic Equipment Directive (2012/19/EU) [57] and EU Waste Framework Directive (2008/98/EC) [58] will be summarized. Further, a country-specific implementation of these directives will be analyzed in Spain's Royal Decree (SRD) (110/125) [59]. Spain is among the top three countries in Europe in terms of solar installations in recent years with 3.8 GW being installed in 2021 [60] resulting in a cumulative installed capacity of 17.9 GW in 2021 [61]. Spain also has a high capacity per capita of 565 watts/capita [62]. Spain was also the first EU country to mandate the re-use of electrical goods [63]. Studying these regulatory frameworks would aid in identifying areas of improvement and support the development of more effective policies and regulations in the future. It is to be noted that these directives are broad and for the purpose of this report only the sections that would aid in the research have been looked into.

2.1. Waste Electrical and Electronic Equipment Directive

The Waste Electrical and Electronic Equipment Directive (2012/19/EU) (WEEE) was adopted in 2012 to preserve, protect, and improve the environment's quality, protect human health, and utilize natural resources prudently and rationally. WEEE 2012/19/EU is an amendment of Directive 2002/96/EC of the European Parliament and of the council under the same name. This policy adheres to the polluters pay principle and encourages preventive actions that prioritize rectifying and mitigating environmental damage at the source. The WEEE directive is applicable to electrical and electronic equipment (EEE). WEEE defines EEE as equipment that requires electric currents or electromagnetic fields for its functionality and is designed for use with a voltage rating of less than 1000 volts for AC and 1500 volts for DC [57].
The directive classifies all the applicable EEE into 10 groups. PV panels fall under category 4 i.e, consumer equipment and photovoltaic panels. The current version of the directive came into force on 15 August 2018. The WEEE is a directive aimed at all EEE mentioned in the annex of the policy and not specific to PV systems. The WEEE directive is used as a framework by member states to establish national-level EoL management policies, in the current section, the articles most relevant to the EoL management of PV modules will be summarised. This will help form a basic understanding of the underlying principles in most of the national-level policies and guidelines for PV module waste management.

Separate collection: Article 5 of the WEEE directive sets out the requirements for appropriate collection in order to minimize the disposal of EEE in the form of unsorted municipal waste. This is done to ensure the correct treatment of all collected EEE and to achieve a high level of separate collection, notably, as a matter of priority, for temperature exchange equipment, fluorescent lamps containing mercury, and PV panels. According to WEEE, the producers, distributors/suppliers are responsible for the costs of the collection, treatment, recovery, and environmentally sound disposal of WEEE arising from private households and must meet individual collection targets for each category of EEE they place on the market. These targets are set as a percentage of the average weight of EEE placed on the market during the preceding three years [57] and will be elaborated upon in the "Rate of Collection" subsection. This is a form of Extended Producer Responsibility (EPR) in which the producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle. An EPR policy can be characterized by [64]

- shifting of responsibility (physically and or economically, fully or partially) upstream towards the producers and away from the municipalities
- the provision of incentives to producers to take into account environmental considerations when designing their products.

Further, the producers and distributors need to provide for collection at retail shops with sales areas relating to EEE of at least $400m^2$ or in their immediate proximity [57]. The various distributors can collaborate and arrange for a single collection point based on parameters such as population density, ease of access to collection points, and any other geographical constraints. The producers must ensure a next to zero cost for the households/customers in regards to disposing of their EEE waste.

Disposal and transport: Article 6 of the WEEE directive enumerates that the member states shall prohibit the disposal of separately collected EEE waste before it has undergone treatment as specified by the directive. The collection and transport of the waste must be carried out to allow optimal conditions for preparing for re-use, recycling, and confinement of hazardous substances. The directive also mandates that the EEE eligible for re-use must be separated from the other waste at the collection points, this can be ensured by granting access to personnel from re-use centers. [57].

Rate of collection: According to article 7 of the directive between 2016 to 2019, the minimum collection rate for a producer was 45% of the average weight of the EEE placed in the market in three preceding years in a member state [57]. It also mentions that the member state has to ensure a gradual increase in collection rate between 2016 to 2019. From 2019, the minimum collection rate to be achieved annually was set at 65% of the average weight of EEE placed on the market in the three preceding years in the member state or alternatively, 85% of the waste EEE generated [4]. These are the minimum rate of collection to be ensured and the member states can set more ambitious targets and report the same to the Commission. On the other hand, in a few member states such as Bulgaria, the Czech Republic, Latvia, Lithuania, Hungary, Malta, Poland, Romania, Slovenia, and Slovakia **??** a collection rate between 40-45% was applicable in post-2019 owing to the lack of infrastructure and low consumption volumes of EEE. However, these member countries were to achieve collection rates of 65% and above by the date of their choice, but no later than 14 August 2021. In order to ensure uniformity in the implementation of Article 7, the commission set up a common methodology for the calculation of the weight placed on the national market and a common methodology for calculating the quantity of WEEE generated by weight in each member state. To ensure that the minimum collection rates have been achieved, the member states are required to annually submit the following information regarding WEEE collection in accordance with Article 5 to the commission and other member states:

1. received by collection and treatment facilities
2. received by distributors
3. separately collected by producers or third parties acting on their behalf

The commission in turn needs to present a report to the European Parliament and to the the council. Any change in the collection rates or the directive needs to be submitted to the European Parliament through the Commission.

Treatment: The treatment standards including recovery, recycling, and preparing for re-use of WEEE are set up by the European Committee for Standardization (CEN). These standards aim to ensure that

WEEE is treated in an environmentally responsible and safe manner and to promote the reuse and recycling of materials. Member states are free to establish their own standards but are required to report the same to the commission and ensure that they are published. Member states can encourage organizations that treat waste to have certified environmental management systems as per the EU regulation 1221/2009 [57]. The treatment operation can also take place outside the member state or European Union provided the exporter can prove that the treatment took place in conditions that are equivalent to the requirements of the directive.

Recovery targets: Article 11 provides a guideline for the minimum target of recovery of all the WEEE collected. The fulfillment of the targets shall be calculated for each category by using the Equation 2.1

$$\text{Recovery rate} = \frac{\text{Weight of properly treated WEEE entering recycling/reuse facility}}{\text{Total weight of separately collected WEEE}} \tag{2.1}$$

In order to track these targets, member states have to ensure that the producers or third parties acting on their behalf keep records on the weight of WEEE, its components, materials or substances when leaving the collection facility, and also while entering and leaving the treatment facility and finally when they enter the recovery or recycling/ preparing for reuse facility.The evolution of PV recovery targets is enumerated below [57]

- **13/08/2012 to 14/08/2015 -** 75% by weight of the WEEE collected were to be recovered and 65% by weight were to be recycled
- **15/08/2015 to 14/08/2018 -** 70% by weight shall be prepared for reuse and recycling and 85% by weight shall be recovered.
- **15/08/2018 onwards -** 80% by weight shall be prepared for reuse and recycling and 85% by weight shall be recovered.

Financing of WEEE from private households and others : Article 12 lays the guidelines with respect to the financing of WEEE from private households. This regulation mandates that producers finance the proper disposal of waste electrical and electronic equipment (WEEE) from private households that has been deposited at collection facilities. Producers are also required to provide a guarantee showing that they will finance the management of all WEEE and to clearly mark their products accordingly. The responsibility for financing historical waste management falls to systems to which all producers contribute proportionally based on their market share. Member States must develop mechanisms or procedures to reimburse producers for EEE that is placed on the market outside their territory. The Commission is requested to consider developing criteria to include real end-of-life costs in the financing of WEEE and to propose any necessary legislation.
On the other hand Article 13 outlines the financing of WEEE generated by other than private households. This directive mandates that producers finance the collection, treatment, recovery, and environmentally responsible disposal of WEEE from non-private household users for products put on the market after August 13, 2005. Additionally, producers are responsible for financing historical waste costs when replaced by new equivalent or functional products, while users other than private households are responsible for financing historical waste costs for other cases. Alternative financing methods may be agreed upon by producers and users outside of private households, as long as they comply with the directive.

Information for users and treatment facilities: The aim of Article 14 is to ensure the flow of information from the producers to the end users regarding WEEE. Producers may be required by Member States to disclose the expenses associated with environmentally responsible collection, treatment, and disposal of WEEE to buyers. In addition, private household users must receive essential information on the proper disposal of WEEE, return and collection systems, their role in the recovery process, hazardous substances in EEE, and the symbol used for WEEE. Member States must also take necessary measures to promote consumer involvement in the collection process and ensure proper labeling of EEE with the WEEE symbol. Lastly, Member States may oblige producers and/or distributors to provide information on WEEE via instructions for use, at the point of sale, and public awareness campaigns.

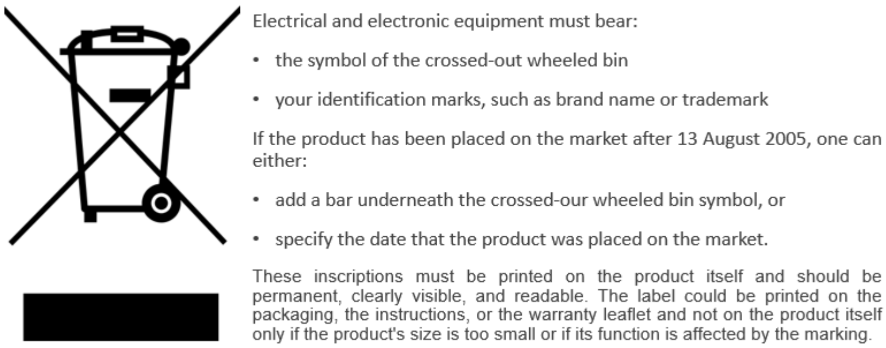


Figure 2.1: Symbol of WEEE and guidelines of the label [65]

Further Article 15 provides information for treatment facilities. It states that Member States must ensure that producers provide free information on the preparation for re-use and treatment of new EEE within one year of its placement on the Union market. This information must be made available in the form of manuals or electronic media. It should identify the different EEE components and materials and the location of dangerous substances and mixtures in EEE. Additionally, a mark specifying that the EEE was placed on the market after August 13, 2005, must be applied to enable the date of placement to be determined. The European Standard EN 50419 should be used for this purpose.

Registry of producers: The directive throught Article 16 states that Member States must create a register of producers to monitor compliance with the requirements of the directive. This includes producers who sell EEE through distance communication, who should be registered in the Member State they sell to. If they are not registered in that Member State, they can be registered through authorized representatives.Member States must ensure that each producer or authorized representative is registered and can enter relevant information about their activities online. Producers must provide specific information when registering and undertake to update it as necessary. National registers should also provide links to other national registers on their websites to facilitate registration of producers.The Commission is responsible for adopting implementing acts to establish the format for registration and reporting, as well as the frequency of reporting to the register. Member States must collect information annually on the quantities and categories of EEE placed on their markets, collected through all routes, prepared for re-use, recycled, and recovered within the Member State. They must also collect information on separately collected WEEE exported, by weight.

Incentive for application of waste hierarchy: Member States are permitted to use economic instruments and other measures to encourage the implementation of the waste hierarchy and achieve the goals of this Directive. Such measures may include those specified in Annex IVa to Directive 2008/98/EC, or other appropriate instruments and measures.

2.2. Waste Framework Directive: Directive 2008/98/EC

Directive 2008/98/EC is a legislation of the European Union that provides guidelines for waste management, covering waste prevention, reuse, recycling, and safe disposal. The objective is to establish a consistent approach to waste management practices throughout the EU, with the aim of reducing the environmental and health risks associated with waste. The directive applies to all forms of waste, including WEEE, and establishes goals for member states to increase recycling and decrease landfill waste.

The waste hierarchy outlined in Article 4 of the Directive and depicted in Figure 2.2, prioritizes waste prevention and management strategies in the following order (including definitions of the same from Article 3) [58]:

1. **Prevention** means measures taken before a substance, material or product has become waste;
2. **Preparing for reuse** means checking, cleaning, or repairing recovery 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;
3. **Recycling** is a process by which waste is reprocessed into products or materials for original use or repurposed. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations ;
4. **Other recovery,(e.g energy recovery)** refers to a process of extracting useful energy from waste and its byproducts in the form of electricity, heat, or fuel. The idea is to make better use of waste and avoid it being dumped in as landfill;
5. **Disposal** refers to discarding waste in a manner that is safe and environmentally responsible.

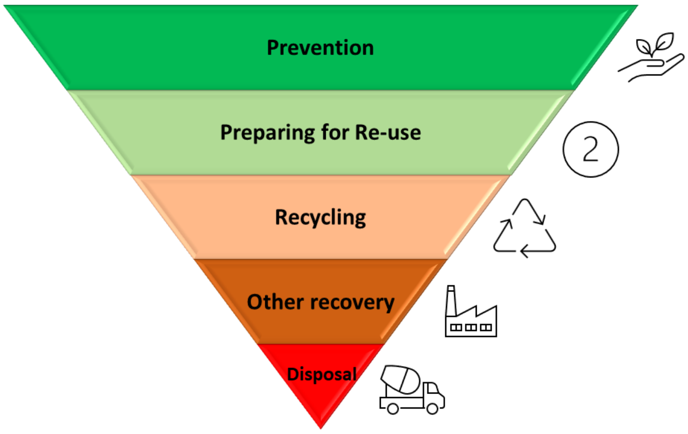


Figure 2.2: Authors illustration of the Waste hierarchy as described in Directive 2008/98/EC [58]

When implementing this hierarchy, Member States are encouraged to choose options that offer the best overall environmental outcome. However, in certain cases, specific waste streams may depart from the hierarchy if justified by considering the overall impacts of waste generation and management. Member States must ensure that the development of waste legislation and policy is transparent and involves consultation with citizens and stakeholders. Additionally, environmental protection principles such as precaution, sustainability, technical feasibility, and economic viability should be taken into account.

End-of-waste status: The directive also provides guidelines for when a product can no longer be classified as waste in Article 6. After the specified waste has undergone recovery, including recycling and operation, and can be grouped into one of the following it can longer be classified as waste

1. the substance or object is commonly used for specific purposes;
2. a market or demand exists for such a substance or object;
3. the substance or object fulfills the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products; and
4. the use of the substance or object will not lead to overall adverse environmental or human health impacts. [58]

However, member states can decide case by case if certain waste has ceased to be waste taking into account the applicable case law and the commission should be notified of such decisions in accordance with directive 98/34/EC.

Extended producer responsibility: Article 8 of the directive briefly enumerates extended producer responsibility. It allows the member states to implement measures to ensure that producers have extended responsibility, including accepting returns of products and managing the resulting waste. The producers should also be encouraged to design products that reduce environmental impacts and waste generation. While exercising extended producer responsibility technical feasibility, economic viability, and environmental, health, and social impacts must be considered while ensuring the proper functioning of the internal market. The extended producer responsibility shall be applied without affecting the existing waste management systems and or the existing waste stream-specific and product-specific legislation. The Directive 2008/98/EC also follows the polluters pay principle, wherein the costs of waste management shall be borne by the original waste producer or by the current or previous waste holders. The decision regarding the distribution of bearing the waste management costs i.e., if the producer has to wholly or partly in conjunction with the distributor of these products is taken by the member state.

Re-use and recycling: Member states are encouraged to promote the re-use of products and by means of incentives to re-use and repair networks. To align with the goals of Directive 2008/98/EC and progress towards establishing a European society focused on recycling and efficient resource utilization, several time-specific targets were specified. The objective is to increase the overall recycling rate of waste materials, such as those from households, to a minimum of 50% by weight by 2020. Similarly, non-hazardous construction and demolition waste, excluding naturally occurring materials, should reach a minimum recycling rate of 70% by weight. Rules and calculation methods to ensure compliance with these targets, taking into account waste statistics regulations are set up by the Commission. Member States are required to report their progress every three years, including reasons for any failures and proposed actions to meet the targets. Additionally, member states were required to set up separate collections for at least paper, metal, plastic, and glass by 2015 [58].

Responsibility for waste management: Article 15 states that Member States are required to implement measures to ensure that original waste producers or holders either handle waste treatment themselves or entrust it to authorized dealers, establishments, waste treatment operators, or waste collectors. The responsibility for complete recovery or disposal of waste cannot be discharged solely during preliminary treatment. Member States have the flexibility to specify conditions and determine cases where the original producer retains full responsibility or shares it with others in the treatment chain. Waste management responsibilities may be assigned to the product producer, with the possible involvement of distributors. Member States must also ensure that professional waste collection and transportation entities within their territories deliver the collected waste to appropriate treatment facilities, in compliance with Article 13, which outlines the importance of waste management without endangering human health and the environment [58].

Principles of self-sufficiency and proximity: Member States are required to take appropriate measures, in collaboration with other Member States when necessary, to establish a comprehensive network of waste disposal and recovery facilities. This network should include installations for handling mixed municipal waste from private households and other producers. The aim is to achieve self-sufficiency in waste disposal and recovery at both the individual Member State and EU levels, considering geographic factors and the need for specialized facilities. The network should prioritize proximity, ensuring waste is disposed of or recovered at the nearest suitable facilities using the most appropriate methods and technologies, to protect the environment and public health. However, it is not necessary for each Member State to possess the complete range of final recovery facilities within their territory. Additionally, Member States have the right to restrict incoming and outgoing waste shipments in order to safeguard their waste management plans and address environmental concerns [58].

2.3. Renewable Energy Directive (2018/2001/EU)

Directive 2018/2001/EU also known as the Renewable Energy Directive is a legislative framework established by the European Union (EU) to promote the use of renewable energy sources and achieve the EU's renewable energy targets. The directive sets a binding target for the EU to achieve a 32% share of renewable energy in final energy consumption by 2030. Each member state is assigned an individual target based on its starting point, potential, and cost-effectiveness. The European Commission will evaluate this target and propose potential increases by 2023 if there are significant cost reductions in renewable energy production, a need to meet international decarbonization commitments, or if a significant decrease in energy consumption justifies raising the target. These binding targets would lead to an increase in renewable energy installations and ultimately at the EoL of these systems a proportionate waste generation. The Renewable Energy Directive leverages the Waste Framework Directive (2008/98/EC) to address concepts of the waste hierarchy, waste management, and creating a circular economy. Even the targets for recycling and waste management are as mentioned in Directive 2008/98/EC and no additional targets are mentioned in the Renewable energy directive.

2.4. Spanish Royal Decree 110/2015 on WEEE

Following the WEEE directive 2012/19/EU the Spanish Royal Decree 110/2015 promoted sustainable production and consumption, the prevention of WEEE, and treatment techniques such as preparation for reuse. The government realized the importance of the two sectors in the waste hierarchy as stated in section 2.1 i.e, prevention and preparation for re-use in terms of employment creation, which would, in turn, add social and economic value in the society. Based on the information from the Subdirectorate General of Foresight and Analysis within the Ministry of Agriculture, Food, and Environment, the waste sector emerges as the primary catalyst for green employment in Spain, constituting approximately 27% of the overall green job market in the country. Within the Biodiversity-Green Employment Project spanning from 2007 to 2013, it was projected that over 4,700 direct job opportunities would be generated through the preparation for the reutilization of WEEE.[59].

The Royal Decree has the following immediate objectives: it aims to enhance the regulation of waste electrical and electronic equipment (WEEE) management in Spain by providing clearer guidelines and establishing specific responsibilities for users, manufacturers, authorized representatives, importers, distributors, and managers. It introduces a unified control mechanism to monitor regional and national WEEE data, ensuring compliance and traceability of waste. The decree promotes re-use and the establishment of re-use centers, fostering job creation in this sector. It also standardizes reporting obligations for EEE producers and WEEE managers, ensuring consistency in WEEE management across the country. Ultimately, the decree seeks to optimize the economic and efficient management of WEEE under extended producer responsibility while maintaining the competitiveness of EEE manufacturers and WEEE managers. Going further the Spanish Royal Decree will be analyzed in terms of EoL for PV modules.

In order to not affect the annual collection fees and targets of other electrical equipment with similar features owing to the long half-life and professional profile of PV modules the SRD categorized PV modules into a new category [59]. In terms of WEEE relating to PV modules, the Royal Decree identifies two technologies. First PV panels that contain silicon, are classified under non-hazardous waste, and second PV panels containing Cadmium-tellurium, are classified under Hazardous waste. The Royal Decree outlines a detailed process for the handling and treatment of these two technologies. To this end, a combined List of Waste (LoW) codes from Decision 2000/532/EC will be used to identify the collection and management of WEEE within the scope of the Royal Decree. The LoW-WEEE has two additional digits that trace the waste to the source and the type of treatment of the equipment.

2.4.1. Silicon photovoltaic panels processing (160214-71)

This section looks into the procedure outlined by the Royal decree for the handling and processing of silicon-based PV panels including the documentation. All the photovoltaic panels containing silicon will be subjected to the following hierarchy of treatment [59]:

- **Stage 0: Reception of the equipment and preliminary dismantling**
  1. This step involves procedures for entry and storage of WEEE considering compliance with the environment and the desirability of preparing for re-use and recycling.
     (a) **Entry into the facility:**
       - Classification of WEEE based on origin with the help of accompanying documentation.
       - Visual check of the WEEE and its conformity with the delivery note.
       - Assortment of WEEE based on LoW-WEEE code and removal of any accessible components such as batteries and accumulators.

- Initial weight of WEEE by LoW-WEEE code
- Entering data into the facility's chronological record and in the WEEE electronic platform.

(b) **Storage before treatment**

- The area where the WEEE is stored before treatment needs to comply with the provisions of Annex VIII of the diective.
- To ensure compliance with the facility's permit, it is imperative that the maximum quantity of stored WEEE does not exceed the specified limit. Additionally, adherence to the time restrictions outlined in Article 20.4.a of Law 22/2011 (dated 28 July) is crucial, wherein non-hazardous waste allocated for recovery should not be stored for more than two years, while waste designated for disposal must not exceed one year [66]. To facilitate monitoring, it is necessary to maintain a record of the entry and treatment dates of received WEEE, categorized by batches or deliveries.
- The stored stocks need to be registered annually and are considered part of the facility's mass balance.

2. It is essential to classify the received WEEE items under the relevant category, with specific emphasis on separating the silicon photovoltaic panels from other WEEE components.
3. In order to facilitate the preparation for environmentally friendly re-use and recycling of components and materials, it is necessary to remove easily accessible parts from the panels, including the protective glass, outer casing, wiring, junction boxes, and other relevant components. This process should be conducted while considering the available information provided by the producers of EEE.

- **Stage 1: Treatment** Following the removal of the module's easily accessible parts in stage 0, the encapsulants, including EVA and other plastic sheeting used for insulation around the PV cells, will be eliminated using heat treatment or comparable methods. It is crucial to ensure that the processes are employed with appropriate security measures.
- **Stage 2: Separation from the rest of fractions** At this stage, the silicon wafers are extracted and separated from the rest of the recoverable fractions. These fractions, along with all the components that were removed, are to be stored in individual containers. These containers will then be transported to authorized waste managers who specialize in the treatment of each specific fraction. Before shipping, it is essential to meticulously record the deposited amounts, intended destination, and the treatment plan for each container in a chronological record. This documentation is crucial for evaluating the extent to which recycling and recovery targets, as specified in Annex XIV, are being met.

Mass balance
Inputs =$\sum$ of inputs to the process

a) LoW-WEEE code: (160214-71)
b) Quantity in tons (t).

Outputs = $\sum$ of removed components$+\sum$ of removed recoverable fractions$+\sum$ of non-recoverable fractions

a) LoW code/description
b) Destination:

- Energy recovery: Quantity (t) and operation (R1, R2, etc.)
- Recycling: Amount (t) and operation (R1,R2, etc.)
- Elimination: Quantity (t) and operation (D1, D2, etc.).
- Destination's manager: Name, EIN and province.

Losses during the process = inputs - outputs - stock
In terms of recovery rates and targets the Royal decree does not deviate from the ones set in the WEEE directive that are listed in section 2.2.

2.5. Current practices

In this section, the actual implementation of the Spanish Royal Decree and WEEE in Spain will be looked at. In Spain, the obligations pertaining to product design, waste management, and associated costs lie with the producer (such as the manufacturer, distributor, or installer). These producers are required to register their electrical and electronic products in the national register of Producers of Electrical and electronic equipment (RII_AEE) administered by the Ministry of Industry, Commerce, and Tourism (MINCOTUR). The registration can be carried out individually or through a producer responsibility organization (PRO). In a collective system, each producer contributes to the system based on the number of products they introduce to the market annually. In an individual system, the producer assumes all costs. Currently, there are 11 authorized PROs, as specified in Royal Decree 110/2015: Reinicia, Ecotic, Ambilamp, Ecolec, Ecofimática, Ecolum, Ecoasimelec, ERP, Eco-Raee's, Sunreuse, and Ecoeche [67]. These organizations are responsible for managing and financing the recycling of waste electrical and electronic equipment (WEEE). They collect funds from producers and fulfill their obligations regarding WEEE management and reporting to the relevant authorities and consumers [68]. The MITERD (Spanish Ministry for the Ecological Transition and the Demographic Challenge) annually releases the WEEE collection targets for collective systems during the first quarter. Individual systems receive their specific targets directly from the ministry. These targets are determined by considering the quantity of WEEE introduced to the market in the preceding three years.
Table 2.1 depicts the installed PV modules in Spain between 2017 and 2020. In the year 2017 around 1532 tons by weight of PV modules were installed and in 2020 around 221998 tons of panels were installed on the market (these are not cumulative installations but year-on-year installations). Table 2.2 gives an insight into Spain's WEEE performance for the years 2017,2018 and 2019. Apart from 2017 where Spain managed to recover 86.4% by weight of the collected PV modules, it wasn't able to meet its recovery target of 85% in the other two years where it only managed to recover 53.8% and 51.8% by weight of the collected PV modules. In terms of targets related to preparation for reuse and recycling, Spain was not able to achieve its target in any of the three years. The closest it came to achieving this target was in 2017 when 65.8% by weight of the modules were prepared for reuse and recycling [67].

Table 2.1: PV Panels placed on the market in Spain [67]

Year	Put on the market (tons)
2017	1532.24
2018	21854.54
2019	83256.34
2020	221998.21

Table 2.2: PV panel collection, recovery, and preparation for reuse and recycling performance in Spain for the years 2017,2018, and 2019. Data obtained from [67]

Year	Total collected Tons	Recovery (tons)	Preparing for reuse and recycling (tons)	Recovery performance		Preparation for Reuse and recycling performance	
				WEEE Target %	Achieved %	WEEE Target %	Achieved %
2017	155.13	134.10	102.21	85%	86.4%	70%	65.8%
2018	461.89	248.55	240.35	85%	53.8%	70%	52%
2019	226.15	117.29	104.33	85%	51.8%	80%	46 %

Despite having a National law in the form of a Royal Decree of WEEE Spain is falling short of its targets for PV module recovery and preparation for reuse and recycling. This shows that the legislative framework alone cannot support the effective EoL management of PV modules. A market structure and economic viability need to be established which supports the stakeholders in facilitating an effective EoL management of PV modules. In general, the WEEE directive addresses the waste management requirements of PV modules in EU member states today, indicating an 85/80 (%) recovery/recycling by weight of the PV modules collected from 2019.Today by default a decommissioned PV module enters the waste stream and is either disposed of or in the best case -recycled. The condition of the panel and the reason for decommissioning are seldom taken into account before processing the module. The current mainstream recycling CIRCUSOL estimates that nearly 80% of the PV waste stream consists of panels that have failed prematurely due to defects that arise during transportation, production defects, and installations. Further, CIRCUSOL estimates that 50% of this waste stream can be diverted from mainstream recycling [69]. Mainstream recycling today for solar panels leads to the recycling of aluminum frames into raw metal feedstock. Whereas, the rest of the solar panel is shredded and ends up as filler material for concrete or subbase for roads mainly [70]. In the next chapter, an estimate of the number of materials by weight and value contained in PV modules is presented by studying the installation trends. The resources and values being discarded can be understood by studying the amount of materials contained in PV modules.

3
Solar Panel Deployment Metrics

This chapter deals with the installation trends for different periods 2014,2020 and 2030. This would provide an estimate of the amount of PV waste expected to be handled over the years. Further, the PV waste is quantified in terms of material (in tonnes) and monetary value (in €)

3.1. Installation trends

A combination of government policies to subsidize renewable energy generators and a low LCOE has contributed to the growth of PV technology in terms of installed capacities. Figure 3.1 depicts the cumulative installed capacities over the years, as a boundary condition the time frame is limited from 2014 to a prediction of 2030. In 2014 the total cumulative installed capacity was about 178 GWp [71], with first generation contributing to 165 GWp which accounts for 92.5% followed by thin film solar cells at 7.5% [3], i.e, 13 GWp. The thin film technologies considered here are CdTe, a-Si, and CIGS. A similar trend can be observed in the other two years considered. In 2020 an increase in the market share of the first generation to 95.2% can be observed from a total cumulative installed capacity of 772 GWp. In the year 2030, a total cumulative capacity of 5200 GWp is assumed as this is the capacity required to meet the 1.5°C climate goal [2]. About 4420 GWp is assumed to come from the first-generation solar cells and close to 10%, i.e. 520 GWp from the aforementioned thin-film technologies. Further, 5% is assumed to be the contribution from other technologies/ third generation [71], and since the 5% will not be dealt with in any form in this report, no further explanation is provided.

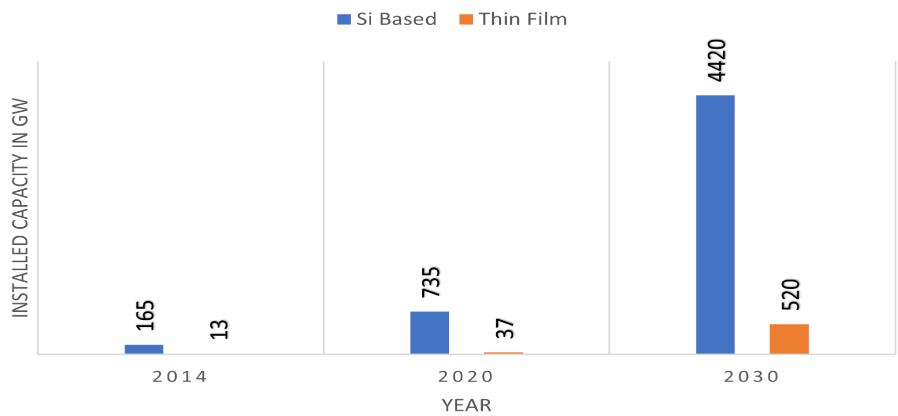


Figure 3.1: Technology wise cumulative installed PV capacity based on data obtained from [2], [71]

3.2. Cumulative installed capacity in terms of material weight

An LG NeON® 2 Bi-facial module is used as a reference module for the calculation of the weight of materials corresponding to the cumulative installed capacities in 2014,2020 and 2030. Utilizing the [kg/W] of a module from table 3.1 and a combination of weight distribution for each of the materials from figure 1.3 and total installed capacity as illustrated in figure 3.1 results in the total amount of each of the materials i.e glass, polymers, aluminum, copper, silver, and silicon utilized to deploy the PV modules. Figure 3.2 represents the millions of tonnes of various materials contained in the installed panels. As expected glass dominates the material usage with 6.44 million tonnes in 2014 and growing almost by 26 times to 172.33 million tonnes in 2030. Followed by aluminum with 1.17 million tonnes in 2014, 5.26 million tonnes in 2020, and 31.60 million tonnes in 2030. In third, polymers (encapsulant) of which 0.81 million tonnes were used in 2014, a threefold increase in consumption to 3.64 million tonnes in 2020 and 21.88 million tonnes in 2030. However, it is to be noted that this calculation does not consider the wastage generated during the production of each component and is only a first-order approximation of the material contained in each of the panels.

Table 3.1: Specification of reference module [72]

Cells	6×12
Cell Type	Monocrystalline / N-type
Power rating in W	400
Dimensions [L x W x H] in mm	2064 x 1024 x 40
Weight in Kg	22
Weight/power [kg/W]	0.055

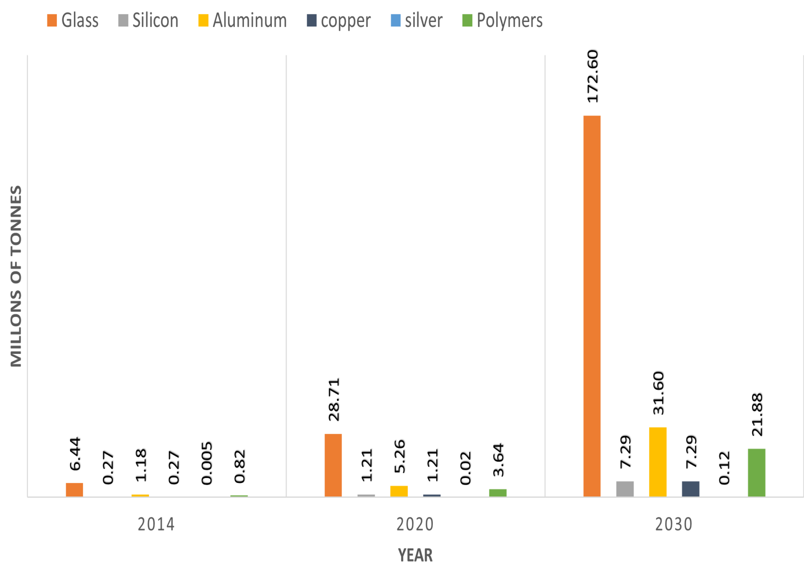


Figure 3.2: Cumulative installed capacity of first-generation modules in terms of materials (million tonnes)

3.3. Cumulative installed capacity in terms of material value

In order to economically quantify the materials that represent the installed capacities of PV panels, this section looks at the value of each of these materials in Euros (€). The cost of any material on a global scale depends on factors such as their demand, time frame of consumption, availability, cost of processing, shipping, storage, and economic stability [73].To capture the trends of the aforementioned factors an average of the rates of different materials from 2014-2020 has been considered to represent the cost of the material used. These costs are only representative of the market buying price of the material. The details of the data and trend of the price considered can be found in Appendix B. Table 3.2 provides a summary of the prices considered for further analysis in this report.

Table 3.2: Average price of materials [74]–[78]

Material	Price [€/unit]	Unit
Silver	480.11	kg
Silicon	11.78	kg
Glass	2	m^2
Aluminium	1.56	kg
Copper	5.17	kg

Combining the millions of tonnes of materials contained in the installed PV modules from Figure 3.2 with the unit price of these materials in the table 3.2 provides an estimate of the value of these materials in billions of euros in the periods of 2014, 2020 and 2030 as depicted in Figure 3.3. Glass and aluminum about 85% of the total weight of the module as can be seen in Figure 1.3. However, in Figure 3.3 glass and aluminum constitute only about 35% of the total value. Throughout the considered timeframe silicon and silver continue to dominate by contributing to 31% and 21% of the total value respectively. These two materials in terms of cumulative installed capacity are worth close to € 86 billion and € 58 billion in 2030. Around 17% i.e., € 1.73 billion in 2014, € 7.72 billion in 2020, and € 46.44 billion in 2030 of the total value can be attributed to glass. Out of materials considered copper is the minority contributor, with only 14% of the total value over the years. Figure 3.4 represents a distribution of various materials as a percentage of their contribution to the total value of the module.

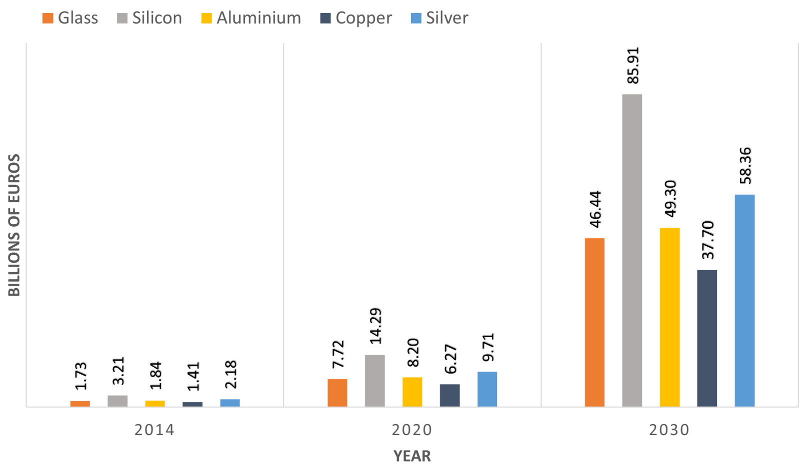


Figure 3.3: Cumulative installed capacity of first-generation modules in terms of material value (Billion €)

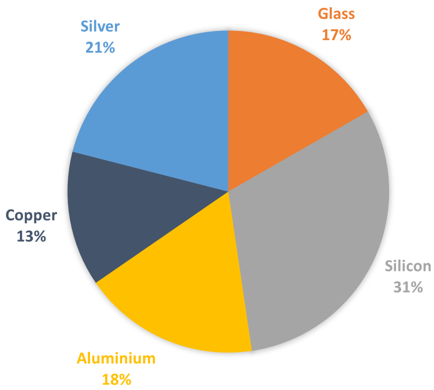


Figure 3.4: Percentage distribution of materials as per monetary value

3.4. Current facts and figures

This section presents a few facts and numbers on the latest installation capacities of photovoltaic (PV) systems across the globe and the efforts to develop recycling processes. The installations will help us understand which countries are contributing to the rapid growth of PV systems. It will also help to visualize where PV waste streams will be concentrated. In 2020, China led the world in cumulative PV installations, with 277 GWp of installed capacity, which represents 36% of the total global capacity. North America and Japan followed with 11% and 10%, respectively. Europe accounted for 21% of the total capacity, and within Europe, Germany contributed 6% of all installations. India and Germany had an equal footing, with 46 GWp of installed capacity each, while the remaining 108 GWp were distributed across various regions of the world.

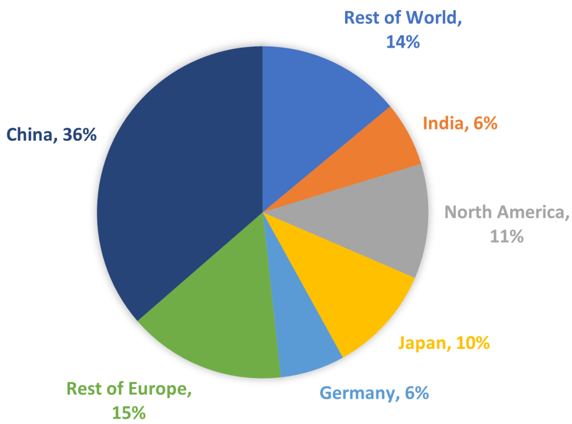


Figure 3.5: Global cumulative PV installations by region based on data obtained from [3]

The WEEE directive requires a recycling rate of 80%-85% by weight post-2018, as previously discussed [79]. To achieve this target, the recycling process mainly involves downcycling glass and aluminum frames, constituting about 85% of the module's weight but only 35% of its total value. However, it has been observed that not all glass and aluminum are recovered, and the remaining mass is either incinerated or ends up in landfills owing to the low landfill costs (€1 per module) [80], [81]. Even if all aluminum and glass are recovered, a significant amount of €181.97 billion worth of other materials contained in the cumulative installed capacity of modules in 2030 will be discarded.

While the discussions to this point may be indicative of the process that has been implemented for EoL management of PV modules, they do not necessarily indicate the extent of efforts that have been devoted to the research of processes that facilitate better EoL. [79] provides a detailed account of the efforts that have been made towards EoL management of PV modules. Specifically, they analyze patents filed for each component of a PV module between 1995 and 2016, across different regions of the world. The various EoL management processes are further categorized based on their nature, such as thermal, chemical, mechanical, optical, and a combination of these.

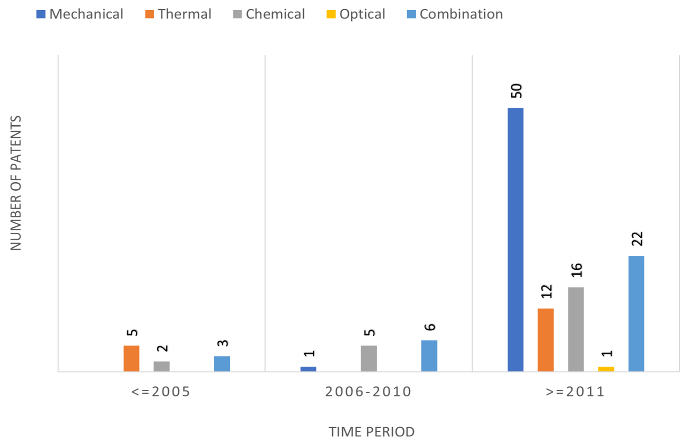


Figure 3.6: Number of patents filed for PV module by time period. Graphical representation of data obtained from [79]

Figure 3.6 illustrates the number of patents filed for various EoL management processes in different countries over the years. Mechanical processing comprises 40% of the total patents filed, with 80% of these mechanical patents being filed in China. Chemical processing methods contribute to 19% of the total patents, followed by thermal methods at 15%. Combination processes account for one in every four patents filed. Figure 3.7 provides a material/component-wise recovery of these processes. Prior to 2011, there were no significant numbers of patents filed for aluminum, silver, and copper recovery. Between 2006 and 2010, patents for Si, solar cells, glass, and aluminum (frame) constituted the majority of the patents filed [79].

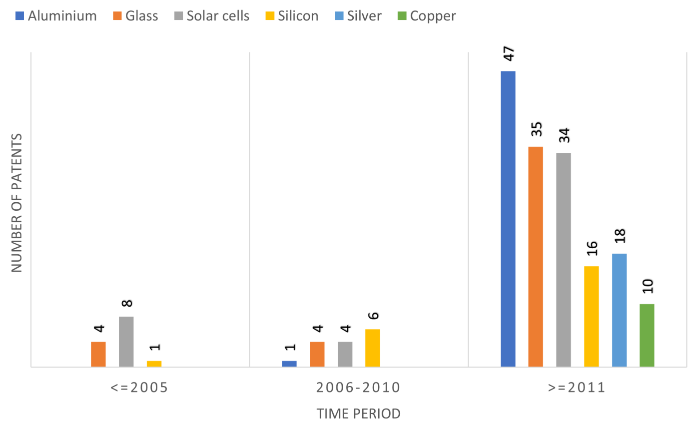


Figure 3.7: Number of patents filed for material recovery from PV module by time period. Graphical representation of data obtained from [79]

Figure 3.8 illustrates the projected amount of PV panel waste in 2050. The waste is categorized into two types: regular loss, which includes panels that have reached the end of their 30-year lifespan, and early loss, which includes panels infant failure, mid-life failure, and wear-out. In 2050, a cumulative amount of 138 million tonnes of PV waste is expected, with 78 million tonnes from regular loss and 60 million tonnes from an early loss [82]. China, the United States, Japan, India, and Germany are the top five contributors to this waste, with China accounting for the largest share at nearly 24% with 33.5 million tonnes. The United States follows with 17.5 million tonnes, while Japan and India account for 14 million tonnes and 12 million tonnes, respectively. Germany is fifth with 6% of the total waste, equivalent to 8.7 million tonnes. Together, these five countries are responsible for 62% of the total expected PV waste, while the rest of the world is expected to account for 38% with 52.3 million tonnes [82]. IRENA estimates 80% of the PV waste stream will consist of premature failures such as production defects or damages from transportation and installation [82].

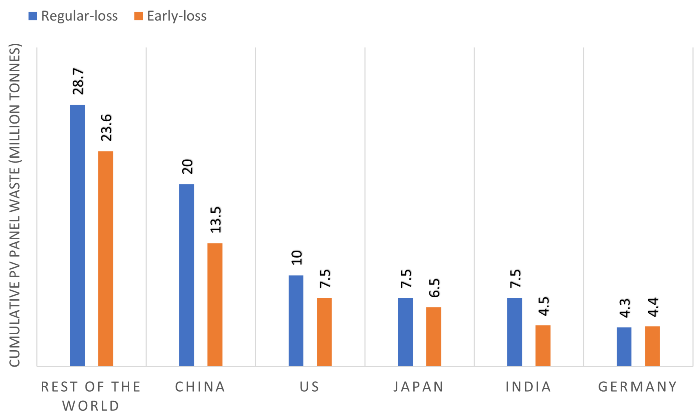


Figure 3.8: Cumulative waste projection by top 5 countries and rest of the world by 2050. Graphical representation of data obtained from [82]

TNO a research organization based in the Netherlands carried out a study to estimate the potential revenues that can be derived from the recovered materials by implementing the best recycling practices [70]. The study considered two scenarios based on the prices of the recovered materials. Scenario one represents the bare minimum of historical market prices and scenario two represents the historically high market prices. Table 3.3 represents the prices and quantity of each of these materials extracted from a 60-cell panel.

Table 3.3: Minimum and maximum values considered for recovered PV panel materials [70]

Material	Value (€/kg)		Quantity (kg/panel)
	Bare minimum	Historical high	
Silver	150	1050	0.0078
Metallurgical silicon	1.58	2.51	0.7
Aluminium	0.93	1.86	3.6
Glass (crushed)	0.037	0.16	14
Copper	4.09	6.51	0.06

Figure 3.9 depicts the value of individual components extracted or recovered from a PV module through recycling. The maximum achievable value amounts to €6.6, with aluminum accounting for half of the total recoverable value, equivalent to €3.35. Silver contributes to 18% of the total value with €1.17 followed by silicon (metallurgical grade) at 14% with €0.95. Finally, €0.61 and €0.56 worth of copper and glass (crushed) can be recovered from a panel. It is to be noted that the silicon recovered here is metallurgical grade silicon and will have to undergo energy-intensive processes to be converted into solar-grade silicon for PV modules or high-purity silicon used in electronic devices.

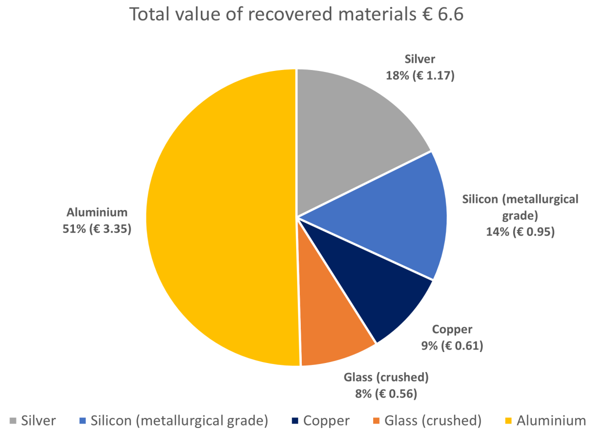


Figure 3.9: Minimum value for all valuable materials extracted from a PV panel, assuming metallurgical grade Si and crushed glass. Absolute material values in euro are given in brackets

Figure 3.10 represents the maximum value that can be obtained considering the historically high prices for the recovered materials from recycling a PV panel. As compared to scenario 1 a value almost 3.5 times higher can be derived from the recovered materials in scenario 2. In this scenario, the total value of recovered materials is around €21. While aluminum remains the highest contributor with 39% of the total value at €8.37 per panel, silicon contributes almost equally with €8.19 of the total recovered value. Glass is the third highest contributor with €2.37 or 11% of the total value with silicon and copper accounting to €1.51 and €1.09 respectively. It is interesting to note that none of the recovered materials in this study can be directly utilized for producing a solar panel. The prices of these recovery techniques are relatively unknown and lack a standardized pricing structure.

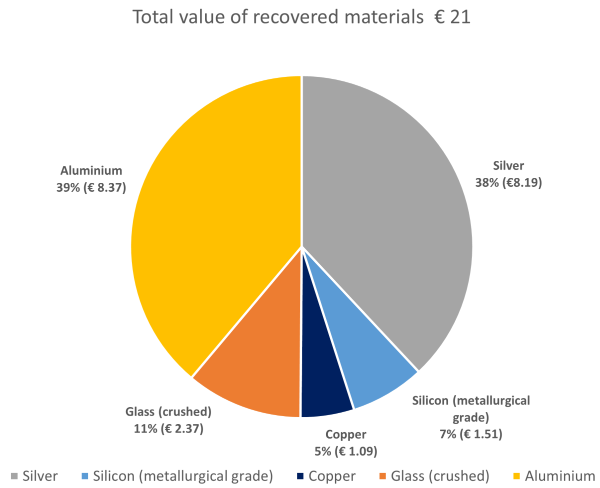


Figure 3.10: Maximum value for all valuable materials extracted from a PV panel, assuming metallurgical grade Si and crushed glass. Absolute material values in euro are given in brackets

The cost of recycling per module ranges between €15 to €30 [70], [83], whereas the revenue from the recovered materials ranges between €6.6 to €21. At the bare minimum historical prices considered in scenario 1, the revenues from the recovered materials i.e. €6.6 do not cover the expenses of recycling. Therefore Scenario 1 does not offer a viable solution for recycling. In scenario 2 with historically high prices, the revenue from the recovered materials does lie in the range of the costs associated with recycling. However, there is only a particular range i.e. from €15 to €21 for the recycling process to be economically viable. It should be noted that the contribution of materials in Figure 3.4 varies from Figures 3.9 and 3.10. This is due to the fact that Figure 3.4 represents the monetary value of materials in solar grade i.e. after they have been processed to improve their purity and characteristics.

However, Figures 3.10 and 3.9 represent the value of materials that cannot be used directly to make solar panels and need to be further processed. Glass and aluminum in Figure 3.4 contribute to 35% of the total value of the module, whereas in Figures 3.9 and 3.10 they contribute to 50-59% of the total value. The main difference between Figures 3.4 and 3.9,3.10 is the processing costs to improve the purity of the materials. Silicon that represents 7-14% in Figures 3.9 and 3.10 respectively contributes to 31% in Figure 3.4. This shows the influence of the process costs on materials. In short, these figures represent materials at different stages and hence the difference in contribution to the total value.

4 Economic Boundaries

The second life of PV modules involves the deployment of appropriate EoL/waste management. Policies such as the ones discussed in Chapter 2 promote the polluters pay principle, i.e the producers and distributors of PV modules are held responsible for setting up and financing the waste collection, sorting, and recycling/reuse networks. These processes are capital intensive and might be a herculean task for the producers, as the WEEE directive states that the recycling network is supposed to be non-profit [57]. In this regard, it might be useful for the producers and policymakers to know the economic boundaries within which establishing and maintaining such processes are feasible.

4.1. Levelized cost of electricity

Levelized Cost of Electricity (LCOE) is utilized as a tool for setting up the boundary condition in terms of the Maximum price per second life module.LCOE is the price at which the generated electricity would need to be sold in order to cover all the costs associated with the system over its lifetime, i.e, the break-even point [84]. LCOE can also be used as a metric to compare various power-generating technologies. LCOE can be calculated using Equation 4.1 [85]

$$LCOE = \frac{\sum_{t=0}^{n} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{E_t}{(1+r)^t}} \tag{4.1}$$

where t refers to the year of operation of the system/project, with t = 0 representing the start of the system construction, and n representing the lifetime of the system. I_t is the investment expenditure in year t, M_t represents the running and operation, and maintenance cost (fixed and variable) in year t. The discount rate is represented by r and finally, the electricity generated in year t is represented by E_t (in KWh). The discount rate r is used to depreciate the cash flows in order to account for the return that the investors would require, and it depends on aspects such as the general economic situation, returns of alternative investment opportunities, real and perceived risks, etc [85].
To serve as a reference point for comparison, the Levelized Cost of Electricity (LCOE) of a new system will be considered. The determination of the maximum price for a second-life (reuse or refurbished) module will be based on the LCOE of a new system. Initially, the LCOE will be calculated without applying any discount (discount factor of 0%). Subsequently, sensitivity analysis will be conducted by incorporating different discount factors. Energy yield plays a crucial role in LCOE calculations, and the Photovoltaic Geographical Information System (PVGIS) was utilized to make the following assumptions for energy yield estimation [86]:

- A location in Amsterdam, The Netherlands was considered with the following coordinates 52.375 °N Latitude and 4.912°E Longitude.
- A residential, roof added, and grid-connected 320 Wp system with a slope of 35°.
- System loss of 14% (to consider the difference in the power generated by the module and delivered to the grid due to losses in cables, power inverters, dirt on the modules, etc.,)

Table 4.1: Inputs for LCOE calculation [86], [87]

Input Parameters	**Unit**
Power of the system	320 Wp
Cost of Module	469.8 €
Cost of Balance of Plant	843.9 €
Soft Costs	1252.8 €
Cost of System (I_t)	2566.5 €
Operation and Maintenance (M_t)	26.05 €/year
Specific Energy Yield (E_t)	926.09 kWh/year.kWp
Lifetime (t)	30 years

Using inputs listed in Table 4.1 and Equation 4.1 the LCOE for a new PV system is 0.1205 €/kWh. This value of LCOE is in very close agreement with the value calculated BY NREL [87].

4.2. Price and LCOE trends

The €/kW cost of PV systems has been declining at a rapid pace. This reduction in price can be attributed to the advancement in technology which has resulted in low material usage and a widespread adaption and implementation of PV technology. PV system costs can be grouped into

1. Cost of the module
2. Balance of Plant (BoP) and soft, costs refer to the non-module expenses, including installation, infrastructure, electrical components, permitting, land lease, and project development costs.

The decrease in PV system costs is a result of a drop in the prices of the above-mentioned components. Although the prices for these elements have reduced over the years they haven't declined at the same rate. Figure 4.1 shows the price change in module price over the last ten years i.e., between 2011-2021 in a solid blue line. The average price for both mono and multi-crystalline modules has been considered. The mono-crystalline module technology has seen a price drop of greater than 10% every year between 2011 to 2021. The highest % price change was a 37% drop in costs between 2018 and 2019 from 0.963 €/W to 0.703 €/W respectively. The price remained constant between 2014 and 2015 [88]. On average, the year-on-year price reduction was around 16%. On this basis, assuming an average 16% reduction in prices year-on-year a price trend for modules over the next 30 years i.e., up to 2051 was calculated. The resulting module prices are as depicted in Figure 4.1 using a dotted blue line. The price of the module in 2030 and 2051 is expected to be around 0.098 €/W and 0.003 €/W respectively.
The costs associated with BoP and soft costs have also had a reduction between 2011-2021. Although not at the same scale as the modules. Figure 4.2 represents the change in costs associated with this component of the PV system over the years using a solid blue line. The price of BoP and soft costs were around 3.78 €/W in 2011. These costs had the highest reduction between 2012 to 2013 when they dropped by 24% from 3.78 €/W in 2012 to 3.054€/W in 2012. Over the years these costs have reduced at an average of 7% year on year. Figure 4.2 shows the expected price trend between 2022 and 2051 in a dotted blue line assuming the same decrease of 7% year-on-year. The costs associated with BoP and soft costs in 2051 are expected to be around 0.238 €/W.

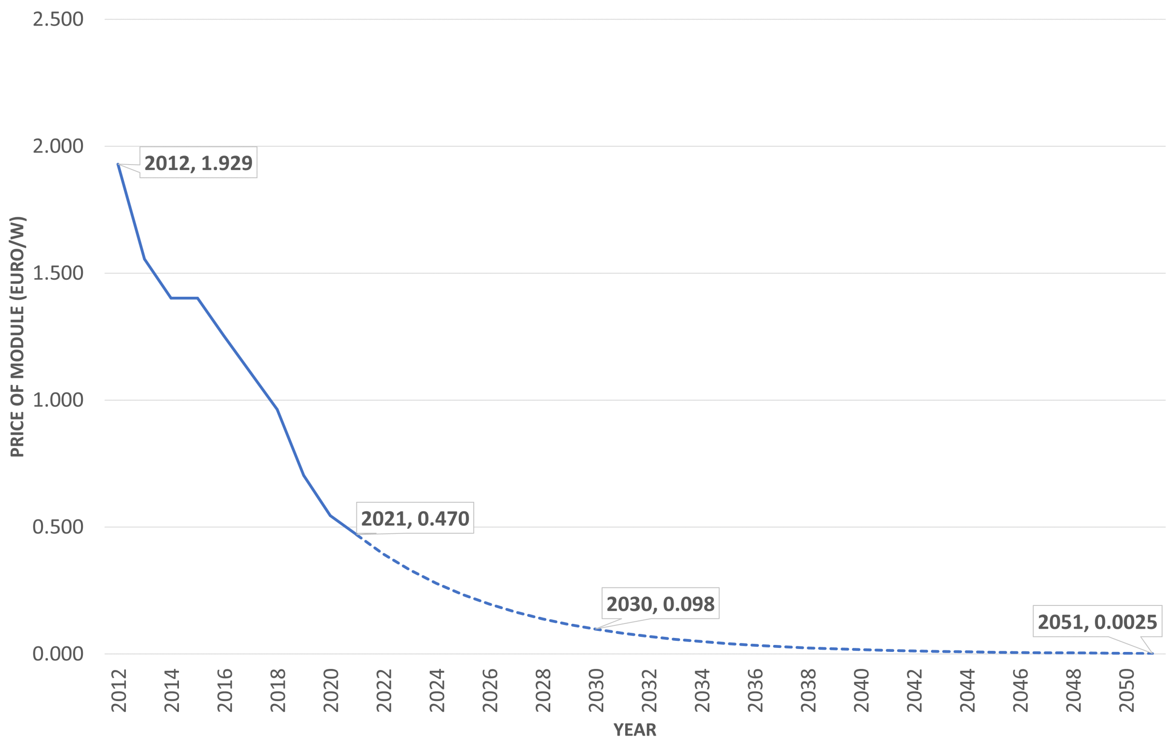


Figure 4.1: Historical prices for first-generation PV modules between 2011 and 2021 are represented in a solid blue line [88]. Future predicted module price by the author from 2022 to 2051 is depicted in a dotted blue line

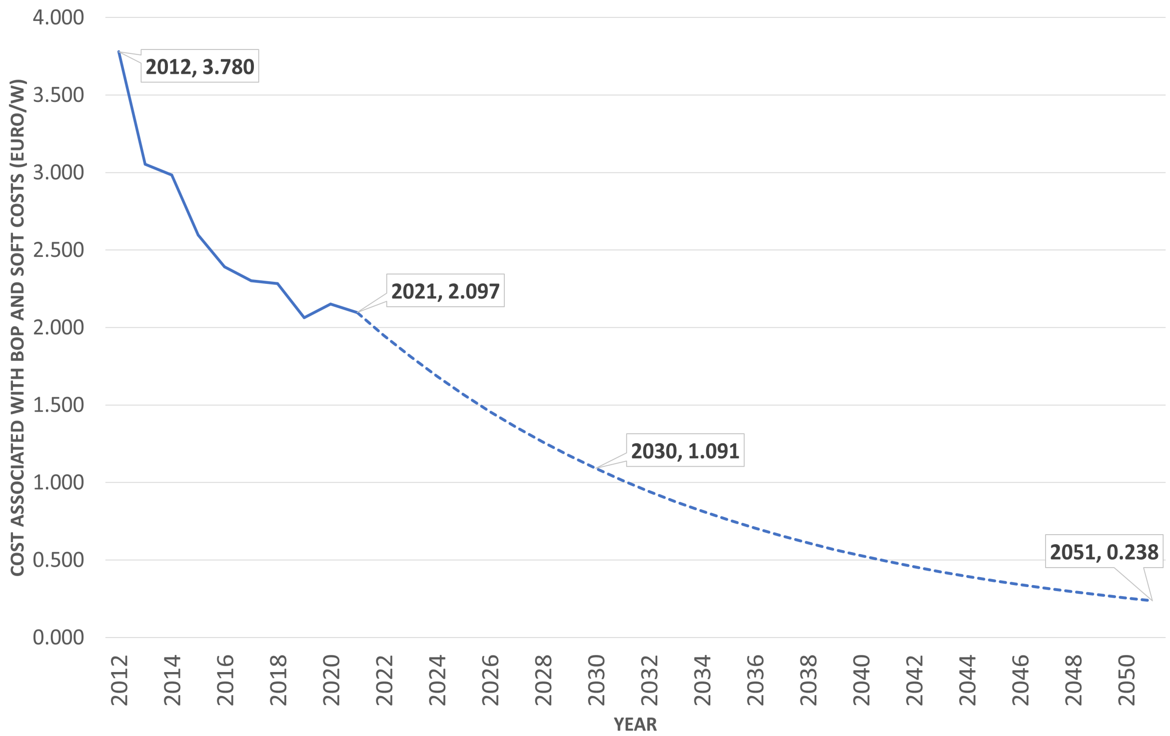


Figure 4.2: Historical BoP and soft cost associated with PV module from 2011-2021 obtained from [87] are represented in a solid blue line. The future predicted costs by the author from 2022 to 2051 are depicted in a dotted blue line

Assuming a change in Module costs, BoP, and soft costs over the years between 2021 and 2051 as depicted in Figures 4.1 and 4.2 and the rest of the components in Table 4.1 such as the capacity of the module, energy yield, operation and maintenance cost constant a future trend of LCOE is calculated. Figure 4.3 depicts the predicted LCOE of first-generation residential-scale PV systems between 2021 to 2051. An approximate 10-fold decrease is expected from 0.1205 €/kWh in 2021 to 0.0121 €/kWh in 2051. The LCOE in 2030 is expected to be 0.0558 €/kWh which is almost 50% of the LCOE in 2021. The change in the predicted LCOE year on year varies between 8.65% to 7.09% with an average of 7.58%. In the next section, a boundary condition in terms of module price will be established based on the predicted cost and price trends. Further, the assumption of LCOE as a baseline for comparison will also be explained.

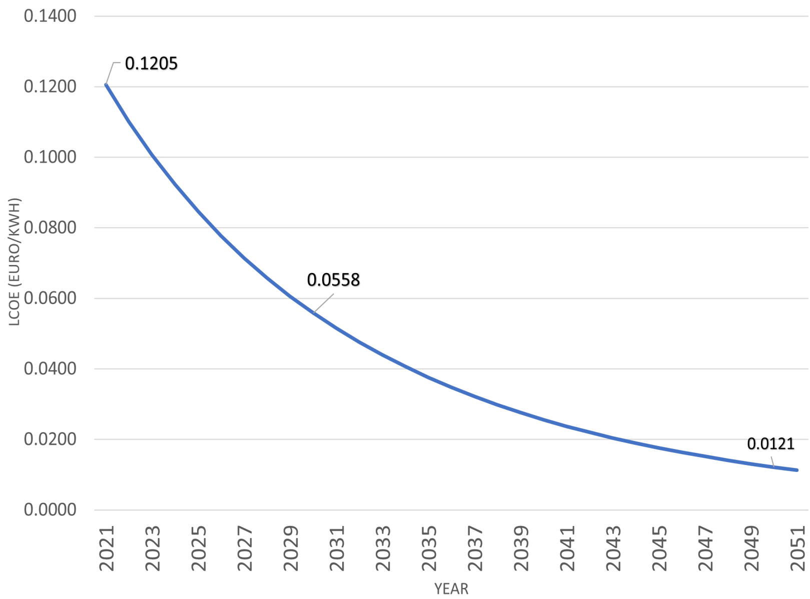


Figure 4.3: Projected LCOE trend 2021-2051

4.3. RE-module pricing

LCOE can be viewed as an economic viability tool for the comparison of different energy systems. For example, it can be used to compare the selling price of electricity generated by fossil fuels versus electricity generated by solar panels. However, it is to be noted that LCOE for all the PV technologies and sizes cannot be represented by 0.1205 €/kWh. This is due to the fact that different technologies have different CAPEX and maintenance costs associated with them and different operating efficiencies. Further location-specific costs and energy yields also play a role in determining the LCOE for a system. A second life panel can be viewed as a new panel with a reduced capacity. For example, a 320W panel at the end of its 30 years life span will be performing close to 86% (278W) of its rated capacity. This is assuming a 0.5% year-on-year reduction in the power of a panel. A degradation study carried out by NREL has shown that solar panels have a median degradation rate of 0.5% per year [89]. But this value could be higher in rooftop systems with hotter climates. A second life panel can be considered viable for the customer if the LCOE for the refurbished system is at least as the same that of a new system. And for a supplier/manufacturer in the reuse/recycle network it would gain traction if they are able to meet the customer expectation with the second-life panels.

In the following subsections, a few scenarios have been considered where a second-hand panel might be deployed. For each of these scenarios, the cost of the module with respect to the second life expectancy in years is calculated. One common assumption for all the scenarios will be a constant LCOE of 0.1205 €/kWh.

4.3.1. Scenario 1: Refurbished module + new BoP

Consider an old 320W system that has reached its EoL. This system as per the assumption stated in the previous paragraph at the EoL is operating at a power of 278W. For this system to be viable in the market the LCOE of the older system has to be at least equal to the LCOE of the system as per Table 4.1. The following assumptions are made for this scenario:

- The BoP of the old system has to be replaced with a new system. And the cost of the BoP and the soft cost is the same as depicted in 4.1, i.e. €843.9 and €1252.8 respectively.
- Operation and maintenance costs are the same as the new system.
- Lifetime of the second life panels varies from 1-30 years.

Keeping all the above assumptions in mind, the only variable left to complete the LCOE equation is the price of the module. This price can help establish a maximum ceiling in terms of cost that can be incurred by the supplier/manufacturer to put the module back into the market and also the minimum second life to make the panel viable. The capex component in the Equation 4.1 consists of the cost of the module and Bop and soft costs. Therefore,Equation 4.1 assuming a interest rate of 0% can be rewritten as follows:

$$LCOE = \frac{(C_M + C_B) + \sum_{t=0}^{n} (C_{OM})}{\sum_{t=0}^{n} E_t} \tag{4.2}$$

Where,

- C_M represents the cost of the module (€),
- C_B represents costs associated with BoP and soft costs (€),
- C_{OM} represents operation and maintenance cost and (€),
- E_t represents energy generated (kWh)

From Equation 4.2 varying the expected lifetime of the module will produce different prices of the module while maintaining a constant LCOE of 0.1205 €/kWh. The resultant prices of the module with respect to the expected second life of the module are as depicted in Figure 4.4.For a second life panel (RE-panel) with an expected lifetime of 30 years a module price of €469.8 yields an LCOE of 0.1205€/kWh. It is interesting to note that for a RE-panel with a lifetime of 27 years, the module price is nearly halved, €268.35 (about 57%) of the cost of a new panel. Going further down in terms of life expectancy a minimum of 24 years has to be assured for the supplier/manufacturer to expect any cash inflow. With a 23 years second life expectancy, the module price is expected to be close to €0. Beyond this point, the module prices are negative indicating a cash outflow for the supplier/manufacturers.

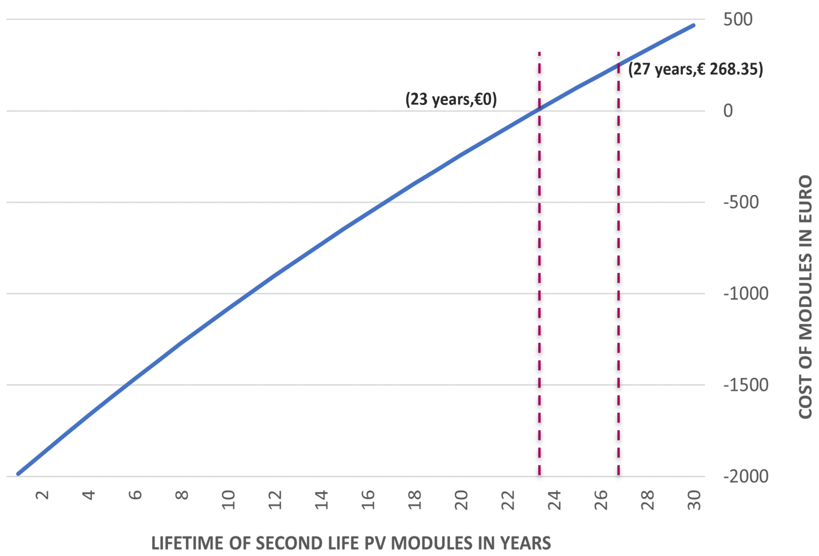


Figure 4.4: Cost of Second life PV modules based on LCOE = 0.1205 €/kWh. The cost of the module includes the retail selling price (RSP), cost of refurbishment of the panel, and transportation costs

So what do these module prices mean for the producers? For example, considering a very optimistic scenario where the RE-module is expected to last for 30 years, the producers have about €469.8 to spend on the module. That means the entire cost involved from dismantling the panel after its first EoL, transportation, inspection, refurbishing, and placing the product on the market including a profit margin of 17% which is typically the case for a residential PV system [87] has to be within €469.8 per panel. For lifetimes of the RE-panel less than 24 years the producers will have to spend money to place the product on the market i.e., the producers will have to pay the customers for the product to be purchased. A negative cash flow for any business is an indication of economic infeasibility. This shows that for a RE-panel to be viable it has to have a minimum life expectancy of 24 years, also keeping in mind the assumptions made throughout this section. However, this high second life expectancy for economic feasibility is only considering the fact that the entire system (module, BoP and soft costs) has to be replaced.

4.3.2. Scenario 2: Refurbished module + existing BoP

Stressors as mentioned in section 1.3 can cause damage to a PV module before it completes its initial lifespan. During such cases, the BoP might still be functional, and only the module needs to be replaced. In such a scenario, the BoP and soft costs while installing the refurbished module are zero. Accordingly, the inputs to determine the cost of the module with respect to the expected second life are tabulated in Table 4.2 and calculated using Equation 4.2

Table 4.2: Inputs for scenarios 1 and 2, where x represents the cost of the module that needs to be determined. In scenario 2 'x' represents the cost of the module including labor charges for installation

Input Parameters	Scenario 1	Scenario 2
Power of the system	278Wp	
Cost of Module	'x' €	
Cost of Balance of Plant	843.9 €	0 €
Soft Costs	1252.8 €	0 €
LCOE	0.1205 €/kWh	
Operation and Maintenance	26.05 €/year	
Specific Energy Yield	926.09 kWh/year.kWp	
Lifetime	1-30 years	

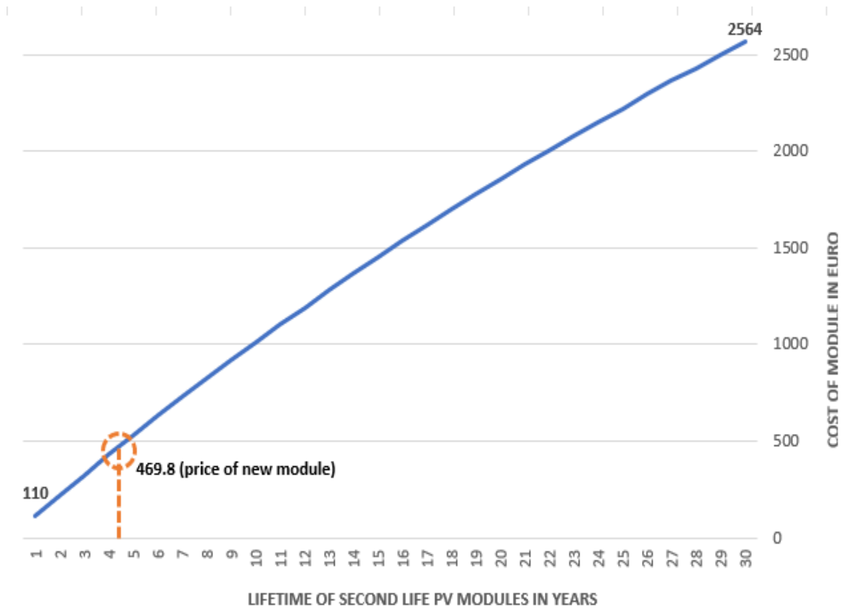


Figure 4.5: Cost of Second life PV modules based on LCOE = 0.1205 €/kWh, utilizing the existing BoP.The cost of the module includes the retail selling price, cost of refurbishment of the panel, and transportation costs

Figure 4.5 represents the cost of the module inclusive of the RSP, profit margin as mentioned in scenario 1 (17%), cost of refurbishment, and transportation cost (collection center - refurbishment facility - retailer) and labor charges for installation. This represents a more optimistic scenario from a supplier/-manufacturer point of view as compared to Scenario 1. In Figure 4.5 it can be seen that for a second lifetime of close to 4.5 years, the cost of the module is €469.8. This is the same as the price of the new module. However, this does not mean that the second-hand module will be sold at the same price as a new module owing to lower capacity and expected lifetime. Although in the same figure, the cost of the module with a second-lifetime expectancy of 30 years is around €2564 it does not mean the module will be sold at such a high price. In a best-case scenario, the cost of a new module can be considered as an upper threshold for pricing the second-hand module. Removing the BoP and soft costs makes the second-hand module viable with positive cashflows and without constraints on lifetime expectancy while maintaining the LCOE at 0.1205 €/kWh.

4.4. Effect of discount rate on LCOE

Subsidies and policies have a significant impact on LCOE, and this impact can be understood by considering discount rates. The discount rate is the interest rate or rate of return used to determine the present value of future cash flows. It is commonly used in financial calculations to evaluate the worth of future income or costs in today's terms. The discount rate reflects the time value of money, which means that a euro received in the future is worth less than a euro received today due to factors such as inflation and the opportunity cost of capital [90]. In practice, the discount rate reflects, among others, opportunity costs of investment as well as different kinds of risk and uncertainty, for example regarding political and regulatory developments, the market design, the system development and future investment and fuel costs[91]. Subsidies and policies can have the following effects :

- Cost reduction: Reducing the upfront costs of renewable energy projects through subsidies and policies can have a direct impact on the initial investment needed. In the calculation of the levelized cost of energy (LCOE), these upfront costs are usually adjusted to their present value by applying a discount rate. A lower discount rate would lead to a reduced present value of costs, thus making the LCOE of subsidized projects appear lower.
- Technology development: Subsidies and policies that support technology development in the renewable energy sector can lead to cost reductions over time. As technology advances and costs decline, the LCOE of renewable energy sources decreases. The discount rate used in the LCOE calculation helps assess the future benefits of these cost reductions, giving them appropriate weight in the present.
- Market Simulation: Subsidies and policies can create market demand for renewable energy by setting targets or mandates for renewable energy generation. This stimulates investment in renewable energy projects and drives economies of scale. Increased market demand can lead to lower costs for equipment, installation, and operation, ultimately reducing the LCOE.
- Risk Mitigation: Subsidies and policies can help mitigate financial risks associated with renewable energy projects. This can include mechanisms like power purchase agreements (PPAs) or guarantees that provide long-term revenue certainty. By reducing the perceived risks, lenders and investors may offer better financing terms, resulting in lower financing costs and ultimately reducing the LCOE.

For studying the effect of discount rates on LCOE, the following discount rates are considered in line with EGC 2020 [91]

- **3%** - corresponding approximately to the social cost of capital
- **7%** - corresponding approximately to the cost of capital of a large utility in a deregulated or restructured market and,
- **10%** - corresponding approximately to the cost of capital in an environment with relatively higher risks.

Utilizing Equation 4.1 with the discount rates as mentioned above, Figure 4.6 shows the variation of LCOE between 2021-2050. It is interesting to note that LCOE increases with a higher discount rate. At a discount rate of 10%, the LCOE in 2021 is around 0.3221 €/kWh as compared to 0.1205 €/kWh with a discount rate of 0%. Discount rates of 3% and 7% yield an LCOE of 0.1695 €/kWh and 0.2515 €/kWh in 2021 respectively. In 2030, a reduction of 54% is observed in LCOE for each of the above-considered discount rates, resulting in an LCOE of 0.0785 €/kWh, 0.1165 €/kWh, and 0.1492 €/kWh for discount rates of 3%, 7%, and 10% respectively. An approximate ten-fold decrease (9.9) of LCOE in 2050 was observed with 0.0.0121, 0.0171, 0.0253, and 0.0325 €/kWh for 0%, 3%, 7%, and 10% respectively.

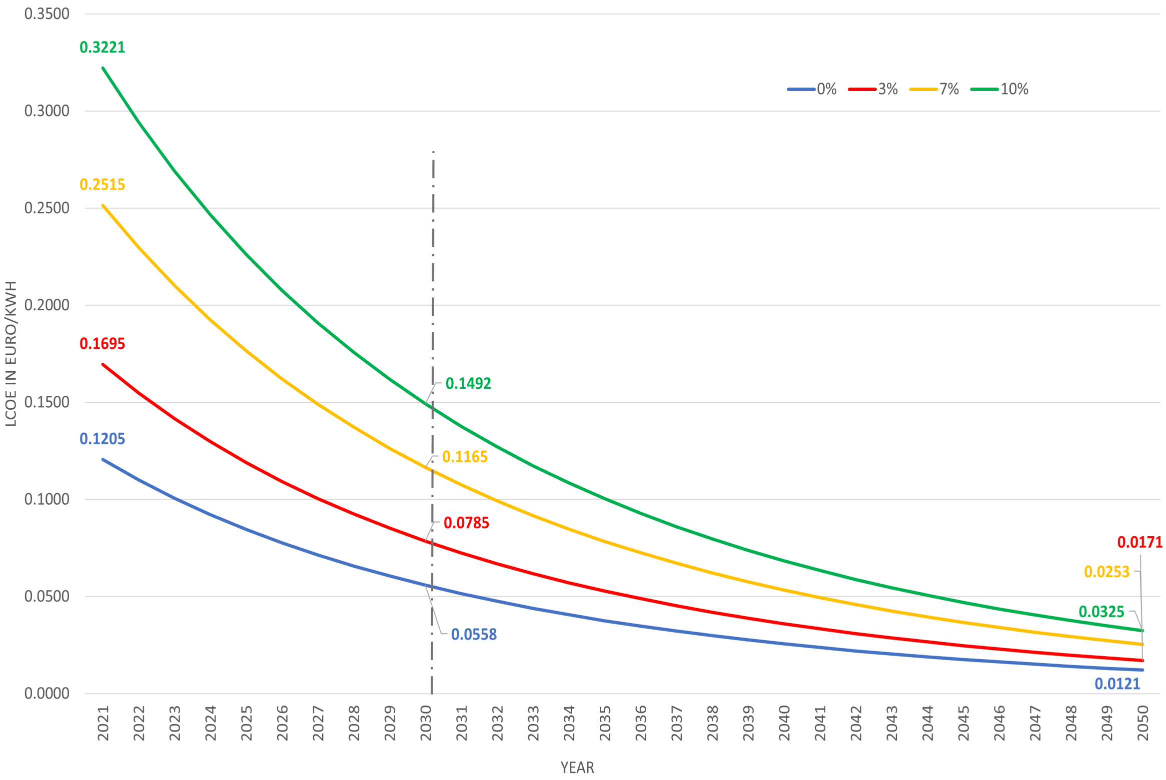


Figure 4.6: LCOE trend between 2021-2050 for various real discount rates

Discount rate accounts for the time value of money, a higher discount rate increases the weight given to future costs and revenues, making future costs less significant in present value terms. This means that the upfront costs, such as capital investments, become more influential in determining the LCOE. As a result, a higher discount rate tends to increase the LCOE.
The cost of a second-hand module for time periods 2021-2050 can be determined by utilizing Equation 4.2 and the LCOE, cost of BoP, and soft cost depicted in Figures 4.6,4.2 respectively. This could be an indicative tool for policymakers while setting up a system to facilitate the second-life PV module market.

5

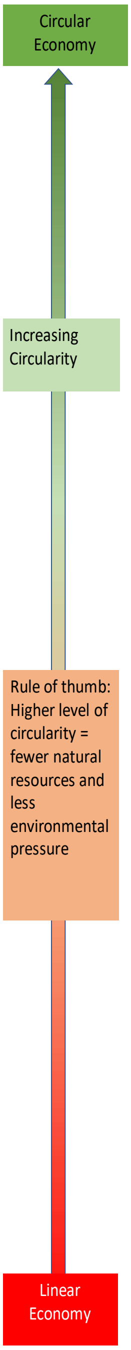
Roadmap to Circularity

5.1. Circularity

Sustainability as defined by the United Nations Brundtland Commission in 1987 “meeting the needs of the present without compromising the ability of future generations to meet their own needs”[92]. To realize sustainability, emphasis has been placed on increasing efficiencies of processes by reducing the use of materials and energy in order to lessen the environmental impact[93]. Although this might be a step in the right direction, it is short-sighted as it still ends up producing a huge amount of waste at the EOL without appropriate EOL handling systems in place. Reduction alone in the usage of materials still leads to the depletion of a finite raw material reserve and defeats the purpose of sustainability as stated above. It is clear that the linear approach of cradle to grave approach isn’t the long-term solution for sustainability.

Therefore, it becomes essential to consider a concept that allows maintaining the flow of materials within the systems through the concept of circularity. Circular Economy or circularity focuses on a cradle-to-cradle approach, which is a design philosophy devised by Micharl Braugngart and William McDonough [94]. This concept aims at creating a closed-loop system in which resources are kept in use for as long as possible, waste is minimized, value of the materials is preserved, achieved by reusing the material at the end of life of a product as raw material for new products. Circularity in simple terms is the design of a product with its own end-of-life considered. In a circular economy, the product is reintroduced into the supply chain instead of being sent to a landfill once it is no longer needed by a user [95].

Several circular strategies are grouped into three focus groups in what is known as the R-ladder as illustrated in Figure 5.1. The order of the various R strategies is according to the preferred level of deployment. The first group smarter product use and manufacture is the most preferred, an example would be product sharing. This would mean that one product is being used by multiple users instead of a multiple of the same being used which would translate to higher material and energy consumption. The next group of R strategies is the lifetime extension of products and the least preferred group would be the energy-intensive and the product in its full form or constituent parts is no longer available for use in other products. As a rule of thumb, higher circularity translates to higher environmental benefits [96]. Going forth the concepts of reuse and refurbish will be utilized for the second life of PV modules. In addition to presenting the conditions of the panel at EoL,the following sections aim to establish a framework that would help navigate the second life of first-generation solar panels, with regard to reuse and refurbishment.



	Stratergies	PV eco-system	Example
Smarter product use and manufacture	R0 Refuse	Utilizing other sources of renewable energy generators which have a lower impact on the environment and natural resources	i) Bio-mass ii) Geothermal iii) Optimizing energy systems and demand
	R1 Rethink	i) Multi-utility PV modules ii) Reorganize the market structure by offering it as a shared product. iii) Redesign PV module.	i) PV module as a community shared service. ii) PV as a leased service. iii) PV as a subscription model. iv) A LEGO based PV module design where only the faulty component can be replaced, or the cells can be upgraded without having to discard the entire module to accommodate a latest module.
	R2 Reduce	i) Reduce the usage of materials in PV modules. ii) Reduction of waste during production processes by optimizing and integrating recycling into production processes.	i) Replacing first-generation solar panels with thin-film technologies. ii) recycling of Si kerf during wafer production.
Extend Lifespan of product and its parts	R3 Re-use	Re-use Moules after their EoL	Second-hand PV modules as depicted in Figure 5.5
	R4 Repair	Repair and refurbish EoL modules and re-supply into the second hand market	
	R5 Refurbish		
	R6 Remanufacture	Design and produce modular panels, that can be upgraded with the latest technology of cells at their EoL instead of being recycled	LEGO based PV modules with interchangeable components
	R7 Repurpose	Finding alternate systems to utilize the PV modules when they can no longer serve in a system them were initially designed for.	If a PV module is no longer suitable for a large- scale PV installation it can be repurposed for an off-grid system such as public lighting, irrigation in agriculture, individual charging points for ebikes
Useful application of materials	R8 Recycle	Processing the module to recover the same (high grade) or lower quality materials such as silicon, silver, copper, etc so that they can be used as raw materials for new modules or other products that utilize these materials depending on the purity of the materials obtained.	i) Recycled silicon from PV modules can be utilized in other electronic devices that would require a lower grade of Silicon purity such as ICs in simple electronic circuits, and lower-cost consumer electronics. ii) Recycled silver can be used and reintroduced into the PV ecosystem or can be utilized for Printed circuit boards, switches and contacts or a few other electronic components.
	R9 Recover	Recovery is a broader term that encompasses (including recycling) the extraction of value from waste streams.	Incineration of PV modules to recover energy.

Figure 5.1: R-Laddder for circular strategies adapted from [96] and modified by author for a PV ecosystem

5.2. Condition of EoL panels

At the beginning of the report in section 1.3 various stressors that the panel is exposed to during its operational lifetime were discussed. As a result of this exposure, the performance of the panels is affected. The gradual deterioration or loss of performance of a system, material, or component over time can be referred to as degradation. Table5.1 illustrates the various degradations in the components of a PV module. In this section the degradations that are listed in 5.7 will be briefly introduced, and this would give a general idea of the condition of the module at their EoL.

- **Damaged glass :** The damage to glass can mean breakage to glass or erosion of coating. Despite being tempered and annealed, up to 33% of the module field failures have been on account of glass breakage [97]. Due to thermal and mechanical stresses, breakage may occur during transportation, installation, and operation. For c-Si modules, the breakage does not immediately affect the performance and safety but facilitates moisture ingress, which might accelerate the encapsulant's degradation [98]. Further, it also might lead to cell or circuit damage and hotspot formation as the ability of the glass to act as a barrier and insulator to moisture has been compromised [9]. PV glass results in optical losses of about 4% due to reflection and close to 50% due to soiling in certain locations [9]. Therefore, PV glass is coated with anti-reflection and anti-soiling coating to minimize these losses. However, over time these coatings erode and affect the performance of the module.
- **Discolouration:** Discolouration or yellowing of the photo-oxidation and thermo-oxidation of the polymer films [99], [100]. Photo-oxidation results in the formation of acetic acid [25] which is a result of the degradation of the additives in the encapsulant. However, over the years this isn't been a prominent degradation thanks to the addition of the hindered amine light stabilizers (HALS) being added to the EVA as an agent to prevent photo-oxidation [25]. The immediate effect yellowing has is the absorption of light in front of the cell which translates to power losses [9], [25].
- **Delamination :** Although less common than discolouration, delamination is a more critical failure mode. Delamination refers to the separation or detachment of different layers within a PV module that is held together by the encapsulant. In other words, Inadequate adhesion of the EVA layer with other components of PV modules undermines the structural stability and mechanical strength of the modules. This aspect becomes particularly crucial in ensuring the modules' reliability in the face of mechanical and thermo-mechanical stresses caused by factors like wind, snow, or variations in thermal expansion. Apart from the above delamination also leads to issues such as increased reflection, and water ingress poses a threat to the electrical integrity of the module. Due to inadequate isolation from the mechanical stresses cell cracking is also a common side effect of delamination. A power loss higher than 10% was estimated due to delamination in panels in a report by IEA [101]. Delamination also leads to the accumulation of water, which might corrode the cell interconnects over time, resulting in a discontinuity in the circuit.
- **Back sheet damage :** PV modules include a broad array of back sheet materials such as transparent tedlar (TPT), thermoplastic elastomer (TPE), Fluoropolymer film (FPF), and a few other combinations of material used in the construction of the back sheets [28] along with glass in case of bi-facial modules. An expansive field evaluation consisting of 286 installations around the world representing 1.047 GW was carried out by DuPont with a primary focus on back sheets [102]. The common degradations observed in back sheets are chalking, yellowing on the inner layer, cracking, and mechanical property loss. While degradations such as chalking and yellowing do not have an immediate effect on performance or safety, they might be indicative of more serious problems that might arise such as cracking and delamination. Cracked back sheets can no longer provide insulation to the electrical components on the backside of the modules and delamination as mentioned in the case of encapsulant allows water ingress and compromises mechanical strength and structural rigidity
- **PID :** Solar panels are typically connected in series to build up the voltage in grid-connected systems, and the module frames are grounded for safety reasons. Due to this a high electrical potential difference is induced between the module frame and the cells at either end of a module string. This potential difference can lead to the occurrence of Potential Induced Degradation (PID). PID manifests as leakage currents flowing from the module frame to the solar cells (or vice versa) within a module string. [25], [56]. This leakage current drives cations (sodium) from the glass into the solar cell, TCO, or anti-reflective coatings [9]. It is to be noted that the presence of

acetic acid (formed due to the degradation of the encapsulant) enhances the transport of cations [25]. The PID effect can lead to significant power losses, efficiency reduction, and voltage and current mismatch. PID is primarily influenced by high humidity, elevated temperatures, and the presence of ionic contaminants on the surfaces of the solar cells and the module's encapsulation materials. Factors such as system design, installation practices, and the choice of materials can also influence the susceptibility of a PV system to PID [9], [25], [56].

- **Hotspots :** Hotspots in PV modules refer to localized areas of increased temperature within the solar panel. These hotspots can occur due to several reasons, including shading, manufacturing defects, glass damage, or electrical faults. When a portion of a solar cell or a group of cells is shaded, either partially or completely, it can create a situation where the shaded area behaves as a resistive load. As a result, the shaded cells can become reverse-biased, leading to a localized increase in temperature. This temperature rise can be significant and may cause damage to the affected cells, resulting in reduced power output and potential long-term performance degradation. Hotspots can lead to accelerated degradation, reduced energy production, and, in severe cases, module failure. The increased temperature can cause irreversible damage to the affected cells and materials, leading to decreased efficiency and potential safety hazards. Manufacturing defects, such as microcracks in cells or faulty electrical connections, can create resistance or impedance within the module and lead to hotspots.[103]–[105].

Appendix C illustrates a detailed figure from literature [9] that shows a relation between stressor, component, failure and effect.

Table 5.1: Components of a PV module and associated degradations

Component	Degradation
Glass	Corrosion Breakage
Encapsulant	Yellowing Delamination
Cells	Fracture Hotspots Corrosion
Interconnects	Disconnection Hotspots Corrosion
Junction Box	Arcs Integrity compromise Delamination
Backsheet	Cracking Yellowing Delamination

5.3. The second life

Extending product lifetime and value beyond its original intended purpose or initial use phase can be one of the ways to tackle waste management and pollution and to reduce the rate of depletion of natural resources [106]. Utilizing the policy examined in Chapter 2 and the economic boundaries established in Chapter 4, a roadmap will be presented with possible explanations that would enable the second-hand market for solar panels.

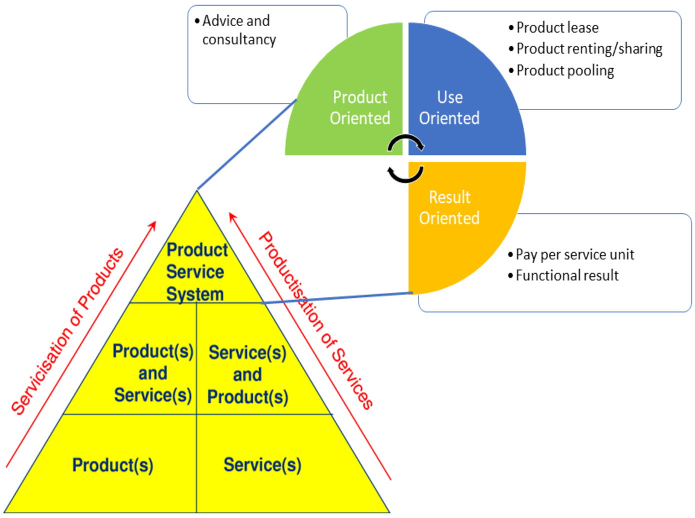


Figure 5.2: Evolution of Product Service System (PSS) and the different types of PSS adapted from[107]–[110]

5.3.1. The product service system

A Product-Service System (PSS) is a form of servitization that expands the conventional role of a product by integrating additional services. It represents a market offering where the focus is on providing the "use" of a product rather than its outright sale. Instead of purchasing the product, customers pay for its usage, which allows for a redistribution of risks, responsibilities, and costs traditionally associated with ownership. This approach benefits both the customer and the supplier/manufacturer. Customers gain access to a comprehensive solution that goes beyond a standalone product, while the supplier/manufacturer enhances their competitiveness by offering differentiated solutions while maintaining ownership of the assets, which improves utilization, reliability, design, and protection [107]. Figure 5.2 depicts the evolution of the PSS concept. Traditionally, products and services were viewed as separate market entities. However, in the ever-competitive market in order to gain an edge the two started intertwining, i.e. products were offered as services (servitization) and services were offered as products (productization). PSS is a result of the convergence of the aforementioned two market strategies. Throughout the literature, there have been different labels and subdivisions describing PSS forms. However, [107]–[110] have been able to classify these into three types as depicted in the top right of Figure 5.2.

1. **Product oriented PSS** involves selling a product in the traditional manner but also providing additional services such as after-sales support, maintenance, repair, re-use, recycling, and helping customers optimize the application of a product by training and consulting. The motivation behind adopting a PSS is to reduce costs, ensure product durability, and consider end-of-life aspects by incorporating reusable, replaceable, and recyclable components.
2. **Use oriented PSS** involves selling the use of a product instead of ownership, such as leasing or sharing. This approach aims to maximize product utilization, meet demand efficiently, and extend the product's and its materials' lifespan, driving sustainability.
3. **Result oriented PSS** entails selling desired results or capabilities instead of physical products. Companies provide a tailored combination of services where the producer retains product ownership, and customers only pay for the attainment of predetermined outcomes. This approach emphasizes value delivery over product ownership. An example of this service could be laundromats and web services.

A model based on product-oriented PSS for PV systems will be presented along with a process flow chart of the PSS provider in the next section. Further, a use oriented PSS is also proposed in Subsection 5.3.4.

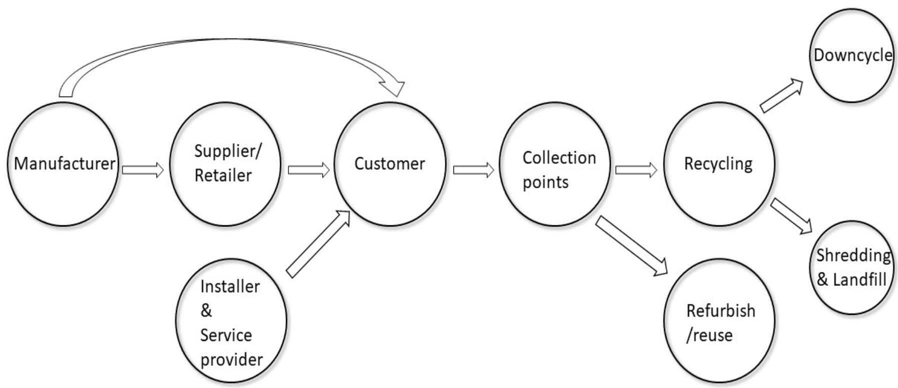


Figure 5.3: Pictorial representation of existing PV ecosystem

5.3.2. PSS for PV systems

To enable the second life of PV modules, strategic positioning of systems is essential. Figure 5.3 illustrates the existing sequential journey of a PV module, spanning from its initial manufacturing stage to eventual recycling. This representation showcases the existing chain that PV modules undergo, highlighting the importance of considering the entire lifecycle to promote sustainability and maximize the lifespan of these modules. Once a PV module is manufactured it is directly supplied to the customer from the manufacturer or through a supplier/retailer. There are several parties involved in the installation, maintenance, and consultancy throughout the lifetime of the module. After the end of its first life, the module is collected locally at what are known as collection points for electrical waste. There exists a central hub that receives waste from all these collection points and segregates them. Depending on the state of the module they are either reused or recycled. Since no data management system is in place on a large scale the condition of individual panels is relatively unknown and even the reusable panels are discarded with the larger lot. Recycling nowadays mainly involves shredding the PV panel after the removal of the aluminum frame and glass and then dumping the shredded panel into a landfill. Consider an example of the Netherlands where it would typically cost €1 to dump the panel as a landfill (including the gate fee and landfill tax) and between €15-30 to recycle the module [81], [83]. Post recycling only €6.6 to €21 worth of material is currently being salvaged [70]. This shows the disparity in investment and outcome for recycling with the current processes in place. Among the enabling processes for second-life applications, such as recycling, reuse, and refurbishment, recycling can be regarded as a well-established process with extensive studies and established systems in place. However, it is to be noted that the reuse and refurbishment prolong the lifetime of the panel with less energy and capital going into the processes to place the panel back into the market as compared to recycling and recovery. CIRCUSOL estimates that about 45% to 65% of panels that have been discarded by premature failure (accounting for about 80% of the PV waste stream in the next 10-15 years) can be refurbished [69].

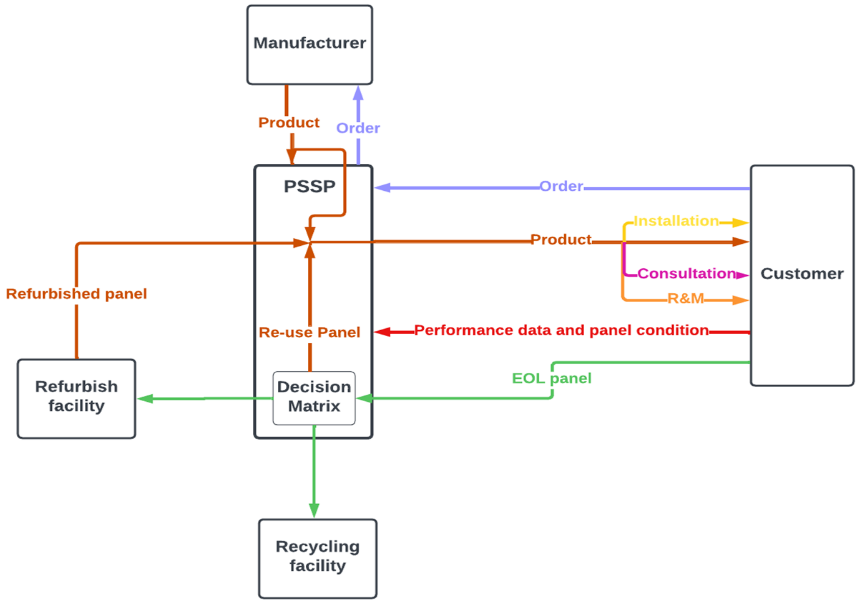


Figure 5.4: The PSS environment for PV systems and functions of Product Service System Provider

Figure 5.4 represents a PSS for PV systems. The product service system provider (PSSP) is a single-point contact through whom all PV system-related processes are routed. The activities the PSSP would be entrusted with are as listed below

1. Procuring new panels from the manufacturer based on market demand and forecast
2. Supplying products as well as allied services to the customer such as installation, Repair & Maintenance (R&M), and consultation on optimal utilization of the PV system.
3. Gather performance data and panel conditions at regular intervals.
4. Collect EOL panels from customer
5. Examine the condition of the EOL panel and route them

    - to a new customer in case of re-use or
    - to the refurbishment facility in case the panel cannot be used in its current condition to meet the market demand or
    - to the recycling facility beyond a certain level of damage/degradation.

The positioning and operational area allocated to the PSSP can be based on a minimum installed capacity per geographical area. This ensures that all the PSSPs have a level playing field and no disparity in terms of opportunities. PSSP is a network of existing dealers/retailers, consultants, R&M, transporters, refurbishing and recycling facilities, and certification institutes. Figure 5.5 is a geographical representation of the municipalities in South Holland. Table 5.2 illustrates an example of the proposed PSSP structure based on geographical area considering a few municipalities in the Netherlands. The allocation of the PSSP in this case was made based on the land area (in m^2), population density, and industrial sectors of each of the municipalities. On the one hand municipalities such as Delft, Risjwik and Zoetermeer are relatively smaller in size and have a lower number of industries as compared to the other municipalities considered hence one PSSP has been allocated. On the other hand, Rotterdam, and Den Haag are one of the most densely populated commercial and industrial hubs in The Netherlands and therefore each of these areas has been allocated two PSSPs. The allocation of the refurbishing and recycling facility is just a ballpark estimate to give a complete idea of the PSSP structure. However, positioning of these facilities would involve various factors such as volumes of PV waste coming out year-on-year (required to ensure the economic viability of the processes), optimal collection and transport, and availability of resources such as land, existing facilities, etc., An example to determine the optimal positioning of collection facilities is provided by H. Yu and X. Tong [111] for Zhejiang province in China.

Figure 5.5: Municipalities in South Holland

Table 5.2: An example of the proposed PSSP structure based on geographical area considering a few municipalities in South Holland

Municipalities	Handler	Refurbishing Facility	Recycling Facility	Governing Body
Delft	PSSP-1	Facility-1	Recycling facility-1	Government appointed central body
Rijswijk				
Zoetermeer				
Rotterdam	PSSP-2	Facility-2		
	PSSP-3			
Den Haag	PSSP-4	Facility-4	Recycling facility-2	
	PSSP-5			

In order to better understand the functions of the PSSP and the decision flow chart as depicted in Figure 5.7 consider a residential customer in need of a PV system. The customer places an order with the local PSSP, who provides the consultation with regard to the capacity of the system required depending on the location and consumption of the residence. After determining the capacity the PSSP allocates a dealer within its network along with installers and transporters to commission the PV system. A rooster can be followed to ensure that all members of the network are given an equal opportunity depending on their handling capabilities and workforce. Post-installation the customer is supported with frequent R&M checks and consultation with regards to the health of the system and its optimal utilization. These checks also ensure that regularly updated data is available with the PSSP with regard to the panel conditions and BoP and can help in scheduling preventive maintenance to ensure the optimal utilization of the system for its intended lifetime. Now there are the following possible scenarios where the PV module will be decommissioned

- **Scenario 1:** Upon the completion of its intended lifetime or
- **Scenario 2:** replaced by a system with higher efficiency or
- **Scenario 3:** decommissioned due to economic viability or
- **Scenario 4:** replaced after being damaged beyond repair on site

In the case of **scenario 1** the PSSP transports the module to the collection point and the panel flows through the decision matrix as described above. Depending on the condition of the panel and the market demand the panel is directed for reuse, refurbishment, or recycling. For **scenario 2** where the owner of the system replaces the modules even if they are in good working condition and before their EoL to make way for the latest technology modules with higher efficiency. In such a scenario the regular data collection regarding the condition of the panel as described in Figure 5.4 comes into play. The PSSP who is aware of the condition of the panel and the market demand can immediately make a decision to direct these modules accordingly and brand them as modules ready for reuse instead of transporting them to the collection point. This is an efficient use of resources and labor and avoids any damages that might arise during the transportation and collection of these modules.
In **scenario 3** (generally commercial) where the PV system is decommissioned due to economic viability, which means the PV system is taken out of service because it is no longer financially viable. This may be due to the change in local policies and legislation that might promote other energy generators leading to lower electricity prices. In such a case these modules can be utilized in residential or public spaces where these PV systems are still economically viable. The process for the PSSP is similar to that of scenario 2, with the only difference being the volume of modules being handled and the endpoints might be multiple locations. Finally **scenario 4** represents the modules that are damaged beyond repair at the site and will be subjected to the same process as scenario 1 where they will be directed to the relevant endpoints (reuse, refurbish and recycle) based on the decision matrix as depicted in 5.7.
The decision matrix depicted in Figure 5.4 is a process flow chart that guides the PSSP in determining the next destination of the end-of-life (EoL) panels. The process flow chart is illustrated in Figure 5.7 and starts with transporting the EoL panels to the collection point where they are cleaned and flash tested. Flash testing generally involves subjecting the PV module to a brief and intense light pulse, typically from a xenon flash lamp. This test helps to determine the module's current-voltage (I-V) curve, which provides important information about its electrical performance. During this stage, the electrical performance of all the modules is recorded against their serial numbers for later use. After the flash test, the module undergoes a visual inspection where it is checked for defects as enumerated in Figure 5.7. If the cell interconnects are corroded or the encapsulant is discolored beyond a certain degree the panels are directed to be recycled as these damages cannot be repaired without removing the encapsulant. And if any of the other three damages considered i.e. back sheet damage, damaged glass, and JB are detected the modules are subjected to non-destructive tests (NDT) to detect any further defects that cannot be identified using the naked eye. If none of these defects are detected during the visual inspection the performance of the module (from the flash test) is compared to the market demand. If the performance of the module is higher than the lowest market demand (LMD) in the PSSP respective market then the module is stored and supplied back to the market for reuse. If there is no demand for the module in the PSSPs market then other markets within the network are considered. If there is no demand even in the network the module is sent to recycled.

The modules that are routed to undergo NDTs will be subjected to Electroluminescence and Infrared imaging. Electroluminescence (EL) and infrared (IR) imaging are commonly used techniques for inspecting solar panels. EL imaging involves applying a voltage to the solar panel and capturing the resulting luminescent image. It helps identify microcracks, hotspots, and other defects that may not be visible to the naked eye. IR imaging, on the other hand, captures the thermal signature of the panel using infrared cameras. It can detect anomalies such as faulty cells, bypass diode failures, or uneven heating [112], [113]. These damages in the module cause regions of elevated temperature and appear as red spots in the IR or EL imaging [112]. A few examples of the images and the associated fault in a module are depicted in Figure 5.6. Combining the IR imaging and the JV curve would help determine the damage prevalent in the module. J.A. Tsanakas et al. [112] illustrates a table that shows the relation between IR image patterns and JV curves and the corresponding damage that causes these patterns. Appendix C contains a copy of this table.
If there is any damage (as illustrated in Figure 5.7) that is detected by the NDT the panel can only be repaired by removing the encapsulant or replacing the cells and it becomes viable to recycle than to refurbish the panel at this stage. The rectification of defects such as back sheet damage, glass damage, and JB defective can be done with relative ease and does not involve high costs. If post-refurbishment the power of the panel is either greater than the LMD or demand for the refurbished panel exists in other markets the repairable defects are rectified. The panel is tested again (JV Curve) and certified and introduced to the market. If the panel's rated power is greater than the LMD, it is introduced to the market operated by the PSSP or shipped to a market where the demand exists. If the above two conditions aren't met the panel is sent to a recycling facility. It is to be noted that damages in the diode in the JB can also be detected using IR imaging and these diodes can easily be replaced.

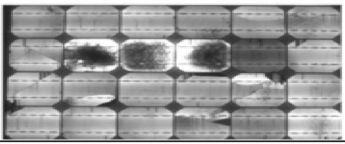
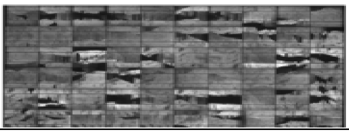
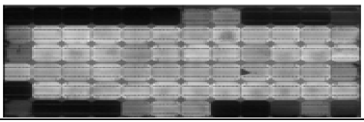
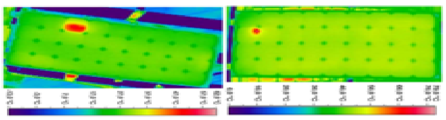
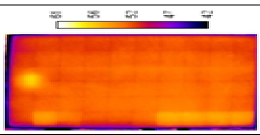
EL/IR image	Description
	EL of a mono-crystalline PV module with various defects
	EL image of a polycrystalline PV module with cracked cells
	EL image of a monocrystalline PV module with potential induced degradation
	IR image of a PV module due to broken interconnection ribbons (left) and defective soldering/busbar (right)
	IR image of a PV module with PID

Figure 5.6: EL and IR images of PV module and corresponding defects. Images collated from [112], [113]

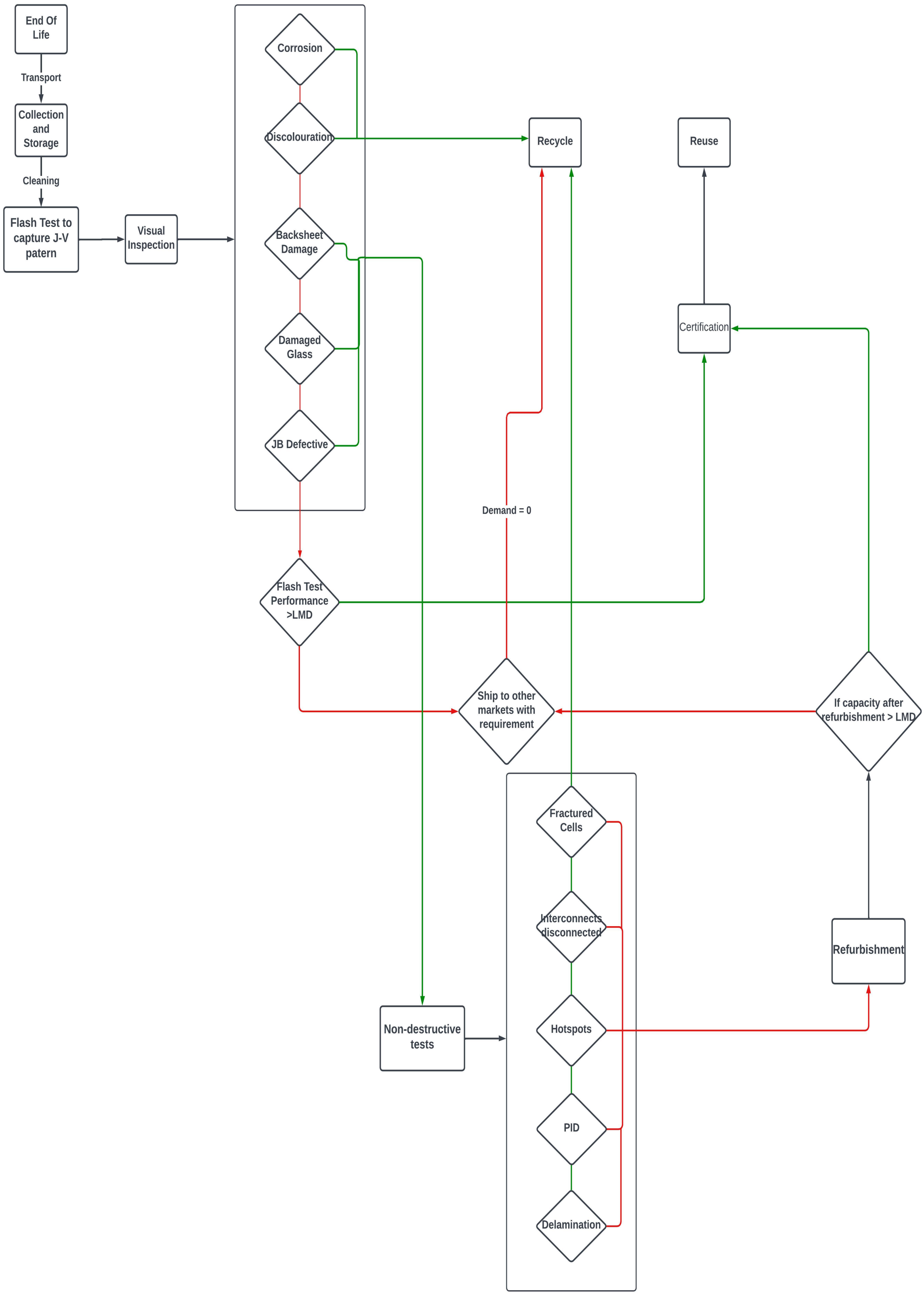


Figure 5.7: Decision flow chart for PSSP. The green lines represent ”yes” and the red lines represent ”no”

5.3.3. Integration of PSS into existing market

The PSS proposed in the previous section might radically change the existing market structure. A radical change although desirable might destabilize the market or die out due to inadequate support systems in the existing market. It is therefore proposed to phase the PSS implementation of the PV ecosystem by leveraging the existing energy market infrastructure. The Distribution System Operator (DSO) plays a vital role as a potential PSSP. There are about 7 DSOs in the Netherlands [Liander, Enexis B.V., Stedin B.V., Cogas Infra & Beheer B.V., N.V. RENDO, Coteq netbeheer, Westland Infra and Endinet] in The Netherlands[114]. The hierarchy of the TSO, and DSO system is as depicted in Figure 5.8.

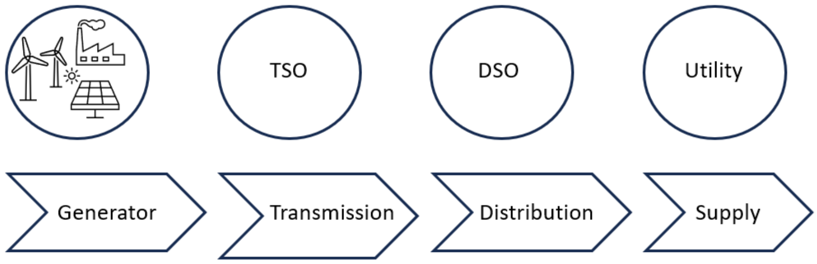


Figure 5.8: A typical TSO-DSO hierarchy

Integration Strategy 1: (based on the size of PV system) The TSO-DSO represents a well-established network of energy service provider systems within the Netherlands. The DSO has the energy profiles of its customers which include both residential and commercial PV systems. As a starting point, the DSO can assume the role of a PSSP and the customers can be limited to residential and small-scale PV systems such as solar-powered charging stations and PV systems for public utilities such as lighting. These sectors are small-scale systems and are a good sample space to pilot the PSSP system. The PSSP system can be rolled out area-wise as well rather than a country-wise implementation of stage 1. A few municipalities can be selected for rolling out stage 1. This could prove effective to identify any shortcomings in the existing proposal of PSSP operations. These shortcomings can be then rectified and the modified PSSP system can be implemented in the rest of the municipalities. A similar strategy can be implemented while deploying PSSPs across larger-scale PV systems as well. Figure 5.9 represents the proposed 3-stage integration of PSSP into the market. Stage-2 represents housing communities, small-scale industries, government buildings, multi-tenant (commercial) buildings, schools, and other educational institutes, etc., these above-mentioned facilities make use of medium-scale PV systems. The final PV market considered for integration is large-scale commercial PV systems such as ports, industries, industrial hubs, business parks, large-scale PV parks, etc.

Integration Strategy 2: (based on geographical area) In this strategy instead of considering the size of the PV systems as a criterion to roll out PSSP a geographical area is considered, in this context, it refers to a municipality. According to this strategy it is proposed to consider one or two municipalities for rolling out the PSSP system. And in these municipalities, PV systems of all sizes as mentioned in Figure 5.9 are considered. For example consider the municipality of Rotterdam and Amsterdam, in these municipalities all the industries, public infrastructure, ports, residential systems, solar parks etc, are considered for rolling out stage 1. In this approach, the shortcomings of the PSSP for all PV system sizes can be ascertained and further rolling out of the PSSP systems can be modified accordingly.

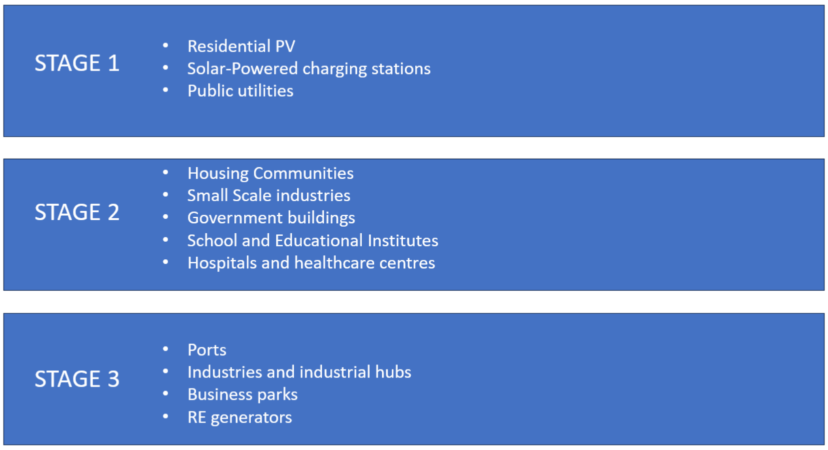


Figure 5.9: Integration Strategy -1 for PSSP into the existing market. The integration is considered based on the size of the PV systems installed

5.3.4. PV subscription - a second-hand market stimulant

Implementing a PSS structure for PV systems facilitates the second-hand market for PV systems and also enables the maximum utilization of a resource. However, these are not the only benefits that can be derived from the PSSP-PV ecosystem. The PSSP-PV ecosystem provides a whole new dimension to the way PV systems are owned and utilized. One of these types of PV system ownership is the subscription model, where the consumer pays a monthly/yearly fee to the PSSP for the supply of PV systems. The subscription model may only be viable for residential and small-scale industries where capital is generally the hurdle. Advantages of the subscription model:

- No large upfront capital is required.
- A good model for ex-pats who cannot have a long-term commitment (25-30 years).
- Increases the reach of PV systems and hence increase in cumulative installed capacity and increase in the share of renewably generated electricity.
- Can utilize second-hand, refurbished modules.

The subscription model stimulates the demand for secondhand PV modules, aiding in making the concept of reuse and refurbishment of EoL panels economically viable. Finally, the subscription model reduces the reliance on large upfront capital requirements and facilitates the ”PV for all” concept.

5.4. Testing and certification

As of today, no set of rules or guidelines exists that address the testing and certification aspects of a second life module. Establishing a system for the same will increase customer trust and confidence in second-hand modules. This could provide a huge thrust to the second-life market of PV modules. In this section, a few testing standards and certifications will be proposed that are seen to be the most relevant to these refurbished modules.

- **IEC 61215 :** These are international standards that outline the requirements for the design qualification and type approval of terrestrial PV modules. Adhering to these standards can ensure that the second-life modules meet the necessary performance, safety, and reliability criteria [115], [116]
- **IEC 61730 :** This standard provides guidelines for the testing of PV module materials, including back sheet materials. It covers aspects such as mechanical properties, weathering resistance, electrical insulation, and adhesion, which are important for assessing the condition and durability of second-life modules [115], [116]
- **IEC 61853 :** The IEC 61853 PV module energy rating standard requires measuring module power (and hence efficiency) over a matrix of irradiance and temperature conditions. These matrix points represent nearly the full range of operating conditions encountered in the field [117].

The above-mentioned are a few examples of international standards, the manufacturer/supplier of these second-life panels can also provide the following certificates to enhance the trust and confidence in the market:

- **Refurbishment certificate**: This certificate confirms that the PV module has undergone a thorough refurbishment process, including inspection, testing, and potential repairs. It assures customers that the module has been assessed and restored to a functional and reliable state.
- **Performance certificate**: This certificate provides information on the performance characteristics of the second-life PV module. It includes details such as the power output, current-voltage characteristics, and efficiency measurements, giving customers confidence in the module's ability to generate electricity effectively.
- **Safety certificate**: This certificate verifies that the second-life PV module meets the necessary safety standards and requirements. It ensures that the module has been inspected for potential electrical hazards, insulation integrity, and compliance with safety regulations.
- **Traceability documentation**: This document includes information about the module's history, such as its original manufacturer, production date, and any previous installations. It helps establish the authenticity and origin of the module, providing transparency to customers.

In order to improve the visibility of these certificates and standards provided by the manufacturer/supplier (apart from the international standards) the organization responsible as depicted in table 5.2 can come up with standard symbols and these can be displayed on the module packaging.

6

Conclusion and Recommendations

This chapter presents the conclusions, recommendations, and suggestions for future research, aiming to provide a concise and informative summary of the findings and valuable insights for future endeavors. Firstly, the conclusions are provided by linking the key findings to each of the four sub-objectives. Next, a set of recommendations is presented based on the insights obtained throughout the thesis. Lastly, several potential directions for further research are enumerated, expanding the possibilities for future investigations.

6.1. Conclusion

The objective of this thesis as stated in section 1.4 is:

"Roadmap for Second Life of First Generation PV Modules based on Reuse and Refurbish"

The four sub-objectives helped in understanding an important aspect that lead to the realization of the main objective. A chapter is dedicated to each of the sub-objectives to realize its goal.

Sub-objective 1: Outline the existing policies and processes

Chapter 2 outlines the existing overarching policies for waste management in the EU such as the WEEE in section 2.1 and EU waste framework in 2.2. Finally, a country-specific implementation of these policies was studied in the Spanish Royal Decree in section 2.4. The overarching policies follow the polluters pay principle, by making the manufacturers and suppliers responsible for establishing (financially and physically) EoL management networks for PV systems. The WEEE sets out targets for the collection of PV waste at 65% of the average weight of the EEE placed in the market in the three preceding years in the member states or alternatively 85% of the waste generated. About 80% of this collected PV waste is to be prepared for reuse and recycling and of this waste 85% is to be recovered. In today's mainstream recycling, the 85% target is mainly achieved by recycling aluminum frames into raw metal feedstock and breaking down the glass into cullets with impurities, and finally shredding the remainder of the components of the PV module encompassed within the encapsulant such as the cells, cells interconnect and use them as filler material in concrete or subbase for roads. Further, a decommissioned panel irrespective of its condition enters the waste stream and is recycled as mentioned above. The Spanish Royal decree that translates the WEEE into a Spanish law categorizes first-generation and this film PV modules into a subcategory of their own and provides details for the collection, storage, and treatment of these modules including the records that need to be maintained. An insight into Spain's WEEE performance shows that Spain still has a long way to go in terms of achieving its WEEE targets for recovery and preparation for reuse and recycling. On the one hand, the waste directive promotes the idea of creating a resource reserve in the EU achieved by qualitative recycling, and on the other hand, WEEE promotes quantitative recycling focused solely on the weight and not the value of the components where the most valuable and exported materials such as silicon are being shredded and used as landfill. In conclusion, despite PV systems being one of the most rapidly growing renewable energy generators their EoL management strategies and systems are still in their nascent stage.

Sub-objective 2: Determine the amount of PV waste expected in the next 30 years
After studying the policies and processes surrounding EoL PV modules chapter 3 established the amount (weight and value) of materials contained in the PV module. The quantity of each of the materials is studied by considering the cumulative installation trends for three time periods 2014, 2020, and 2030. In 2030 a cumulative installed capacity of 5.2 TWp was assumed as this represents the cumulative global capacity required to meet the 1.5°C Paris climate goal according to IRENA. Assuming a lifetime of 30 years for the PV modules gives a good estimate of the amount of PV waste to be expected in the next decade or so. Silver and silicon constitute 52% of the total module value and in 2030 the value of these metals is €58.30 billion and €85.91 billion. And if the current system of classifying decommissioned PV modules directly as waste irrespective of their condition and recycling them only for glass and aluminum continues it would be equivalent to wasting the resources without realizing its complete worth and also dumping billions of euros into landfill. Glass and aluminum make up close to 85% of the weight of a PV module and are only 35% of the total value of the components in a module. And most of the recycling today is downcycling so not even the 35% is completely recovered. Recycling although the most well-researched EoL management strategy is not able to provide a pathway to an effective waste management strategy in the PV ecosystem. In conclusion, closing the loop alone for PV systems is not a solution for the optimal use of PV modules and their EoL management. The answer to optimal use of resources might lie in the second life of PV modules via the processes such as reuse and refurbishment.

Sub-objective 3: Economic boundary conditions for reuse and refurbishment
Chapter 4 focused on setting up economic boundary conditions for the viability of the second life of PV modules. LCOE is one of the key determinants in the rapid deployment of PV systems. Utilizing the same concept as a means of comparison between first and second-life panels an economic boundary was set up in terms of the cost of second-hand modules in €with the expected average second lifetime in years. While considering the deployment of a secondhand module in a scenario where the entire cost of the balance of plant and soft costs are involved, a minimum second lifetime of over 23 years ensures a cash inflow for the manufacturers/suppliers and a second lifetime of 27 years prices the second-hand module at 57% cost of a new module. These lifetimes might be a bit difficult to achieve with modules that have already completed their first intended lifetime but this would be an ideal scenario for modules that have been decommissioned due to economic viability and for modules that have been replaced by modules of higher efficiencies. In the latter two cases, the modules might not require capital-intensive refurbishment processes and some of the panels might be ready for reuse right away. In the modules that are ready for reuse right away the only costs associated with the modules would be the transportation and preparing for reuse such as cleaning. The second scenario is considered where only the cost associated with the PV module comes into play along with the cost of labor for installation. This represents a more optimistic scenario for the reuse and refurbishment of PV modules as there is no minimum second-lifetime expectancy to ensure a positive cash flow. Therefore, in this scenario, even PV modules that have completed their initial intended lifetime can be supplied to the market. In conclusion, it is possible for PV modules of any condition (provided they can still be refurbished and meet the criteria as discussed in figure 5.7) and age can be utilized in the PV market with careful consideration of their second-hand use.

Sub-objective 4: Market structure to facilitate second life
As seen in the previous sub-objective PV modules irrespective of their age can be utilized if they are in good condition. Chapter 5 recommends a market structure to facilitate the second-hand modules and figure 5.7 provides the basis for determining the ”good condition” of panels fit for second-hand market use. The product service system provider needs to be integrated with phases into the existing market utilizing either integration strategy 1 or 2. The PSSP is meant to be a tool to leverage the existing systems and gradually shape the market to better facilitate the second-hand market. A PSSP at any given point in time has all the data pertaining to modules in their locality across the entire supply chain, unlike the existing market structure where information is compartmentalized. Access to data across the entire lifetime of a PV module can allow for better decision-making for the stakeholders

involved. This data allows the PSSP to determine the correct scenario for a particular PV module to be deployed. Delaying the recycling process ensures more income from an asset to the manufacturers and suppliers. Consider an example of today's market, where it takes €15 per module to be recycled and there are two modules, so there is a cash outflow of -€30 in total for the manufacturer. And if the recovered materials from this recycling are worth €6.6 per panel then the total cash flow will be reduced to -€16.8. Now consider the PSS environment where the condition of the module is ascertained before it can be recycled and one of these above-mentioned modules can be reused the cash outflow for the manufacturer and supplier reduces to -€15 and on top of this assume the module is sold back into the market at a price of €110 so the net cash flow for the manufacturer now becomes + €101.6 including the recovered materials from one recycled panel. In conclusion, an appropriate market structure and integration can facilitate the second life of PV modules.

6.2. Recommendations

This thesis is a gateway into the realm of the second life of PV systems. There are still improvements and areas within the research domain that need to be explored. In this section, a few important recommendations will be provided that will help the second life of PV modules realize their complete potential.
Policy recommendation: As seen in chapter 2 the overarching policy is rather quantity based meaning the importance of recycling and recovery is placed on the weight rather than the value of the materials in the module. Following the concepts of waste hierarchy and recycling to create a material resource, a policy needs to be devised where reuse and refurbishment are mandated before recycling. And recycling needs to be quality-based, i.e., emphasis must be placed on recovering silicon, silver, and other metals. The extent of recovery can be phased following the current example of WEEE recovery and recycling targets.

Way forward:

1. As already stated in chapter 5, the positioning of refurbishing and recycling systems needs to be modeled. Geography-specific models need to be developed in order to optimize the capacity and placement of these centers across areas and time.
2. EoL management processes are an employment and revenue-generating arena. An analysis of the jobs created and value added at the regional level using appropriate value analysis frameworks. An example of such a framework is the Wertschöpfung und Beschäftigung durch Erneuerbare Energien developed by IOW which is used to analyze the generation of economic value and job opportunities through the utilization of renewable energy sources.
3. Modelling for the positioning and allotment of PSSP using optimization models. The basis for allotment in this study was assumed to be the installed capacity per m^2 and that needs to be validated. The possibilities for other criteria for allotment and positioning of PSSP need to be explored.
4. LCA for second life modules and how it compares against the LCA for the existing system. This could also help understand the environmental impacts of creating a second life for PV modules.
5. Stakeholder analysis for the value chain of second life PV systems to identify any potential barriers for the deployment of the market structure proposed in chapter 5.
6. An analysis of how the subscription model can be an advocate for the second life of PV modules and market segmentation for this model and product.
7. The effectiveness of the integration strategies suggested in section 5.3.3. The shortcomings and other alternate systems and strategies that could prove effective for facilitating the second-hand market.

The recommendations made in this section could help in providing the required market structure and devising policies. Both of which are essential to stimulate and establish a second life market for PV modules and make the PV sector a truly universal and sustainable sector.

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A
Appendix A

Table A.1: An overview of effect of temperature of PV performance [20]

Reference	Temperature Effect	Location	Type of cells
Rahman et al. [118]	For every 100 W/m^2 increase in radiation, solar cell temperature improved to 4.93 °C and 2.64 C respectively with and without cooling. For 1000 W/m^2 irradiation and 80 L/h water cooling system, solar cell temperature reduced to 22.4 °C, output power and efficiency improved by 8.04 W and 1.23% respectively.	UM, Malaysia.	Mono-crystalline
Touati et al. [37]	For monocrystalline PV, during the day (8:30 a.m. to 15:45 p.m.), the change in temperature (41.9, 48, 49.9 and 40.4 °C) increases PV efficiency (0.71, 0.76, 0.78 and 0.8). For amorphous PV, during the day (8:30 a.m. to 15:45 p.m.), the change in temperature (42.9, 48.4, 45.4 and 40.9 °C) increases PV efficiency (0.385, 0.383, 0.358 and 0.616).	Doha, Qatar.	Mono-crystalline and amorphous
Rahman et al. [119]	The electrical efficiency decreased by 0.22% for 1 °C increase in solar cell temperature. Similarly, the solar cell temperature and output power increased by 3.82 °C and 3.14 W, as the solar irradiation increased by 100 W/m^2. The incorporation of a water cooling system enhanced the performance by 15.72%.	UM, Malaysia.	Mono-crystalline
Gaglia et al. [120]	PV voltage dropped between 91 and 97 mV/ °C for 400 and 1000 W/m^2 irradiance levels which are higher than the laboratory standard conditions (73 mV/°C). The instantaneous efficiency reduced to 7% from 10% for a voltage drop of 5 V.	Athens, Greece.	Multi-crystalline
Elibol et al. [121]	An increase of 1 °C ambient air temperature increased the efficiency of amorphous crystalline panels by 0.029%, polycrystalline panels by 0.033% and decreased the productivity of monocrystalline panels by 0.084%.	DUBİT, Turkey.	Mono, poly,& amorphous crystalline

B

Appendix B

Table B.1: Price trend of Silver between 2014-2020 [74]

Year	€/kg
2014	461.82
2015	454.34
2016	494.85
2017	478.36
2018	429.09
2019	468.81
2020	573.42

Table B.2: Price trend of copper between 2014-2020 [75]

Year	€/kg
2014	5.16
2015	4.94
2016	4.37
2017	5.36
2018	5.54
2019	5.4
2020	5.41

Table B.3: Price trend of Aluminium between 2014-2020 [76]

Year	€/kg
2014	1.40
2015	1.49
2016	1.44
2017	1.71
2018	1.79
2019	1.61
2020	1.48

Table B.4: Price trend of poly silicon between 2014-2020 [77]

Year	€/kg
2014	15.41
2015	14.4
2016	13.5
2017	13.92
2018	11.05
2019	8.1
2020	6.09

C

Appendix C

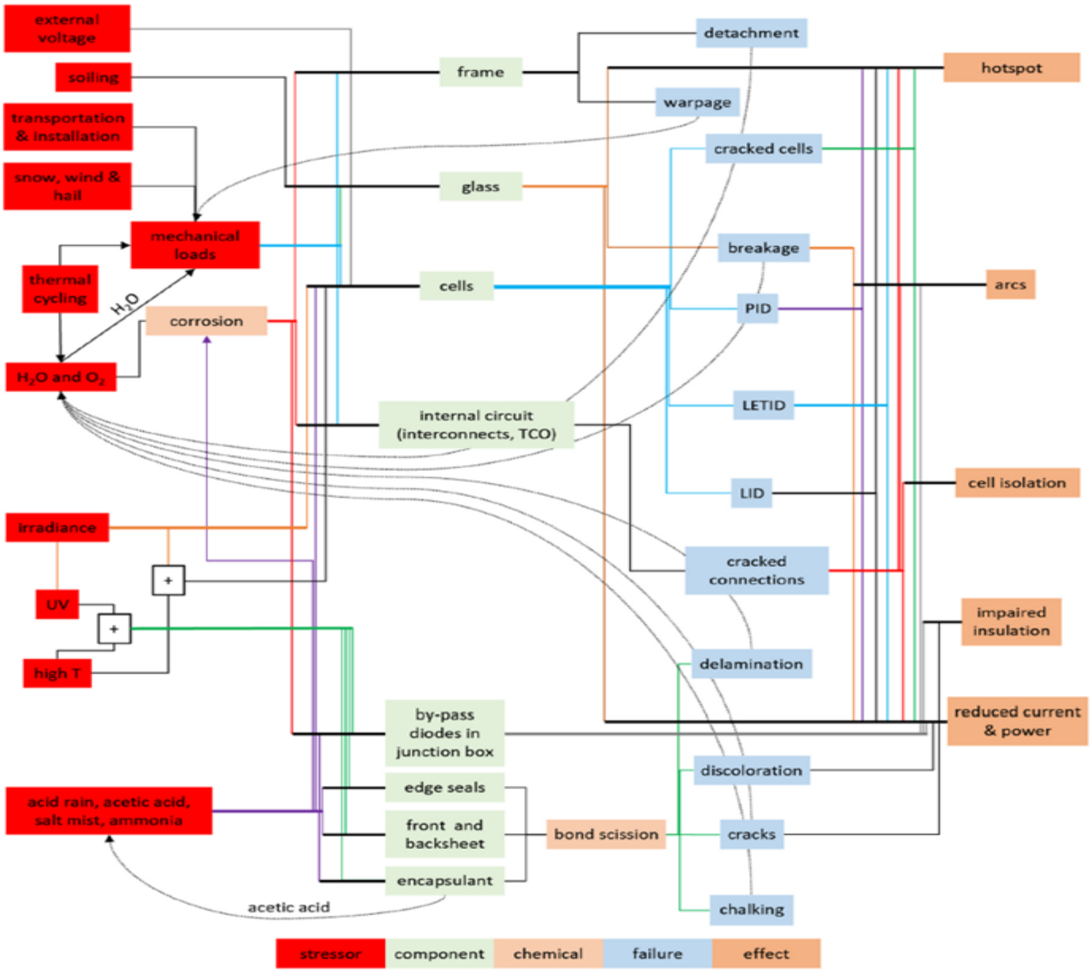

Figure C.1: Flow diagram representing the relation between stressors, component, failure and effect [9]

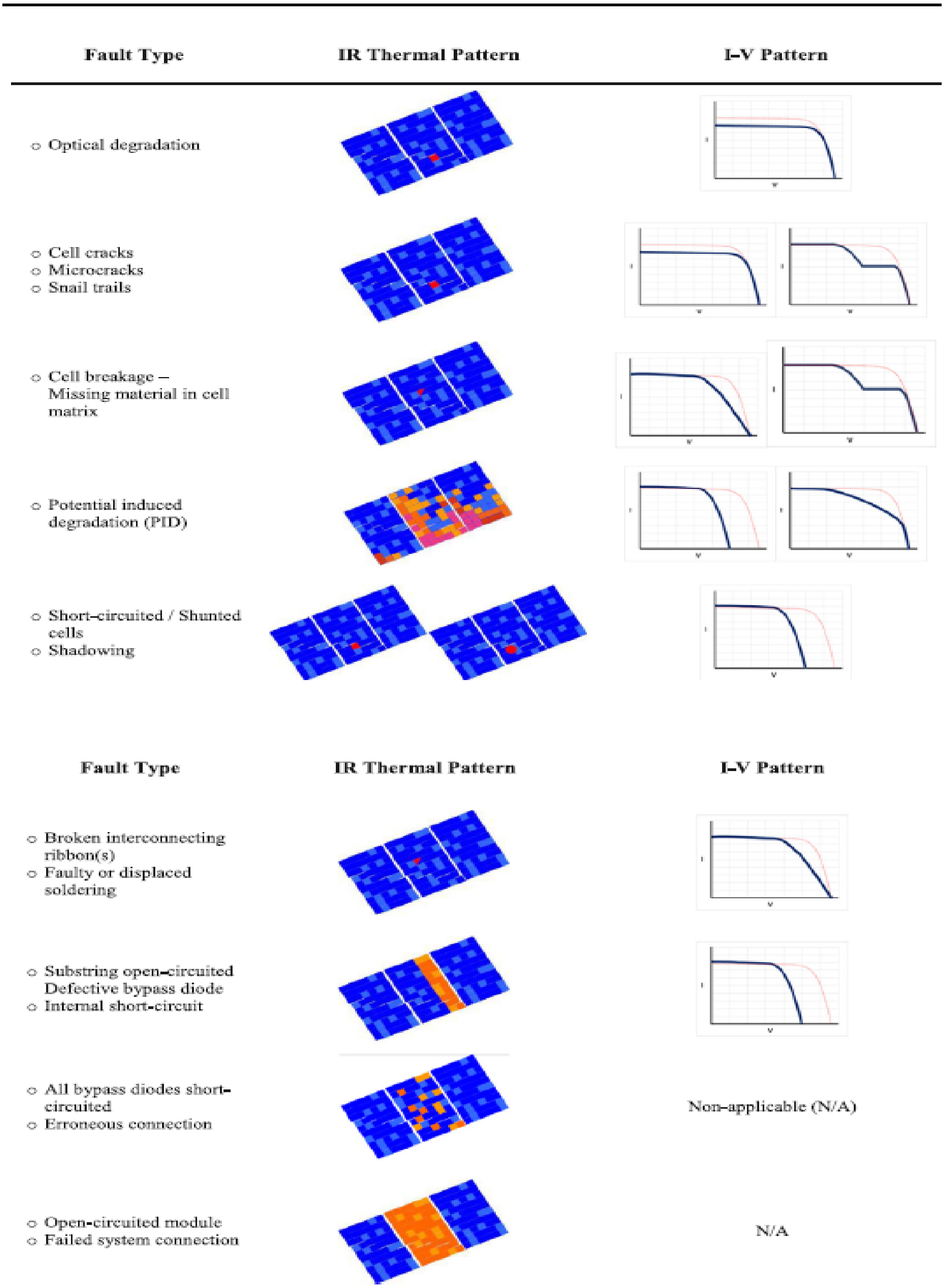

Figure C.2: Relation between IR imaging and JV curve for few module degradations