

# Developing an Open-Source Circular PV Module

## Abstract

This master thesis covers the development of an open-source circular PV module. Besides incorporating circularity and suitability for open-source in the design, the research aims to incorporate low Levelized Cost Of Energy (LCOE), high efficiency and high quality in the design. Using the morphological chart method, a tradeoff is made between design choices according to these research objectives. In addition, an extensive literature review was carried out to gain an overview of the current state of the PV industry, predicted future developments in the PV industry, and previous work on PV circularity and open source. The final design was tested in four sprints. In sprint 1, multiple edge-seal encapsulation designs were tested through a 1000 hour damp heat (DH) test. In sprint 2, a novel modular interconnection technique was tested, and found to be unfit for use in PV modules without redesign. In sprint 3, a 750 hour DH test was performed on a minimodule to test its ability to withstand moisture ingress; the encapsulation was found to be adequate, but the cell interconnection failed. Finally, in sprint 4, a 24-cell module was constructed, and Electro-Luminescence (EL) and Current-Voltage (I-V) characteristics measured. The final module design is a glass-glass module, with regular Front-Back Contact (FBC) interconnections, and a double-edge seal consisting of butyl rubber and silicone sealant. Although suitability for open-source and circularity were achieved, further research is needed to increase quality, reduce LCOE and increase efficiency; thus, directions have been presented to work towards these objectives.

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## Glossary

[Separate section: glossary, only add abbreviations you use a number of times]

# 1. Introduction

## 1.1 Background

On the one hand, we have ecological ecosystems which consist to a large extent of closed material loops. These loops are sustained by external energy sources and of these, mainly, if not entirely, solar energy. The technosphere on the other hand, is mainly characterized by linear material flows powered nearly entirely by fossil energy sources. To curb the most critical effects of climate change, a rapid transition away from carbon-intensive energy systems is needed; a transition towards material and energy efficiency.

To move towards a sustainable technosphere that mimics ecological ecosystems, closed-loop industrial systems powered ultimately by renewable energy are needed. Photovoltaics (PV) is one of the most important renewable energy sources available today, as it delivers solid-state, low cost, and efficient photon-electron conversion. PV energy generation is growing at a rapid rate worldwide. Global PV capacity additions are expected to reach over 142 GW in 2021, and renewables are expected to become the largest source of electricity generation worldwide in 2025 (IEA, 2020). However, there is still significant progress to be made on closing the material loop in the PV energy system.

The majority of PV modules being produced today are monocrystalline-silicon modules (Sica et al., 2018). These modules are generally produced as follows: PV cells are connected together with tabbing wires on the front and back to form strings, and an ethyl-vinyl acetate (EVA) lamination is used to encapsulate the cells and protect them from degradation due to moisture or oxidation (Sica et al., 2018). The laminated cells are sandwiched between a high-transmittance front glass and a tedlar back sheet. A junction box and an aluminium frame are then added (Sica et al., 2018). Although this is the most common production line process in place today, it should be noted that many variations exist.

Despite the above-mentioned production process of PV modules having been highly optimized over the previous decades, modules have yet to be designed with an end-of-life (EoL) system in mind. This often leaves recycling as the only circular EoL option, with most PV modules worldwide finding themselves landfilled (Farrell, et al., 2020). The total amount of solar module waste is estimated to reach around 78 million tonnes by 2050 (Chowdhury et al., 2020). During recycling, the lamination can be removed through a combination of thermal and chemical treatment (Muller et al., 2006). However, it is currently not possible to recover the silicon wafer nor the polysilicon (the raw material needed to produce PV cells) at a quality similar to a virgin silicon wafer or virgin polysilicon. Due to the high energy intensity of wafer production, recovering wafers at the module's EoL would reduce the energy payback time (EBPT) of PV modules by about half and subsequently greatly decrease the life-cycle environmental impacts of PV energy (Muller et al., 2006).

The majority of global polysilicon, wafer, cell, and module production occurs in China, with Chinese manufacturing having been a major driver in the steep price decrease and global growth of PV energy production (Huang et al., 2017). However, the use of Chinese-manufactured PV modules entails relatively high life-cycle environmental impacts. This is mainly due to the high carbon intensity of the Chinese electricity grid, causing excessive upstream carbon emissions, predominantly related to polysilicon production and wafering (Yue et al., 2014). Moreover, among various social and environmental factors related to polysilicon production for PV cells, journalists and academics increasingly report situations of forced labor of the Uyghur minority in the Chinese Xinjiang province (Sahu, 2015; European Parliament, 2020).

In order to reduce social costs, lower PV waste production, and close the material loop, a new PV module design is needed. Additionally, reducing dependency on carbon-intensive and exploitative PV module manufacturing will require the development of a distributed manufacturing system. As such, this research proposes a PV module that adheres to the principles of circular economy, allowing materials to be recovered at a high value, and one that is suited for distributed manufacturing according to the principles of technological sovereignty and open hardware.

## 1.2 Technological Sovereignty, Open-Source Hardware & Commons-Based Peer Production

Open-source technologies are technologies of which the relevant documentation and design is held in the commons and freely accessible (OSHWA, n.d.a). The commons are shared resources where each stakeholder has an equal interest (Kostakis et al., 2019). The production of open-source technology can thus also be called commons-based peer production (CBPP), referring to a new way of value creation and distribution that appears within the ecosystems of

commons-oriented communities. Here, open technological infrastructures allow individuals to communicate, self-organize and create non-rivalrous use value without the need to seek permissions. Commons-oriented technologies are developed through autonomous, participatory and asynchronous collaborative efforts and thus are not centrally controlled by specific owners and/or managers (Kostakis et al., 2019). From a political standpoint, CBPP and open-source hardware development render technological sovereignty: “the right and capacity by citizens and democratic institutions to make self-determined choices on technologies and innovation” (DiEM25, 2019). Technological sovereignty is a way of democratizing innovation and the process of technological development (DiEM25, 2019).

The open hardware movement is a global, loosely affiliated community of product developers who develop and share their work in an open-source way. This means the intellectual property is held in the commons, freely available for anyone to use, but still subject to the limitations of an open-source license. Such a licence can, for example, require the attribution of the original creator, or require sharing of derivatives under the same or a less restrictive license (Lin et al., 2006).

The open-source concept started in the software field, where developers began freely sharing their code over the internet so others could use and improve it (von Krogh & von Hippel, 2003). Later on, the idea began being applied to the production of hardware where large communities of individuals used open technological infrastructures to communicate, self-organize and create non-rivalrous use value (van Abel et al., 2011; Kostakis et al., 2013; Rifkin, 2014; Kostakis et al., 2018). Today, open-source hardware projects tend to apply a think-global, manufacture-local model, sharing designs freely online, and manufacturing using standard benchtop manufacturing technologies such as 3D-printers, laser cutters and other low-tech tools (Kostakis et al., 2018). Open-source hardware should thus be designed in a way for others to contribute, and so that the product of interest can be made or repaired by anyone who has the basic tools and components available (OSHOWA, n.d.b; Kostakis et al., 2018). Some sustainable technologies that have been developed under an open-source hardware license include: wind turbines, hydropower turbines, carbon capture technology and plastic recycling machines (Piggott, 2010; Openair, n.d.; Precious Plastic, n.d.).

Although some open-source hardware projects have been widely successful, so far open-source hardware projects have not been a game changer to most industries, unlike open-source software. Yet, open-source software can be seen as a proof-of-concept for the possibilities in open-source hardware. To have more impact, business models and value creation concepts related to open-source hardware still need to be fully understood, described and harnessed (Moritz et al., 2016). Some fields where open-source hardware has been game-changing for the industry have been microcomputing (e.g. Arduino, Raspberry Pi) and 3D printing (e.g. RepRap).

The benefits of open-source hardware are that technology developers can tap into a large network of contributors, harness a free flow of information, save costs in R&D and IP protection, innovate and develop faster, and benefit from a more efficient technological design process (Moritz et al., 2016; Buitenhuis & Pearce, 2012). Although there is no empirical evidence supporting the notion that open-source hardware developers apply design-embedded sustainability, it is likely that commons-oriented makers aim in many cases to design for sustainability (Kostakis et al., 2018; Kostakis et al., 2015; Kohtala, 2015). This is because open-source hardware design removes the incentive for planned-obsolescence, leads to resource efficiency, supports technological literacy, empowers technology users and leads to

higher-quality products (Moritz et al., 2016). Challenges related to open-source hardware development include: a lack of governance and coordination over the project management; legal risks; issues related to liability; unclear project outcomes; hard-to-incentivize communities; warranty and safety issues in case of product failure; success being dependent on the attractiveness and ‘cool factor’ of the project; and the limited interoperability between closed and open components (Moritz et al., 2016). People have been found to contribute to open hardware projects for multiple reasons, including wanting to create better or cheaper products, work or business interests, or simply to learn about hardware (Moritz et al., 2016).

### 1.3 Circular Economy & Design for Circularity

Over the last decades, the Circular Economy (CE) has been increasingly proposed as an alternative to the incumbent make-take-dispose mode of production and consumption. By now, a broad range of definitions have been coined to describe the CE (Kirchherr et al., 2017). In essence, however, the CE is an economy in which materials are circulated within society at the highest value possible, for as long as possible (Ellen MacArthur Foundation, 2013). This can be done through the 9Rs as presented by Potting et al. (2017) (see figure 1).

*Figure 1: The 9R framework. From Potting et al. (2017).*

Besides designing products with these so-called ‘re-options’ in mind for the EoL, it is important to reduce virgin material inputs during production, and this so by designing circular materials into the product (Haas et al., 2015). In addition, an important consideration is the economic feasibility of circularity. Practice often shows that a recyclable material is only actually recycled when that process is economically beneficial (Reck & Graedel, 2012). Therefore, the design of a circular product should take into account the context in which that product will be discarded, which actors will handle the product at its EoL, and whether it will be economically beneficial for that actor to handle the product in a circular way.

Another strategy that can be applied to reduce the environmental impact of resource extraction and fossil energy use, is to increase resource efficiency. Resource efficiency can be increased by both slowing and closing material loops. Slowing material loops refers to designing products for a long life and being able to extend the product life. This intensifies and extends the use phase, meaning resource flows are slowed down (Bocken et al., 2016). Closing material loops is achieved by recycling resources after the product life, which does not influence the speed of material flows through the economy, but prevents materials from being wasted into the environment and new materials from being extracted (Stahel, 1982). Thus, a circular product design refers to a design that is made for a long useful life, can be repaired, refurbished, or remanufactured, and can be recycled with minimal loss of material value at its EoL (Potting et al., 2017; Bocken et al., 2016; Hopewell et al., 2009; Kumar et al., 2011; Boulding, 1966).

Where to place the emphasis in the product’s design strategy depends on the “product category life cycle stage” it is in (Bakker et al., 2019). A product category life cycle refers to the time between the first introduction of a product category in a market (for example, solar panels), and the final purchase in that product category. The stages of a product category life cycle are the introduction, growth, maturity, and decline stages. For example, 3D printers are in the growth stage, washing machines are in the maturity stage, and VCRs are in the decline stage (Bakker et al., 2019). Looking at the year-over-year sales of PV modules, it becomes clear the product category is in the growth stage (IRENA, n.d.). According to Bakker et al., (2019), a product category in the growth stage should place emphasis on: design for product attachment and trust; design for standardization and compatibility; design for upgradability and adaptability; and design for dis- and re-assembly.

Design for product attachment and trust is a complex topic as it is highly dependent on human perception, which also tends to change over time. However, many designers have worked on strategies to create attachment and trust, including timeless design and products that interact with their user, creating a bond between the user and the product (Bakker et al., 2019).

Design for standardization and compatibility can be done by adapting to industry standards where possible. Setting standards is only possible with a high degree of control over the market, and many companies apply alternative standards as a means of exerting competition. Moreover, differences in standards can arise over time through technological lock-ins such as those seen in rail infrastructure or electrical power grids (Bakker et al., 2019). In the design of long-lasting products, it is important to ensure that the components needed to service the product will be available throughout the product's life cycle, which is why using standardized parts which are expected to remain prevalent over the product lifetime is key.

Design for upgradability and adaptability is difficult because technology evolves with great speed and it is very difficult to predict socio-technological developments as well as the landscape factors affecting those developments (Geels et al., 2017). However, based on research it is possible to foresee some developments in the near future such as the introduction of perovskites in the PV industry (Sofia et al., 2020).

Design for dis- and re-assembly to make sure every part of the product remains available and ready to be reused or recycled, each part must be developed as an independent product and has to be designed and tested as such (Bakker et al., 2019). The parts should be made of homogeneous, non-hazardous materials as far as possible and it should be relatively straightforward to separate them using common tools in limited time (Rossi et al., 2006). Although easily reversible connections are preferred, the use of glue, nails or rivets in the design is acceptable as long as it does not interfere with the disassembly and reassembly procedure (Bakker et al., 2019).

Besides these design considerations, general design for sustainability principles include: closing the material gap by ensuring the entire product is able to go from new to recycling to new; minimizing the energy required for manufacturing; usage and EoL treatment; and applying as much homogeneous material use as possible (Bakker et al., 2019). From a technological sovereignty standpoint, the combination of open-source hardware and circular product design is beneficial as it ensures the right to repair. This refers to buyers of a product having the right to repair the product or any aspect of it, and restricting manufacturers from using IP rights or fixed technical standards to prevent repairs (DiEM25).

## 1.4 Cost, Quality and Performance of PV

With these definitions and design criteria in mind, this research involves the design and development of an open-source and circular PV module. However, for such a module design to be relevant and applicable in the global PV market, it must adhere to a number of other standards, mainly falling in the categories of cost, quality and performance. The increasingly low cost of PV modules is the main driver of the global growth of PV energy production (VDMA, 2020). In the incumbent industry, low module prices have been achieved through large scale production, process optimization, and reducing costs of inputs. Currently, wafering and cell production form the largest part of PV module cost (Powell et al., 2015; VDMA, 2020). Simultaneously, a reliable and low cost energy source is guaranteed through the high quality standards PV manufacturers adhere to.

Generally, for new PV modules to enter the global market, rigorous accelerated lifetime testing is carried out according to standards such as IEC 61215 and IEC 61730 standards (IEC, 2016a; IEC, 2016b). Module manufacturers use such tests to ensure an operational lifetime of 20 to 30 years, as well as to reduce safety hazards related to the installation and operation of PV modules (Ancuta & Cepisca, 2011; Granata et al., 2014).

Finally, the technological development of PV is characterized by constant improvements in cell and module efficiency (NREL, 2021). The efficiency of PV modules is measured as the efficiency at which irradiance is converted into electrical energy. The difference between cell and module efficiency is denoted as cell-to-module (CTM) efficiency. For a new module design to be competitive in the global PV industry, its module efficiency should not be significantly lower than average.

## 1.5 Research Question

With these considerations in mind, the following research question is stated:

*RQ1: How can the PV module be redesigned to incorporate circularity, reduce the levelized cost of energy (LCOE), and allow for low-capital, local (re)manufacturing without giving up on efficiency and quality?*

To further narrow down the aims of this research, the research question can be dissected into the design requirements denoted in table 1. As cell technology is not a main focus of this research, and the cell type applied in the design is relatively interchangeable, the focus of the design effort is on reducing CTM losses. Within the scope of this research, module quality will be determined according to the module's ability to withstand two accelerated lifetime tests, namely damp heat (DH) and thermal cycling (TC) (Kurtz et al., 2009). Furthermore, the mechanical integrity of the module will be evaluated according to the mechanical integrity of its components. Circularity (more specifically the level of design for reuse, repair, refurbishment and recycling) will be determined by evaluating the module's durability, ease of dis- and re-assembly, ease of material separation, and the number of different materials used (Potting et al., 2017; Bocken et al., 2016; Hopewell et al., 2009; Kumar et al., 2011; Boulding, 1966). The suitability for open source can be determined through the accessibility of materials and components, as well as the number of specialized equipment needed (OSHWA, n.d; Kostakis et al., 2018). Accessibility of materials and components is tested by checking availability with common global merchants such as aliexpress.com and amazon.com. Finally, LCOE can be reduced by lowering the module's life-cycle cost, increasing its lifetime, and maximizing its energy yield over the lifetime.

*Table 1: Research aims and desired outcomes*

<b>Design Requirements</b>	<b>Desired Outcome</b>
Module Efficiency	High CTM efficiency
Quality	DH Resistance, TC Resistance, Mechanical strength
Circularity	Modular, Repairable, Recyclable
Open Source	Built using basic tools, using commercially available components
LCOE	Low material cost, high lifetime energy production

The second research question addresses the difficulty of reconciling these design requirements and making decisions between a large set of design choices. Answering this research question acknowledges the difficulty in simultaneously meeting all research objectives, and only through making tradeoffs and weighted choices an optimal final design can be reached.

*RQ2 How can trade-offs between the research objectives be made to optimally meet the design goals?*

This research has been carried out within the temporal scope of a master thesis, which is set to around 840 hours of work. This work was completed within the timespan of 6 months. Furthermore, the thesis was carried out using the equipment available at the university, resulting in a limited scope of work in terms of manufacturing and testing.

In the following chapters, the findings of the research will be extensively presented and discussed. First, a background research is presented, which uses scientific literature to shed light on the following questions: What is currently the incumbent design of PV modules? What are degradation and failure modes of incumbent PV modules? What is currently done with EoL PV modules? What are industry trends and predicted developments in the PV industry? What is the current state-of-the-art in circular PV modules? And what is the current state-of-the-art in open-source PV modules?. Once these questions have been addressed, the research moves to the actual design of an open-source circular PV module. First, the design and testing methods are presented in the methodology section. Second, the outcome of the design and testing procedures are presented in the results & discussion section. Third, the extent to which the research objectives have been met in the final design is discussed in the analysis section. Finally, the conclusion section presents the limitations of the research, the findings are presented and discussed, and directions for further research are presented.

## 2. Literature Research

### 2.1 PV Modules

The PV industry and researchers worldwide have worked for decades on developing an efficient and cost-effective way to manufacture PV modules which can withstand several years of outdoor exposure (Lunardi et al., 2018). The current standard c-Si module uses a high-transmittance glass at the front, an aluminium frame, two layers of EVA that encapsulate the cells to protect them from moisture and oxygen, a PV backsheet (usually made of Tedlar) and a junction box at the rear of the module (Klugmann-Radziemska & Ostrowski, 2010, Farrell et al., 2020). To gather a clearer understanding of how each of these can be designed for circularity and open-source, the following sections will cover each of these components in further detail.

#### 2.1.2 Cells

PV cells are semiconductor-based devices made to convert solar energy into electricity. Crystalline Silicon (c-Si) technologies had an average market share of 80-90% over a 36 year period from 1980 to 2016, and are currently holding more than 90% of the PV market shares (Lunardi et al., 2018; Farrell et al., 2020; Phillips et al., 2019). Although the cells only contribute about 14% to the weight of the module, they account for the majority of the module's embodied energy and climate change impact (83% and 66% respectively) (Olson et al., 2013; Liu et al., 2015; Huang et al., 2017). This has to do with the fact that the production of PV-grade polysilicon, ingot production, and wafering are energy intensive and polluting processes (Farrell et al., 2020; Moen et al., 2017; Yadav et al., 2015; Huang et al., 2017).

Although a variety of cell architectures exist, currently the most common cell type is the M2 (156.75±0.25 mm<sup>2</sup>) p-type Cz mono-Si wafer, onto which a silver grid is screen-printed existing of 3, 4 or 5 BBs (see Figure 1) (VDMA, 2020; Ranjan et al., 2011). Additionally, modules come in a variety of sizes, with the most common numbers for cells per module are 60 and 72 (Lunardi et al., 2018; VDMA 2020).

*Figure 1: A 3BB M2 cell with tabbing ribbon soldered onto its BBs*

### 2.1.3 Interconnection

Solar cells are interconnected in series using flattened copper wire coated with molten solder (tabbing ribbon), which is either lead or silver based (see Figure 1) (Lunardi et al., 2018; Farrell et al., 2020). In standard FBC cells, the series connection is established by connecting the front and back contacts of adjacent cells together. In order to avoid hot-spot heating one or more bypass diodes can be used, connected with inverted polarity to the cells. The string of cells is connected with a broader tabbing ribbon to the junction box (see Figure 2).

*Figure 2: Circuit diagram of a 60-cell PV module with three bypass diodes inside the module, which prevent hotspot heating in the neighboring strings of cells, and one bypass diode inside the junction box.*

The Junction box (or J-Box) of a module features the positive and negative terminals of the module, as well as the bypass diodes (see Figure 2). Usually, three bypass diodes per module are used, each protecting a substring. Each substring consists of 20/24 cells in a 60/72 cell module (see Figure 2).

### 2.1.4 Encapsulant

To protect the interconnected cells from the damaging effects of moisture and oxygen, they are laminated in an encapsulant, typically EVA. Additionally, the encapsulant acts as a bonding layer between the cells, front sheet and back sheet; provides some degree of resistance to thermal stress, mechanical stress and UV exposure; and also acts as an electrical pottant for the cells (Ndiaye et al., 2013; Hasan & Arif, 2014). Although the encapsulant provides the cells with protection for a period of 20-30 years in the field, the adhesive property of encapsulants makes separating the encapsulant from the cells and interconnections a complex task. Hence, encapsulation forms the main technical barrier for high-value PV recycling (Lunardi et al., 2018; Farrell et al., 2020).

### 2.1.4 Front Sheet, Back Sheet, Frame and Junction Box

The front of a PV module almost always consists of a sheet of glass; typically, low-iron high-transmittance glass with a thickness of 3-5 mm (VDMA, 2020). In addition, the glass is complemented with anti-soiling and anti-reflective coatings (ARCs) (Couderc et al., 2017). Although some modules feature a glass backsheet, TPE or TPT is most commonly used, typically in a bright shade of white to reflect light towards the solar cell, increasing the efficiency and output of the module (Vogt et al., 2017; VDMA, 2020). Besides framing, an edge seal is used in some cases to further prevent moisture ingress (Kempe et al., 2010).

The main purpose of the front sheet, back sheet and frame is to increase mechanical strength of the module, making it resistant to stresses occurring during transportation, installation, and use (e.g. wind loads) (Ndiaye et al., 2013).

## 2.2 Module Degradation & Failure Modes



PV modules have a lifetime of 25-30 years, most of which is guaranteed under warranty (Granata et al., 2014). This means there has been limited interest in investigating EoL options so far (Lunardi et al., 2018). Manufacturers consider a module degraded and as having reached its EoL when it reaches a level of <80% of its original power capacity (Ndiaye et al., 2013). As PV modules have a failure rate of around 0.15-0.25% per year, approximately 2% of an entire fleet of a PV plant is predicted to fail after 11-12 years (Koentges et al., 2014). These PV modules, or in some cases a whole PV string, is decommissioned and in most cases directed towards disposal or recycling (Tsanakas et al., 2020).

IRENA estimates that by 2030 there will be between 1.7 and 8 million tonnes of PV waste, increasing to 60-78 million tonnes by 2050 (IRENA, 2016). During the module lifetime, it is not uncommon that physical degradation, defects or failures, occur in only a single PV component (e.g. cell cracks or bypass diode failures), whilst the rest of the module remains intact (Köntges et al., 2014). The predominant modes of module degradation and failure are corrosion, discoloration, delamination, breakage, PID, hot-spots, and bypass diode/electrical contact failure (Ndiaye et al., 2013; Jordan et al., 2012; Ye et al., 2014); in many cases, these failure modes go hand-in-hand and mutually reinforce one another. A brief description of each of these failure modes is given in table 2.

*Table 2. Overview of the common degradation and failure modes of PV modules*

<b>Failure Type</b>	<b>Description</b>	<b>References</b>
Corrosion	<p>This occurs when moisture enters the encapsulation edges, causing leaking currents and degradation of the adhesion between the cells and metallic frame.</p> <p>Oxygen can also corrode the Si junctions and Na in the glass can react with moisture.</p> <p>EVA, the commonly used encapsulant, also has the potential to corrode PV cells as it releases acetic acid.</p>	Ndiaye et al., 2013; Hsu et al. 2010
Discoloration	The encapsulant or adhesive material between the glass and PV cells turns yellow, sometimes brown, reducing the light which can reach the cells.	Ndiaye et al., 2013; Jordan et al, 2012; Ye et al., 2014
Delamination	<p>Refers to adhesion loss between the encapsulating polymer and the cells, or between the encapsulation and the front glass. This causes light reflection and moisture ingress into the module structure, leading to corrosion, power degradation and electrical risk.</p> <p>Delamination can also occur in small areas due to chemical reactions that emit gases trapped in the PV module, thereby creating bubbles. Besides light reflection, bubbles can cause a loss in heat dissipation.</p>	Ndiaye et al., 2013

Breakage	<p>Breakage of the glass or PV cells mainly happens during installation, maintenance and transportation. Broken glass can lead to other degradation types due to moisture infiltration, discoloration and delamination.</p> <p>Cells have been produced increasingly thin to reduce costs, making them more susceptible to cracks. Cracks in cells are impossible to see with the naked eye, and do not cause an immediate disruption of current flow. However, over time a cracked cell can lead to hot-spots due to power dissipation at the fracture.</p>	Ndiaye et al., 2013; VDMA, 2020; Jordan et al., 2012
Potential Induced Degradation (PID)	According to relevant rules and regulations, PV systems are mostly electrically grounded to prevent people from electric shock. PID occurs when the electrical insulation between the grounding structure and the active components of the PV module is not sufficient. When many PV modules are connected in series, the resulting high voltage can cause current leakage from the PV cells to the ground via metal components of the module such as the frame.	Ndiaye et al., 2013; Luo et al., 2017
Hot-spots	Refers to areas in the module with an elevated temperature. Hot spots are mostly caused by power dissipation due to a cell fracture, partial shadowing, cell mismatch, or a failure in the interconnection between cells. The elevated temperature of hot-spots can cause thermal stresses to cells and glass, as well as melting or burning of encapsulation and back-sheet polymers, eventually leading to irreversible damages and complete PV module failure.	Ndiaye et al., 2013
Cell Degradation	This is mainly light-induced degradation (LID), which refers to a loss in solar cell efficiency during excess carrier injection by above-bandgap illumination or forward biasing. Although LID has been studied and mitigated for over 40 years, it remains a multifaceted problem which is not fully understood yet in both the industry and academia. However, it is known that in some cases LID can be reduced by using Ga doping in the p-type material or by using n-type cells.	Lindroos & Savin, 2016; Metz et al., 2000; Madon et al., 2015

	<p>In addition, recent years have seen the observation of a novel, slow but particularly strong degradation mechanism prevalent in some mc-SI PERx and Al-BSF cells, called LeTID or LID2. More research is needed to thoroughly understand this degradation mode.</p>	<p>VDMA, 2020; Lindroos &amp; Savin, 2016</p>
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### 2.3 PV Module EoL

As previously mentioned, according to the industry standard modules reach their EoL at <80% of their original capacity, generally after 20-30 years of operation. However, the exact point of EoL can vary further, as depending on the conditions, PV modules may still be able to generate power for many years after they reach their <80% of original capacity. Additionally, due to the rapid advances in module price and efficiency, the operator of the PV system may consider modules at their economic EoL many years before they have reached their technical EoL.

The various EoL options available today are presented in the following sections.

#### 2.3.1 Recycling

Most EoL PV modules worldwide are currently landfilled, causing significant environmental damage, among other things due to the leaching of heavy metals such as Pb and Sn and subsequent soil and groundwater contamination (Lunardi et al., 2018; Farrell et al., 2020). However, RoHS have prohibited the use of Pb in many jurisdictions. Only about 10% of PV modules are recycled worldwide, which is low mainly due to lack of legislative requirements (Lunardi et al., 2018). Yet, recycling of PV modules has the potential to ensure the sustainability of the long-term supply chain, and reduce CO<sub>2</sub> emissions and EPBT related to PV modules and the PV industry (Bustamante & Gaustad, 2014; Lunardi et al., 2018). However, recycling implies the downcycling of a product, and the recovery of only a portion of the materials and value (Lunardi et al., 2018; Farrell et al., 2020). In addition, recycling has so far been unprofitable for c-Si modules as they do not contain enough valuable materials to be recovered economically, and in jurisdictions where landfilling is allowed, the cost of the recycling process is usually higher than the landfill option (disregarding externalities) (Sener & Fthenakis, 2014).

The quantity of PV waste compared to other WEEE has so far been considered insignificant, making the set-up of specific recycling plants for PV modules uneconomical (Monier & Hestin, 2011; Lunardi et al., 2018). In response, the EU has enacted a legislative framework for extended producer responsibility of PV modules through the WEEE Directive 2012/19/EU (European Union, 2012). Europe is currently the only jurisdiction mandating PV recycling, but other jurisdictions such as Japan, USA, Australia are likely to instate laws in the near future (Lunardi et al., 2018; Farrell et al., 2020). Although this suggests recycling of PV waste may become increasingly acknowledged in coming decades, research points out that the EU recycling framework is not sufficient. This is because environmental damage is not avoided, nor does recycling sufficiently close the PV material loop as modules and their constituent materials are shipped to a wide range of recycling facilities with heterogeneous standards causing negative environmental impact due to transportation emissions and landfilling of some materials (Farrell., 2020; Latunussa et al., 2016; Stolz et al., 2018). These challenges further highlight the importance of incorporating circularity and local remanufacturing in the PV industry.

### **2.3.2 Other EoL Options (e.g. Refurbish, Repair, Remanufacture)**

Repairing or refurbishing PV modules can be worthwhile for certain defects, such as defective frames and mounting clamps, faulty bypass diodes and defective wire connectors in j-boxes, certain backsheet defects, and PID (Tsanakas et al., 2020). After refurbishing, the modules may undergo I-V characterization, EL-testing and an IEC 61730-based high voltage test (Tsanakas et al., 2020). These activities are carried out by private companies, without any support from the original manufacturers. PV repair and refurbishment thus remains rather informal and is neither systemized nor standardized in the PV industry and the overall PV value chain today (Tsanakas et al., 2020).

Farrell et al. (2020) point out that “due to the PV design method of lamination and encapsulation, opportunities for repair and maintenance, re-use and remanufacturing of PV cells and associated secondary materials without aggressive processing is very limited” (Farrell et al., 2020). Thus, in order to advance EoL options that are higher on the waste hierarchy than recycling, PV modules should be designed to allow easy delamination and recovery of high-quality silicon wafers which could be incorporated directly back into production processes (Farrell et al., 2020). This would reduce the energy payback time of PV modules considerably (Frisson et al., 2000; Muller et al., 2006), as well as the CO<sub>2</sub> emissions related to production (Fthenakis & Kim, 2011). However, this would also require PV producers to take more responsibility for the EoL and shift business models away from selling products and towards collaborative consumption, incentivised returns or performance/service models (Farrell et al., 2020; Rossi et al., 2020; Hopkinson et al., 2020; Tsanakas et al., 2020).

## **2.4 Industry Trends and Future of PV**

To design a PV module for circularity and low-capital re-manufacturing, this research takes a thorough look at the relevant industry trends and projected future of the PV industry. This is important as the design of a PV module for a long lifespan including repairs, refurbishment and remanufacturing should take into consideration the availability of required parts and the technical relevance of that design at the point in time where the repair, refurbishment or remanufacturing will be carried out. However, given the long lifespan of PV modules and the rapid technological developments in the industry, knowing parts availability and technical relevance for certain is impossible. Nonetheless, an inference is made based on the international technology roadmap for PV (ITRPV) by VDMA (2020). The ITRPV covers anticipated technological developments in c-Si PV modules for the coming decade and is based on data collected from leading companies in the PV industry. In most fields, the predictions made in the ITRPV over the last years have turned out to be fairly accurate (VDMA, 2020). The focus here will be on the most relevant developments for this research, namely cell development, LCOE reduction, and interconnection methods.

### **2.4.1 Cells**

#### **2.1.2.3.1 Wafer and Cell Types**

As mentioned, the current dominant wafer type is Cz mono-Si, which is expected to remain the case over the coming decade. N-type Si wafers are expected to grow from 5% in 2019 to 50% of the market in 2030 (see Figure 3) (VDMA, 2020). Some of the most common PV cell types in use currently are Al-BSF, PERx, SHJ, tandem cells, IBC, and bifacial cells. These cell types will be discussed here.

*Figure 3: Predicted global market share of different cell types over the next decade (VDMA, 2020)*

With Al-BSF, an Aluminium back surface field is screen printed to apply back surface passivation which is simple, low-cost and can be performed at a high throughput (Park et al., 2016). Al-BSF cells have been the industry standard over the past decades, but only made up 33% of the market in 2019 and are expected to be fully phased out by 2027 (Lunardi et al., 2018; Narasinha & Rohatgi, 1997; Riverola et al., 2018; VDMA, 2020).

PERx refers to a range of technologies where both the front and rear contacts are passivated (PERC, PERL, PERT, TOPCon). PERx made up about 60% of the global market in 2019 and is expected to make up 74% of the global market by 2030 (Green, 2015; Farrell et al., 2020; VDMA, 2020). In PERx, the back contact is the cell substrate through holes in the rear passivating oxide, allowing for wafer thickness to drop under 150 $\mu$ m (Green, 2015; Cornagliotti et al., 2012). The expectation is that PERx will continue to be applied mainly to p-type mono-Si (63% in 2030), with PERx on n-type mono-Si gaining 27% of the market by 2030 (VDMA, 2020)

In SHJ cells the high temperature diffusion of the p-n junction is replaced with the low-temperature deposition of a p-doped amorphous silicon layer on an n-type mono Si wafer. This has the benefit of increasing cell efficiency and reducing temperature coefficient (Louwen et al., 2016). Moreover, the production process is well known and SHJ cells benefit from the application of thinner wafers (Louwen et al., 2016). SHJ cells are expected to gain some space with predictions of 17% of the total market share by 2030 (VDMA, 2020).

Tandem cells contain a stack of multiple cells with different band gaps. A technology often proposed to be used in tandem with c-Si cells is perovskites. Perovskites have a tunable bandgap and have shown promising results in terms of production costs, as well as achieving record lab-efficiencies when used in tandem with c-Si cells (Sofia et al., 2020; NREL, 2021). However, remaining challenges with perovskites include improving efficiency, stability, sustainability and size of the cells (Rajagopal et al., 2018). Commercial solar cells can be used in tandem with perovskites, either in a 4 terminal (4T) tandem or 2 terminal (2T) tandem, the latter requiring current matching between subcells and an interconnecting layer connecting them in series, making it expensive and complex to manufacture (Rajagopal et al., 2018; Sofia et al., 2020).

IBC cells are cells where the p-type and n-type regions are interdigitated, allowing all cell contacts to be placed at the back of the cell. This type of cell has the benefits of reduced internal series resistance, non saturating  $V_{oc}$ , and an absence of shadowing by front surface metallization (Lammert & Schwartz, 1977). IBC cells can include heterojunctions to reach cell efficiencies of >26% (Yoshikawa et al., 2017). However, due to the higher cost of production, IBC cells are expected to remain a market niche in the coming decade, with <5% market share (VDMA, 2020).

Bifacial cells are cells which feature rear-side light capture, allowing a 10-20% relative increase in power output compared to monofacial cells which is influenced by increasing albedo illumination and optimizing the mounting of the module (Sugibuchi et al., 2013). Bifaciality can be achieved with multiple cell types, including PERx, SHJ, and tandem (Baliozian et al., 2018; Asadpour et al., 2015). Bifacial cells are expected to become increasingly prevalent, with >70% market share by 2030 (VDMA 2020).

#### 2.1.2.3.2 Cell Size

Upon module refurbishment, the main requirement for new cells used is that they fit with the old encapsulant. Therefore, developments in cell sizes should be taken into consideration during the design. Until 2020, the dominating cell format was M2 (156.75 x 156.75 mm), but this format is expected to disappear in the next 5 years, being replaced by larger formats such as M4 (161.75 x 161.75 mm), M6 (166 x 166 mm) and M12 (210 x 210 mm) (see figure 4). The advantage of larger cell sizes is that it requires less wafering while increasing module power output, thus reducing  $W_p$  costs. Formats larger or equal to M6 are expected to make up over 70% of the market by 2030. M12 is currently being introduced in the market, but market penetration will depend on the introduction of corresponding new module products (Condorelli et al., 2020; VDMA, 2020). With the introduction of larger cell sizes, cell cutting was introduced in the market to reduce interconnection losses, increasing area efficiency and module power. This is usually done through laser scribing and/or cleaving (Baliozian et al., 2018). Currently, over 20% of the module market applies half-cut cells, which is expected to grow to over 60% by 2030. Additionally, some 10% of the module market is expected to apply quarter-cut cells or even 1/3rd-, 1/5th- and 1/6th-cut cells, which are used for the shingling interconnection technique (VDMA, 2020).

*Figure 4: Predicted market share of Cz-mono-Si wafer sizes over the next decade. From VDMA (2020)*

### **2.4.1 LCOE Reduction**

For increasing PV competitiveness and speeding up the global transition away from fossil energy sources, a continued reduction of LCOE is needed. LCOE is a function of investment expenditures, operation and maintenance expenditures, fuel expenditures, energy generated, expected lifetime and a discount rate. For PV modules, a reduction in LCOE can be achieved through module  $W_p$  cost reduction, lifetime extension, and efficiency improvement.

#### **2.4.1.1 Module cost reduction**

With constant optimization in the PV module supply chain and increases in production capacity, PV module prices are steadily falling year over year, with a 65% price drop between 2015 and 2020 (VDMA, 2020). The trend towards larger wafers, higher module power and larger module sizes have caused higher material costs, meaning the non-Si portion of module cost is now 53% of the total module cost (VDMA, 2020). Continued module price decreases can be made possible through improved area efficiency, overall production equipment efficiency and specialized module products. Area efficiency ( $W_p/m^2$ ) should be increased without significantly increasing the processing costs. This can for example be done with cell efficiency improvements and new module concepts (VDMA, 2020). Sofia et al. (2019) show that near-future perovskite-silicon tandems can achieve a 15-20% relative LCOE reduction compared to the single junction sub-cells. Overall equipment efficiency refers to using the production capacity in more efficient ways by using Si and non-Si materials more efficiently (VDMA, 2020). Finally, specialized module products can be developed to reduce installation costs in specialized niche applications. However, introducing new, immature technologies that do not show reductions in the per- $W_p$  cost from the beginning will remain challenging (VDMA, 2020).

#### **2.4.1.2 Lifetime**

Currently the industry standard for module lifetime is a product warranty of 12 years and a performance warranty of 25 years. Over the coming decade these warranties are expected to increase to 20 and 30 years respectively (VDMA, 2020). Further lifetime increases could be achieved by enabling repairs, refurbishment or remanufacturing. Additionally, given the fast technological developments, design for upgrades is needed to ensure the continued technological relevance of the PV module.

### **2.4.1.3 Power Generation**

Increasing the total power output of a module, besides increasing area efficiency, can be achieved by limiting degradation. Module degradation, in particular LID and LeTID, is expected to be reduced over the next two years through cell technology advancements, meaning that by 2022 modules will have an expected degradation of 2% in the first year of operation and subsequent degradation of 0.5% during the performance warranty, compared to 2.7% and 0.7% respectively today. After 2022, these reductions are expected to plateau over the rest of the decade (VDMA, 2020). Furthermore, the industry is moving to new standards for modules which are fully PID resistant (VDMA, 2020). These are relevant developments to consider whilst designing a circular PV module today.

### **2.4.2 Interconnections**

With current cell topologies, there are various interconnections possible and used in the PV market. Of these, Cu-based tabbing ribbons are the most common. These are flat copper ribbons coated in soldering tin, making them suited for soldering onto cell BBs and back contacts. Cu wire-based interconnections are an alternative interconnection method where small copper wires are soldered directly onto the cell fingers. These are expected to increase in market share to about 45% by 2030, and overlapping interconnection technologies (i.e. shingling) using conductive adhesive are expected to gain a market share of about 15% by 2030 (VDMA, 2020). These developments are a result of the success of half-cut cells, which among other things provide a higher voltage and lower resistance losses. These interconnection techniques, alternative to the conventional FBC interconnection are further covered here.

#### **2.4.2.1 Multi-wire Interconnection**

In multi-wire interconnection (also called wire-based interconnection), a large number of thin Cu wires coated in tin are soldered directly onto the fingers, eliminating the need for BBs. Multiple methods exist for achieving this. For example, infrared light can be used to solder wires directly onto the cell, or the wires can be embedded in a special foil, and then soldered onto the cell during lamination using low-temperature solder (Walter et al., 2017). Benefits of multi-wire technology is that it reduces shading, silver consumption, current per finger, enables smaller finger width, reduces the effective current paths, and increases overall module power (Braun et al., 2012; Walter et al., 2014; Yao et al., 2015, Volk et al., 2013). In addition, Walter et al. (2017) show that multi-wire interconnections show better mechanical stability in accelerated aging tests than standard BB ribbon-based interconnections.

#### **2.4.2.2 Paved Interconnection**

With paved interconnection, (also called tiling), cells are connected front-to-back using a ribbon and seamless soldering, which is similar to normal front-to-back interconnections. However, the difference is that cells are slightly overlapped to eliminate gaps between solar cells (VDMA, 2020). This results in a higher active module area and higher CTM efficiency.

#### **2.4.2.3 Shingled Interconnection**

Shingling technology means solar cells are cut into 5 or 6 strips, and placed in the module like shingles on a roof (Dickson, 1960). At the overlap between adjacent cells, the front and back contact of the respective cells are connected using an ECA or low temperature solder. Connecting 1/5th or 1/6th cut cells in series reduces module current, leading to lower temperature and increases module voltage, leading to lower series resistance (Klasen et al., 2017). Further advantages include a higher module active area due to the absence of inter-cell spacing and BB shading, a reduction in metal usage due to the absence of tabbing wire or ribbons, and a more homogeneous aesthetic as no wires are visible at the front of the module (Klasen et al., 2017). Moreover, due to the absence of soldering, shingled modules show better performance in accelerated thermal cycling tests than ribbon-based and multi-wire

interconnections (Schiller et al., 2019; Baliozian et al., 2018). However, downsides of shingling are higher silicon usage due to overlapping regions, the addition of a process step for cell separation and edge passivation and lower process throughput due to the additional cells which need to be interconnected (Klasen et al., 2017).

## **2.5 Prior Work on PV Module Design for Circularity**

As mentioned, the main technical barrier of circularity for a PV module is adhesive laminates, especially EVA, which cannot be separated from the cells without compromising cell integrity or Si purity. To overcome this problem and make it possible to remanufacture or recycle PV modules and their components, the literature suggests two design approaches: design for delamination and lamination-free designs. These design approaches will be covered here, including a report of the published research work that has been carried out on them.

### **2.5.1 Design for Delamination**

Design for delamination refers to the use of laminates which reliably encapsulate the cells during the module lifetime, but can be separated from the cells at the module EoL. Such a design approach enables various EoL options, such as recycling or refurbishment.

Doi et al. (2003a; 2003b; 2005a; 2005b) developed a double encapsulation module (DEM) in which a transparent nonadhesive PET film is placed between the PV cell and EVA. The films are thermally welded between cells and cells can be extracted from the module at the EoL by cutting the encapsulation around the cells from the back side of the module (Doi et al., 2005a). This approach is a simple, straightforward method to PV design for circularity, based on a low-cost and widely available material. Additionally, this material only needs to be added to the lamination process, thus not requiring any additional process steps during manufacturing. However, the addition of PET in front of the cells reduces CTM efficiency, due to increased light absorption, which can potentially increase over time with UV-induced degradation of the material (Prasad et al, 2011).

Another approach to design for delamination is using an alternative encapsulant to EVA. Although EVA is a thermoplastic, its co-polymer nature and subsequent two-stage thermal decomposition makes it more difficult to recycle than alternative encapsulants such as POEs or oxidized LDPE (Adothu et al., 2020; Hsu et al., 2010; Goris et al., 2015). Goris et al. (2015) show that intact cells can be recovered from such encapsulants by first bringing the laminate to softening temperature, at which point the back can be peeled off; then bringing the laminate to the temperature where it becomes viscous, at which point a wire saw is used to separate the cells from the glass; and finally cleaning the remaining laminate off the glass mechanically and off the cells using pyrolysis at 450°C. Goris et al. (2015) also point out that TPO, the POE used in their research, has additional benefits over EVA, such as lower sensitivity to air leakage, higher peel strength, and less discoloration over the module lifetime. However, the downside of POEs is their higher price, making them unattractive for most module manufacturers (Goris et al., 2020).

An approach to design for delamination not yet documented in research is the use of a so-called 'release-foil'. This is a laminate which can be released during the module EoL under an external trigger. In collaboration with three private companies, the Dutch research institute TNO has developed such a laminate, requiring minimal energy and not emitting toxic substances during release (TNO, n.d.). However, the details of this laminate's composition, as well as the nature of the external trigger remain undisclosed at the time of research.

### **2.5.2 Lamination-free Design**



Another approach for circularity of PV modules is to eliminate the laminate entirely. Eliminating the laminate from the module allows for the easy recovery of intact cells, saves the cost of laminate-related materials and processes, and reduces laminate-related degradation modes such as yellowing and acetic acid release (Hsu et al., 2010; Mittag et al., 2017). However, replacing the interface between glass and cells with a gas increases the reflectivity of the module, thus decreasing the CTM efficiency (Mittag et al., 2017; Couderc et al., 2017). This effect can be slightly mitigated by adding ARCs on both sides of the front glass, but CTM efficiency is still lower for laminate-free, gas-filled modules (Couderc et al., 2017; Mittag et al., 2017). During this research, two research teams were found working on laminate-free modules. These module designs are called ‘NICE’ and ‘TPedge’ respectively. Both of these outperform standard EVA-laminated PV modules in accelerated lifetime testing (Saint-Sernin et al., 2009; Depuis et al., 2010; Madon et al., 2010; Mittag et al., 2017). However, the industry is yet to catch on with such laminate-free designs, partly because of the aforementioned downside of such a design.

#### 2.5.2.1 NICE

New Industrial Cell Encapsulation (NICE) PV modules are glass-glass modules where the edge of the module is double sealed using PIB and silicone. These sealants simultaneously act as adhesives to keep the front and back glass attached. A PIB adhesive is used to keep the solar cells and metal interconnecting ribbons in place (Dupuis et al., 2010; Saint-Sernin et al., 2008; Saint-Sernin et al., 2009; Depuis et al., 2011; Depuis et al., 2012; Forster et al., 2014; Madon et al., 2015; Reinwand et al., 2018; Einhaus et al., 2018). The desiccant-filled PIB seal is at least 10 mm wide, resulting in a humidity tightness of more than 30 years (Dupuis et al., 2010; Saint-Sernin et al., 2008; Saint-Sernin et al., 2009; Madon et al., 2015). This method of sealing two glass panes has been widely tried and tested in the double-glazing industry.

NICE PV modules feature standard FBC cells. In order to allow intact cell recovery, NICE PV modules feature solderless cell interconnections, where bare copper ribbons are pressed onto the PV cell contacts through underpressure inside the module (Depuis et al., 2010; Depuis et al., 2011; Einhaus et al., 2018; Reinwand et al., 2018). This underpressure is created in the last step of the production process, where the module is pressed to the desired thickness. In this step, the interior of the module is flooded with a neutral gas and an underpressure between 100 and 300 mbar is created in the interior of the module (Saint-Sernin et al., 2008; Saint-Sernin et al., 2009). This underpressure is enough to reliably hold the bare copper tabbing wires onto the bus bars during the module lifetime (Depuis et al., 2010; Einhaus et al., 2018). Einhaus et al. (2018) point out that adhesive used to hold cells in place makes it difficult to recover cells in one piece, so the research team is looking for adhesives that ease cell recovery.

As mentioned, replacing the glass-cell interface with a gas increases reflectivity, lowering CTM efficiency. Couderc et al. (2017) showed that by applying a 0.76nm ARC to the front glass with a refractive index of 1.23 on both the external and internal side of the front glass light transmission can be optimized. In this case, the front glass has a thickness of 3mm and the spacing between the front glass and cells is 450 $\mu$ m. In addition, a 76nm ARC is applied to the cell with a refractive index of 1.85. Despite this optimization, the results indicate that when illuminated with higher angles of incidence, the performance of a laminate-free module could be lower than that of a module laminated with EVA. In a solar simulator test the research finds the maximal  $J_{sc}$  of the laminate-free module to be almost equal under an AM1.5G spectrum, but the EVA module was found to perform better (with a current density of +0.25mA/cm<sup>2</sup>) under the unfiltered Xe light source used for solar simulation tests, which is attributed to its bias towards infrared wavelengths.

The production facility developed for the NICE PV module is 100% in line and completely automated, requiring only three operators per shift for a 45MW/year line. The required floor space is reduced by a factor of 5 compared to a state-of-the-art module assembly line. As described by Saint-Sernin (2008), the process consists of the following steps:

- Loading
- Washing & drying
- Adhesive deposition
- Positioning of metal connectors and cells on the rear sheet
- Positioning of the junction box and module busbars
- Deposition of sealant around the perimeter of the backsheet
- Mounting of front and rear sheets, pressing the sandwich to the desired thickness
- Flooding the module interior with a neutral gas
- Creation of underpressure through pressing
- Testing

In pursuit of industrialization, the research team has applied for numerous patents. However, these filings have only been accepted by the French patent office, and have been rejected by the European and International patent offices due to the existence of prior art, a lack of novelty, and a lack of an inventive step as evaluated by a person skilled in the art (Hubert & Bamberg, 2007; Saint-Sernin & Lauvray, 2010; Lauvray & Einhaus, 2003; Chefiet et al., 2010; Reyat et al., 2007; Beret et al., 2004; Baret & Lauvray, 2003a; Baret & Lauvray, 2003b).

#### 2.5.2.2 TPedge

Similar to NICE PV modules, Haedrich et al., (2012), and Mittag et al. (2014; 2015; 2017), describe the development and testing of a laminate-free, edge-sealed and gas-filled glass-glass module called “TPedge”. The TPedge module has a thermoplastic spacer seal on the inside filled with drying silicates and a silicone seal on the outside which adheres the two glass panes, rendering the mechanical stability of the module and eliminating the need for an aluminium frame (Mittag et al., 2015).

The cells are soldered front-to-back using standard tabbing ribbons, and fixated using small pins of a transparent UV-curing adhesive. These pins cover only 0.02% of the frontal module area and are applied in the same positions both on the front and the back of each cell, simultaneously acting as a spacer between the cell and the front glass (Mittag et al., 2015). One version of the TPedge for BIPV features MWT HJT back-contact PV cells (Mittag et al., 2017).

The module showed higher than average performance in accelerated lifetime testing, including damp heat, thermal cycling, mechanical load, PID, hot-spot, and hail tests (Mittag et al., 2015). In a CTM efficiency analysis, Mittag et al. (2017) found the  $CTM_{power}$  ratio of TPedge modules to be 0.906, compared to 0.954 for EVA-laminated glass-foil modules and 0.947 for EVA-laminated glass-glass modules. This has to do with the above-mentioned fact that the coupling between EVA and glass leads to lower reflectivity.

As described by Mittag et al. (2017), the production of TPedge modules consists of the following steps

- Glass washing
- Dispensing the fixation pins
- String layup
- UV-curing of fixation pins
- Dispensing distance pins
- UV-curing of distance pins

- Sealant application
- Sealing press
- Silicone application
- Testing

This process is reliable and fast, with expected cycle times of less than one minute (Mittag et al., 2017).

In a cost comparison between TPedge modules, conventional EVA-laminated glass-foil modules, and EVA-laminated glass-glass modules, Mittag et al. (2017) found the  $W_p$  cost of TPedge to be 1.2% lower than conventional modules. This was mainly due to the absence of frame and foil-related/lamination costs. In addition, Mittag et al.(2015) found the TCO of TPedge modules to be 12.3% lower. The research also found TPedge modules to be 0.4kg lighter than conventional modules and having a potential 34% lower CO<sub>2</sub> footprint due to the absence of the frame and foil. However, this CO<sub>2</sub> footprint analysis did not take into account the reduction in energy consumption during production, nor the emissions savings related to recycling solar cells; adding these criteria could further lower the CO<sub>2</sub> footprint of the modules.

### **2.5.3 Re-options for Circular PV modules**

Modules designed for delamination can be repaired, refurbished, or remanufactured by delaminating the module and desoldering the cells. Although the advancements of NICE and TPedge PV modules ease repair, refurbishment and remanufacturing, these goals are not specifically mentioned in the research. Moreover, the adhesives used to fixate cells in both of these modules complicate the recovery and replacement of individual cells. Thus, although these research teams have made steps towards design for repair, refurbishment and remanufacturing, they still mostly fall in the category of design for recycling. Moreover, no research was found on designing PV modules with upgrades in mind.

## **2.6 Prior Work on PV Open-Source**

In this final section of the background research, the existing academic work on open-source PV is covered.

### **2.1.4.1 Open Source PV**

Although some projects exist on the open-source development of PV systems and BoS components, very little work has been done on the open source development of PV modules. Research by Buitenhuis & Pearce (2012) on the open source development of PV technology shows that the PV industry mostly uses proprietary models of design and innovation which can slow down the development of PV technology. The research shows advantages of open-source in the PV industry could be faster problem solving, lower R&D costs, more reliable and robust hardware, increased innovation, decreased dependency on monopoly suppliers, faster adoption of latest technology by manufacturers and an overall more efficient technological design process. However, barriers for solar PV firms to adopt open-source technologies as identified by the research are the risk of competitors improving products, lowering the barriers for new entrants, and reduced funding to R&D due to the increased competition. In addition, the research mentions several limitations to PV technology that could hamper its open-source development. These are low user expertise; which means users generally do not have the expertise to improve PV module design, a weak hacker community; since PV development mainly occurs in academic and corporate spheres, the lack of an ad hoc culture of people coming together to solve problems and share ideas, and the low modularity of PV modules; which means that not all challenges in the module design can be attacked independently and solutions scaled across the industry.

#### 2.1.4.2 DIY PV

Despite the lack of open-source PV module designs, a large on-line community around DIY PV modules exists. These are people building their own PV modules and sharing these designs with one another in forums, instructions, and videos. In some cases, these makers encapsulate their solar cells using epoxy resin, making it impossible to recover the PV cells (learn share, 2017; GreatScott, 2018). In other cases, a silicone edge seal is used (Klements, 2016; Gabay, 2021) Usually, these tutorials apply commonly used front-to-back cell interconnections. The cells needed to build DIY modules can be ordered online for little money and in many cases, the maker can save on material costs by building the module themselves (Klements, 2016).

### 3. Methodology

In this chapter, the design method is presented by which trade-offs between the research objectives are made to reach a final design. In addition, the testing methods are presented by which the suitability of the design choices for use in real-world PV modules are evaluated.

#### Morphological Chart

The overall functionality of the PV module arises out of a number of sub-functionalities such as encapsulating the PV cells, allowing light to hit the PV cells, and allowing electricity to flow from the terminals through all the PV cells. Based on the literature review carried out, a number of design choices were identified for each of these sub-functionalities. However, given the number of sub-functionalities and possible design choices, the amount of possible designs was found to be very large. To map these choices, and make weighted design decisions, a morphological chart was constructed.

The morphological chart was developed by Swiss astrophysicist Fritz Zwicky as a tool for solving multi-dimensional, non-quantifiable complex problems, and is often used in industrial design (Zwicky, 1969; WikID, n.d). The method works by first stating the problem to be solved by the design. Next the design requirements and sub-functionalities are listed. Next components are listed, which offer ways to satisfy each sub-functionality. Finally, the components are ranked based on each design requirement and each sub-functionality into a top-two. This process then renders a final product, which fits best with the design requirements (WikID, n.d.). In this research, these final design choices are further narrowed down through tests carried out during four sprints. The methodology carried out for each sprint is briefly described below.

#### Sprint 1: Encapsulation

The goal of sprint 1 is to test whether the encapsulation methods selected through the morphological chart are adequate to ensure a module lifetime of >25 years. To this end, DH testing was performed in a climate chamber for 1000 hours at 85°C and 85% RH. The goal of damp heat testing is to identify the level of moisture ingress over a module lifetime. 1000 hours of damp heat testing is generally used to ensure a PV module lifetime of over 20 years in a tropical climate (Hülsmann & Weiss, 2015). However, for temperate and dry climates, 350 and 100 hours respectively are enough to simulate degradation over a period of 20 years (Otth & Ross, 1983; Kuitche, 2014). Intermediate results were collected at 200, 400, 600, and 800 hours. To visualize moisture ingress and oxidation, the encapsulants are filled with four sheets of Cu foil in place of the cells, according to the test method by Goris et al. (2015). These will discolor as they oxidize, indicating the presence of oxygen and moisture inside the encapsulant. As a control, one sheet of Cu foil is placed in the climate chamber without any encapsulation.

The climate chamber used is a Hielkema SH-661 benchtop chamber with a temperature range of -60 to 150 °C, a humidity range of 30 to 95% RH. Its internal dimensions are: 399 mm depth, 399 mm width, 399 mm height. The test set up can be seen in figure 9.

## Sprint 2: Interconnection

In sprint 2, multiple mini-modules were constructed with the goal of testing the ideal method of interconnection according to the predetermined research objectives. The ideal method of interconnection according to the research objectives was first selected using the morphological chart methodology and subsequent testing was carried out in sprint 2, 3 and 4. Mini-modules using both the selected modular interconnection, as well as the standard interconnection were constructed to compare their suitability for open-source, circularity, quality, low LCOE and high module efficiency. The quality of the cell interconnections was tested using both electroluminescence (EL) and current-voltage (I-V) curve measurements. EL imaging refers to the photographic surveying of light emission from a PV cell under forward bias. This way the minority carrier diffusion length can be mapped, and cell defects can be uncovered (Fuyuki et al., 2005). I-V curve measurement refers to measuring the module current at different voltages, which is performed under STC (i.e. irradiance of 1000W/m<sup>2</sup>, 25°C, AM1.5 spectrum) (Smets et al., 2015)

## Sprint 3: Performance

In sprint 3, a four-cell minimodule, using the modular soldered FBC interconnection method was subjected to a DH test at 85°C and 85% RH, in conjunction with the encapsulations built in sprint 1. The goal of this sprint was to test the durability of withstanding long-term exposure of the minimodules to outdoor environments. The DH test was carried out for a duration of 750 hours.

In addition to damp heat testing on a minimodule, a minimodule was constructed to test the resistance of the soldered interconnections and encapsulant to thermal cycling. The thermal cycling test to be carried out is a 200 TC test proposed by Schiller et al. (2019) with heating/cooling rates of 8K/min and a 25 min dwell time. The benefit of this method is that it achieves similar accelerated aging effects as the IEC 61215 200 TC test, but in a period of only 9 days (compared to 30-50 days in the IEC 61215 TC test) (Schiller et al, 2019). However, due to technical failure of the climate chambers during the research, in combination with limited temporal scope, the thermal cycling test was unfortunately omitted from the research.

For the minimodule tested, EL imaging and I-V curve measurement was carried out both before and after the test to measure the effect of accelerated aging tests on the module's performance.

## Sprint 4: Large scale module

In this final sprint of the research, a 24-cell module was constructed. The 24-cell module size was chosen as it can be handled by a single researcher, and is large enough to obtain the results needed to satisfy the research aims. The goal of this sprint was to obtain a construction method for the first working prototype of the open-source modular PV module, as well as draft the open-source documentation needed by makers to replicate and further develop the module.

# 4. Results & Discussion

In this section, the results obtained from building, testing and comparing the different PV modules are presented and discussed. A description and discussion of the morphological

chart will first be given, followed by a thorough narrative of the subsequent decisions which constituted the creation of the minimodules as described in sprints 1, 2, 3 and 4.

## Morphological Chart

Table 3 and 4 shows the morphological chart mapping possible design of a PV module incorporating circularity, reducing LCOE and allowing for (re)manufacturing at low capital costs without giving up efficiency and quality, as stated in the research question. The main design requirements regard module efficiency, quality, circularity, suitability for open source, and a low LCOE.

The functionality of a circular PV module has been subdivided into a number of sub-functionalities. Table 3 shows all possible design choices for each sub-functionality. First, a transparent frontal structure is needed to let light onto the cells while protecting them from mechanical stress and other environmental influences. Likewise, a rear structure is needed to hold the cells in place and protect them from mechanical stress and other environmental influences. Besides the front and rear structure, further encapsulation is needed to protect the cells from environmental influences. When there is empty space inside the module, that space needs to be inert, meaning it cannot negatively influence the performance of the cells. Furthermore, the interface between the glass and that space needs to have a low refractive index to minimize CTM losses. The module needs PV cells, of which multiple are available, each with their own distinct advantages and disadvantages. These cells need to be interconnected, for which multiple methods are possible. Besides these inner connections, outer connection points need to be present that can be used to connect the module to other components of the PV system. Finally, there is the choice between a framed or frameless module. The design choices that are possible for each of these sub-functionalities are presented in table 4 and will be elaborated on further in the following sections.

*Table 3: All possible design choices for each subfunctionality of the circular open-source PV module*

	<i>Options</i>					
<b>Transparent Frontal Structure</b>	<i>Low-iron high-transmittance glass</i>	<i>UV Resistant Polymer</i>				
<b>Rear Structure</b>	<i>Glass</i>	<i>UV Resistant Polymer</i>	<i>Recycled Polymer</i>	<i>Tedlar</i>		
<b>Reversible Cell Encapsulation</b>	<i>EVA-PET Double Encapsulation</i>	<i>Release Foil</i>	<i>Butyl Tape &amp; Silicone Edge Seal</i>	<i>Two-Component PIB &amp; Silicone Edge Seal</i>	<i>Hot-melt PIB &amp; Silicone Edge Seal</i>	<i>Polycarbonate Welding</i>
<b>Inert Atmosphere Creation</b>	<i>Flooding w/ neutral gas</i>	<i>Oxygen &amp; Moisture Scavenging</i>	<i>Moisture Scavenging</i>			
<b>Reduced Refractive Index</b>	<i>Double ARC</i>	<i>Transmittant Foil</i>	<i>Transformer Oil</i>			
<b>PV Cells</b>	<i>AL-BSF</i>	<i>PERx</i>	<i>Bifacial</i>	<i>IBC</i>	<i>Pin-up</i>	
<b>Modular Cell Interconnection</b>	<i>FBC Plug connection</i>	<i>FBC magnetic connections</i>	<i>FBC soldered connections</i>	<i>Shingled magnetic</i>	<i>Shingled dry ECA</i>	<i>Multi-wire foil</i>

<i>Outer connectors</i>	<i>J-box</i>	<i>Edge J-BOx</i>				
<i>Frame</i>	<i>Frameless</i>	<i>Al Frame</i>	<i>Plastic Frame</i>			

Table 4: The first and second choice of design option for each research objective according to each design requirement.

<b>Circular Open-Source PV Module</b>	<b>Circularity</b>		<b>Open-Source</b>		<b>Module Efficiency</b>		<b>Quality</b>		<b>LCOE</b>	
<b>Transparent Frontal Structure</b>	Low-iron high-transmittance glass	UV Resistant Polymer	Low-iron high-transmittance glass	UV Resistant Polymer	Low-iron high-transmittance glass		Low-iron high-transmittance glass	UV Resistant Polymer	UV Resistant Polymer	
<b>Rear Structure</b>	Glass	Recycled Polymer	Glass	UV Resistant Polymer			Glass	UV Resistant Polymer	UV Resistant Polymer	Recycled Polymer
<b>Reversible Cell Encapsulation</b>	Butyl Tape & Silicone Edge Seal	Hot-melt PIB & Silicone Edge Seal	Butyl Tape & Silicone Edge Seal	Two-Component PIB & Silicone Edge Seal	Release Foil	EVA-PET Double Encapsulation	EVA-PET Double Encapsulation	Release Foil	EVA-PET Double Encapsulation	Release Foil
<b>Inert Atmosphere Creation</b>	Flooding w/ neutral gas		Moisture Scavenging	Oxygen & Moisture Scavenging			Oxygen & Moisture Scavenging	Flooding w/ neutral gas	Moisture Scavenging	
<b>Reduced Refractive Index</b>	Transformer Oil	Transmittant Foil	Transformer Oil	Transmittant Foil	Transmittant Foil	Transformer Oil			Double ARC	Transmittant Foil
<b>PV Cells</b>			PERx	AL-BSF	Bifacial	IBC			PERx	AL-BSF
<b>Modular Cell Interconnection</b>	FBC Plug connection	FBC magnetic connections	FBC soldered connections	FBC Plug connection	Shingled dry ECA	FBC Soldered connections	FBC soldered connections	Shingled dry ECA	FBC soldered connections	Shingled dry ECA
<b>Outer connectors</b>			J-box							
<b>Frame</b>	Frameless	Plastic frame					Al Frame	Plastic Frame	Frameless	

### Transparent Frontal Structure

For both the front and back sheet the choice in materials is between glass and polymers. As shown in the literature review, 4mm thick low-iron high-transmittance hardened safety glass is the standard in the PV industry. Some researchers and module manufacturers have turned to the use of polymers as a front sheet to slash costs, weight and carbon emissions (SABIC, n.d., Kutter et al., 2020; Lisco et al., 2020; Martins et al., 2018). For the front sheet, these polymers need to be UV-resistant, as well as impact and surface-damage resistant.

In terms of circularity, glass is beneficial as any layers deposited on top of glass are easy to etch away, making it suited for re-use. For both glass and polymers, ample recycling technologies exist. However, for high-grade recycling, material separation is key, which may be problematic in case some specialty polymer is especially developed to serve as a PV module front sheet. Moreover, to enable recycling, the polymer needs to be thermoplastic. For open-sourcing, both solar glass and polymers are available to makers around the world. However, for some specialty polymers availability may be more limited. In terms of quality and module

efficiency, glass is beneficial as it has higher transmittance and less moisture transmissivity than most polymers. To reduce costs, polymers are beneficial in case of common polymers. However, specialty polymers may be more expensive, especially when produced on a small scale. Clearly, when using polymers the outcome of the design requirements depends highly on the polymer chosen. In this research UV-resistant polycarbonate is investigated. Polycarbonate is a common thermoplastic polymer with a tensile strength of 55-75 MPa, a suitable upper working temperature of 115-130°C and transmittance of 80-90% in the visible and near infrared wavelengths. The advantages of polycarbonate over glass are its high impact resistance, lower cost and lower weight. However, the disadvantages are lower transmittance, lower rigidity, susceptibility to surface damage, and higher water vapour permeation. Accelerated aging and optical tests are needed to further assess the suitability of polycarbonate for use in PV modules.

### **Rear Structure**

The rear structure mainly solves to hold the cells in place and form a first barrier to external influences. In conventional PV modules, the most common rear structure is a tedlar backsheet (Klugmann-Radziemska & Ostrowski, 2010, Farrell et al., 2020). A glass-glass design is also common, where glass is used for both the front-and backsheet of the module. Glass-glass is mainly beneficial when bifacial cells are used, meaning the rear side of the module is also active. Moreover, in edge-sealed modules, glass-glass designs are required as the edge-seal material may not adhere properly to polymers. This proposition will be tested in accelerated aging tests. Most considerations applying to the use of glass or polymers for the back sheet of the module are similar to those made for the front sheet. The only difference is that when unifacial cells are used, transmittance and thus module efficiency is not affected by the choice between glass and polymers for the backsheet. Since transmittance is not an issue for the backsheet when using unifacial cells, there is the possibility to use recycled plastic, given that this plastic forms an adequate barrier to moisture and oxygen. In terms of circularity, besides the possibility to separate materials, an additional consideration could be to limit the amount of materials used in the module to simplify production and recycling. Following this line of argumentation, the back sheet could be made of the same material as the front sheet, as is the case in a glass-glass module. The additional benefit of using the same material as a front- and back sheet is that there is no difference in TEC, increasing module quality.

### **Reversible Cell Encapsulation**

The encapsulation mainly serves to protect the fragile PV cells from oxidation and moisture. In order to achieve a circular PV module, the encapsulation must be reversible. In order to achieve an open-source PV module, the materials and equipment used for the encapsulation must be readily available. Based on the literature review, three options are identified: (1) double encapsulation using traditional EVA encapsulation, but with a PET film around the cells to avoid adhesion; (2) using a special encapsulant that can be released under the influence of an external trigger (TNO, n.d.); or (3) using an edge seal like in the NICE and TPedge modules (Saint-Sernin et al., 2009; Mittag et al., 2017). The edge seal materials used by these research groups are tried and tested in the insulating glass industry. A fourth option would be to create a transparent polymer encapsulant where the edges are welded together once the internal components of the module are in place.

The benefits of this fourth approach would be that the module encapsulant can exist of a single material, possibly a material that is recyclable, and the potential elimination of a front- and backsheet, creating a sort of monocoque module encapsulant; potentially saving costs, weight and lifecycle GHG emissions. The downsides of this approach is that generally polymers show



less mechanical integrity, UV stability, transmittance and resistance against surface damage. Moreover, the welded polymer encapsulant may be difficult to open and close for maintenance. All of these issues could be addressed through clever design and material choices. However, to limit the scope of this research, this approach is not investigated in-depth.

Out of the other reversible encapsulation options, double encapsulation and release foils will mainly be beneficial in terms of cost; as a laminated module does not require a costly glass backsheet, in terms of quality; as lamination is a tried and tested method for protecting the electronic components of a PV module, and in terms of CTM efficiency; as it avoids the refraction losses occurring in gas-filled modules. For the latter design requirement, release foil is more beneficial than double encapsulation since the PET foil introduces increased absorption losses in front of the cell. Edge sealing is more beneficial in terms of circularity; as repairs and refurbishment is facilitated by a module without lamination, and beneficial in terms of suitability for open-source; as the edge seal technique does not require a laminator. However, the hot-melt PIB used in double glazing does require a PIB extruder. Thus, for makers without specialty equipment, two alternatives are available: a two-component PIB caulk or a Butyl Tape which is already in the right shape. The latter option is beneficial since it avoids a curing process and potential weaknesses introduced by the solvent in the two-component PIB caulk.

Although EVA-PET double encapsulation was found to be most beneficial across the design requirements, circularity and open-source weigh more heavily in this subfunctionality. Moreover, an edge seal does not introduce significantly higher costs, nor does it significantly reduce module quality (Saint-Sernin et al., 2009; Depuis et al., 2010; Madon et al., 2010; Mittag et al., 2017). However, accelerated aging tests are needed to point out whether the butyl tape performs as well as extruded hot-melt PIB at sealing the module edges and encapsulating its internal electronic components.

### **Inert Atmosphere Creation**

To safeguard the cells and the metal inside the module against oxidation, any atmosphere surrounding them should be inert. To achieve an inert atmosphere, three possibilities exist. First, one could try to completely eliminate the inner atmosphere using a vacuum. However, the pressure difference would increase the probability of failure dramatically. The second possibility is to flood the module with an inert gas, which can be done in combination with underpressure, as is the case with NICE PV modules (Saint-Sernin et al., 2008; Saint-Sernin et al., 2009). Both of these approaches require special machinery and components such as compressors, nipples or decompression chambers, which rules out an open-source approach to PV module manufacturing. A low-tech way of flooding the module with an inert gas could be to assemble the module in a bath of a heavier-than-air gas such as halon. However, the least complex way to create an inert atmosphere is through the use of scavengers, namely desiccants and oxygen absorbers. This approach is also mentioned in Hubert & Bamberg (2007). Interestingly, Mittag et al. (2015) do not mention any inert gas being used to fill the TPedge module, rather the glass spacing is filled with air. The research does not mention how moisture is kept out of the module or how oxidation of the cells and contacts is prevented. For the reasons mentioned above, oxygen and moisture scavenging is chosen for creating an inert atmosphere. However, the significance of using these scavengers is tested in an accelerated aging test.

### **Reduced Reflection and Refraction**

To reduce reflection at the front of the module, an ARC can be applied. Some commercial ARCs are available, used to reduce glare in for example television screens or shop windows. These should be used at the front of the module, preferably using a foil that can be easily

separated from the glass at the point of recycling. The other benefit of using an anti-reflective film is that the application results will be more consistent. However, of the anti-reflective films that are commercially available, it is often unclear to what extent they increase light transmission, what lifetime they have under outdoor conditions and if the potential added transmission warrants their high cost. In conclusion, more research is needed to identify the optimal manner of applying ARCs in line with the design objectives.

For encapsulation, this research has chosen to use an edge seal. The downside of laminate-free, edge sealed, gas filled modules is the refraction losses at the interface between glass and gas. Therefore, multiple potential methods for eliminating this problem are listed in the morphological chart. These methods will not be tested to limit the scope of this research, but they are discussed, and could be interesting directions for further research. The first method is discussed in Couderc et al. (2017) and involves applying a 0.76nm ARC to the front glass with a refractive index of 1.23 on both the external and internal side of the front glass to optimize light transmission. However, the precision required to apply ARCs at such a minute thickness lays beyond the capabilities of open-source makers. Moreover, the double ARC method only slightly mitigates the problem, but does not yield the level of transmission achieved when using EVA lamination (Couderc et al., 2017). Thus, methods are explored that achieve optical coupling between the glass and cell without adhering materials to the cell. The goal here is to minimize both the refraction at the interfaces of the material and the light absorption introduced by the material. One option would be to use a plastic foil that is optically highly transmittant and does not degrade overtime from exposure to sunlight. Another option would be to fill the module with transformer oil. Many types of transformer oil exist, but for PV modules, colorless oil should be the most suited due to its good transmittance. Added benefits of oil could be that it is electrically insulating, and that it could be used for cooling. However, downsides are that an a volume of gas should be added to the module to avoid pressure buildup under thermal expansion, and that some transformer oils are highly flammable as well as environmentally damaging in case of a leak. To address the last point, a biobased alternative such as coconut oil could be used (Abeyundara et al., 2001).

### **PV Cells and Interconnection**

The type of cells used has a high impact on other aspects of the design, mainly the interconnection. The choice here is limited to the major cell architectures. Cell size, amount of BBs, and potential cutting are left out of the equation. Also, future developments such as perovskite tandem cells are left out. As shown in the literature review, the industry is currently moving from Al-BSF to PERx cell architectures, which generally show the best performance versus price (Green, 2015; Farrell et al., 2020; VDMA, 2020). Also, PERx cells are widely available through common global merchants such as aliexpress.com. IBC and Bifacial cells are also available, although they are less common and come at higher  $W_p$  prices. Less commonly available are pin-up cells, cut cells and cells suited for shingling. Thus, PERx cells are identified here as the cell type of choice for open-source makers. Alternatively, with a glass-glass module architecture, bifacial cells could be an economically interesting alternative. However, in this research the available Al-BSF cells at the university are used for a proof-of-concept.

The interconnections between the cells are, besides encapsulation, a key determinant of the module's circularity as desoldering a cell from a PV module is time consuming and can result in cell breakage. (Depuis et al., 2010; Depuis et al., 2011; Einhaus et al., 2018; Reinwand et al., 2018). Thus, ways of interconnecting cells alternative to the traditional FBC tabbing ribbon are explored here. Besides FBC, the literature review uncovered two interconnection

techniques: shingling and multi-wire interconnections. Multi-wire technology is mainly beneficial for module efficiency, but requires specialty components and tools which are not widely available to open-source makers (Walter et al., 2017). Shingling could be an interesting technique to boost module efficiency without needing specialty tools. However, the cut cells with passivated edges needed for shingling are not widely available through global merchants. Moreover, the ECA used to interconnect the shingled cells will make separation of the cells very difficult, resulting in low circularity. Thus, for a circular shingled module, further research is needed into reversible ECAs, dry ECAs, or for example magnetic connections. For now, FBC interconnections are still the most accessible and cost effective, with well proven quality. However, steps can be taken to increase the ease at which individual cells can be replaced during for example a repair. It would for example be possible to use magnetic interconnectors between the cells, or build modules like very large PCBs, where the cells can be plugged or soldered onto the backsheet. However, the downside of these approaches is that they introduce new costly components to the module. A more simple way to ease the replacement of single cells could be to have about 2 mm of loose tabbing ribbon at the extremities of each cell which are soldered together at the space between the cells. This ‘soldered FBC’ is illustrated in figure 5. The advantage of this is that it effectively interconnects the cells without introducing any new components and still makes it easy to disconnect a cell when needed. Furthermore, manufacturing can be streamlined by presoldering the cells, making the installation process of the cells into the module very straightforward.

*Figure 5: Side view of cell interconnection. A. shows the traditional method of interconnecting cells, with a tabbing wire running from the front of one cell to the back of the adjacent cell. B. shows the proposed soldered FBC connection method. Note that the thickness of the different components is exaggerated in this illustration.*

### **Frame and Outer Connectors**

For the finish of the module the main choice is between a framed or a frameless module. Frameless modules come at a lower cost, and have increased ease of remanufacturing (Mittag et al., 2015). Moreover, the downside of a frame is that it can cause a buildup of soil around the edges of the module, resulting in lower module efficiency and increased degradation (Ye et al., 2014). However, the benefits of a frame are the added mechanical integrity and protection of the module during transportation and (de)installation. Accelerated lifetime tests need to be carried out to decide whether a frame is needed. If a frame is not needed, frameless has the preference.

For the outer connectors, a J-box should be fitted. In case of a glass-glass module, a special edge-mounted J-box can be used to avoid the need for holes in the backsheet and potting to seal those holes. The disadvantage of this approach is that these edge J-boxes are less available through global merchants.

### **Sprint 1: Encapsulation**

The encapsulants tested use a double edge seal, with a butyl rubber thermoplastic spacer as well as a silicone blocking seal around the outside. The difference between the edge seal used by the TPedge and NICE research groups versus the edge seal used in this research is that this research applies a butyl rubber tape which is not filled with dessicant (Saint-Sernin et al., 2009; Mittag et al., 2017). Butyl rubber differs from PIB in that it contains minor amounts of isoprene (ca 1.5 mol%) whereas PIB is a homopolymer of isobutylene (Lewis, 2008). The advantage of this tape is that no extrusion equipment is needed to apply it, making it suitable for CBPP.

To test the significance of desiccants and oxygen absorbers, each of the two encapsulant designs were constructed with no desiccant or oxygen absorber, only desiccant, and both desiccant and oxygen absorber respectively. In addition, with the leftover material, one glass/polycarbonate encapsulant was constructed with both desiccant and oxygen absorber. For clarity, these encapsulants have been codenamed, as seen in table 5.

*Table 5: overview and codenaming of the encapsulants constructed in sprint 1*

	Glass/Glass	Polycarbonate/ Polycarbonate	Glass/Polycarbonate
Oxygen absorber and Desiccant	GG-DO	PP-DO	GP-DO
Desiccant	GG-D	PP-D	
No scavengers	GG	PP	

The encapsulants built have a size of 365mm by 365mm, as this is close to the maximum possible size for the climate chamber used in the damp heat test. The desiccant used is 2.5g of silica gel grains, crushed into a powder to fit the 1mm vertical space. According to the manufacturer, 1g of silica gel is enough to dehumidify about 1 liter of air. With an internal empty volume of about 0.1 liter, the amount of silica gel added would be enough to dehumidify the volume 250 times over. The silica gel used has the property to discolor from orange to green to indicate its level of moisture saturation. In addition, the silica gel is free of cobalt-chloride, heavy metals, or dimethylfumarat. The oxygen absorber used is 5g of Fe grains.

The butyl rubber tape used as an edge seal has a width of 20mm and a thickness of 2mm.. This is more than the recommended 15mm width used by Saint-Sernin et al. (2009) and Mittag et al. (2017). However, since these research teams used a desiccant-filled PIB, extra sealant will be needed to obtain the same results. Similar to Saint-Sernin et al. (2009) and Mittag et al. (2017), a silicone-based blocking sealant was used around the butyl tape to protect the butyl rubber from degradation induced by the outer atmosphere. This design results in adequate mechanical fixation between the front- and backsheet at room temperature.

During the construction of the minimodules, reopening was successfully attempted multiple times to assess the remanufacturability of an edge-sealed module using this type of sealant. Under the application of heat, the sealants increased in viscosity, resulting in a rather easy removal of the front sheet. However, significant amounts of excess sealant remained present on both the front- and back sheet. This proved rather difficult to avoid, even when using mechanical cutting. In addition, the deformation of the sealant during the opening process made the sealant material difficult to re-use directly.

In the initial design, a vertical plastic spacer with a thickness of 2 mm was used to create the space between the front- and back sheet. However, due to minute inconsistencies in the thickness of the edge seal, the use of this 2 mm spacer resulted in the presence of air bubbles between the front/backsheet and the sealant (see Figure 6). Thus, a thinner spacer vertical of 1 mm was used. However, the extra compression in the edge seal led to the seal flowing out sideways, partly flowing over the copper sheets and out of the sides of the module, reducing the space available for the silicone blocking sealant. Thus, the design of the modules with

cells should aim for a spacing of about 1.5 mm between the front- and back sheet, as well as the application of a sufficient margin between the edge seal and the cells.

*Figure 6: when using a 2 mm vertical spacer in combination with a 2mm thick butyl tape, a full seal cannot be achieved all around the module.*

The encapsulants consisting only of polycarbonate were found to be too flexible to hold solar cells without causing cracking of these. Thus, to use polycarbonate encapsulation for a PV module, an additional structural element should be added. Moreover, the adhesion between the polycarbonate and butyl rubber was not found to be sufficient. As a result, the polycarbonate encapsulants opened before 200 hours of DH testing, as can be seen in figure 7, and were thus considered to have failed. For this reason, the test with polycarbonate-polycarbonate encapsulants was ended at 200 hours, as can be seen in figure 8.

*Figure 7. De-adhesion and deformation of polycarbonate encapsulant following 200 hours of DH testing*

The copper oxidation and discoloration process of the control and the other encapsulants can be seen in figure 8. One mistake made in this research was touching the copper foil with unprotected fingers, which left fingerprints on the copper that only became apparent after the oxidation process. Thus, researchers using copper to test for oxidation should avoid touching the copper with bare hands.

Although the silicone sealant used as a primary seal is rated for use up to 120°C, it was found that after 200h of damp heat testing, this sealant became rather viscous, losing its mechanical strength. In addition, the butyl sealant becomes more viscous at higher temperatures. To maintain mechanical integrity in all cases and to protect the glass edges, an aluminium frame was added to the subsequent minimodules after sprint 1.

*Figure 8: All encapsulants before the DH test and after 200, 400, 600, 800 and 1000 hours of DH. The encapsulants using plastic had been taken out of the test after failure at 200 hours. The glass-glass encapsulants were photographed at 1000 hours next to untested copper for comparison.*

*Figure 9: The encapsulants inside the climate chamber.*

The results of sprint 1 show that the encapsulation built is not adequate to stop all oxidation, but forms a barrier against moisture ingress that should ensure a module lifetime of about 25 years. Furthermore, the desiccant and oxygen scavengers seem to reduce oxidation levels. Nonetheless, more work is needed to improve the quality of the barrier and deduce the expected module lifetime more precisely. Early attempts of re-opening the encapsulant showed that it is difficult to do so, and due to the adhesive and elastic properties of the butyl rubber, it is difficult to fully separate the material from the glass and re-use it without further processing. Furthermore, once applied, the silicone blocking sealant and the butyl rubber are difficult to separate, making recycling of these materials at high value difficult. Thus, when using these materials as an edge seal for circular PV modules, methods should be developed that allow for reusability of the edge seal after opening of the module for maintenance. Alternatively, other sealant materials or configurations can be explored that aid the reusability, but still satisfy the aims of being suited for open-source, being low-cost, and ensuring a long module lifetime. Some oxidation was observed on the copper inside the encapsulants, visible as slight discoloration. However, the level of oxidation on the copper encapsulated was much less than the oxidation on the control sheet. The highest level of oxidation was observed at the edges,

close to the butyl tape, as can be seen in figure 10. An extra benefit of the aforementioned EPDM O-ring that can be added to the inside of the butyl tape is that it would act as a third barrier for moisture and oxygen, further delaying the oxidation process of the module's internal components.

*Figure 10: GG-DO Close ups of the encapsulant edges at 600, 800 and 1000h.*

## Sprint 2: Interconnection

According to the morphological chart, soldered FBC interconnections are chosen as the optimal interconnection method to meet the research goals. As mentioned, the soldered FBC connection refers to an interconnection method where the tabbing wire is disrupted at the space between neighboring cells, and subsequently soldered together (see Figure 5). This interconnection method has the main benefit of allowing for easy disassembly of the module or replacement of a single cell.

The I-V characteristics of the minimodules with these two interconnection techniques show a minimal difference in current (see Figure 11). However, it should be noted that measuring the current at such low voltages is difficult and leads to inaccurate results. Although no significant difference in I-V characteristics were found, the soldered FBC interconnection was found to be much more prone to failure during assembly and handling.

*Figure 11: Top; I-V characteristics of the minimodule with soldered FBC connections.  
Bottom; I-V characteristics of the minimodule with direct FBC connections*

During sprint 2, the original design was iterated once to account for practical difficulties uncovered during the assembly process. The differences between the 2 iterations are summarized in table 6. In the first iteration of the minimodule, 2mm vertical spacing between the front- and the rear glass was used. This spacing was created by fusing two layers of 1 mm thick PETG plastic, with the bottom layer containing the desiccant and oxygen absorber. These two layers were laser cut to shape and fused using a dimethyl chloride as a solvent. For the edge seal, an extra amount of butyl rubber was added to provide enough thickness to seal the module with the 2mm spacer. This was necessary as the butyl tape itself has a thickness of 2mm with small inconsistencies, which when pressed did not allow for a complete all-around seal of the module. In the first iteration the cells were placed on top of a plastic pad, which held the scavenger. This underlying plastic pad melted during soldering of the interconnecting tabbing ribbons at the space between the cells. These interconnections were subsequently polluted with molten plastic. Additionally, multiple interconnecting contacts failed during the assembly process, and too small a horizontal margin for error caused problems when fitting the cells between the spacers located at the cell corners.

For the second iteration of the minimodule, a 1 mm vertical spacing between the front and the rear glass was used. This was achieved by using 1mm spacers lasercut from PETG plastic, and placed at the cell corners. The spacers were glued directly onto the glass. The desiccant and oxygen absorbers were added to the inside of the spacers instead of being placed in the bottom layer. Additions also included a 1 mm margin around the cells to ensure an easy placement of the cells, and the placement of small pieces of foam rubber to the back side of cells. These foam rubbers push the cells against the front glass, and their high friction coefficient allows for the cells to be held in place during the lifetime of the module.

*Table 6: comparison of the first and second iteration of the minimodule.*

<b>First Iteration</b>	<b>Second Iteration</b>
2mm spacing of front and rear glass	1 mm spacing of front and rear glass
Desiccant and oxygen absorber on bottom layer	Desiccant and oxygen absorber at cell corner spacers
No pieces of foam rubber	Pieces of foam rubber placed under cells
Extra amount of butyl rubber for edge seal	Single layer of butyl rubber for edge seal
Cells placed on plastic pad	Only plastic at the cell corners

Multiple minimodules were constructed using the second iteration described above, some with standard FBC interconnections, and some with soldered FBC interconnections. To observe the effect of assembly on the integrity of the interconnections, EL testing was done before and after this. The EL test results showed disconnection of the soldered FBC interconnection after assembly on multiple occasions, and this was likely for various reasons. First, manual soldering resulted in a difficult soldering position, further complicated by the fact that the wires are suspended about 0.8 mm above the back glass. Second, the area of contact is around 2 mm<sup>2</sup>, making for a very small surface to work with. Third, manual soldering inevitably creates inaccuracies and inconsistencies, which, even when occurring at a low rate, will cause failure of numerous modules in larger production batches.

Based on the early results of the encapsulation testing, an aluminium frame was added to the minimodule. The frame was constructed out of 15mm U-profile aluminium cut to the size of the module at angles of 45°. The inner dimension of this aluminium profile is 12mm. As the glass panes are 4mm, and the space between them 1mm, that leaves a 3mm gap between the glass and the profile. This gap was filled using small plastic spacer rings that fit snugly inside the gap and are held in place by both the pressure, and the primary silicone sealant, which is applied on the inside of the frame before its mounting on the module. The use of such a frame has two primary advantages: it maintains the mechanical connection between the front and back sheet, protects the glass edges, and it allows for the application of a greater amount of the primary silicone sealant.

In sprint 2, it was found that the soldered FBC interconnection method, found to be ideal in the morphological chart methodology, was difficult to apply in practice as it led to multiple failed interconnections. Nonetheless, this interconnection method was further tested in sprint 3 to examine whether it could still be interesting to explore this new interconnection further, since it does increase the ease of disassembly. A major unexpected finding of sprint 2 was the iteration on the plastic spacers acting as vertical placeholders between the front- and rear glass, and horizontal placeholders between the cells. The second iteration of the spacer design led to a much more elegant solution, requiring much less material.

### **Sprint 3: Performance**

In sprint 3, a four-cell minimodule was constructed with the goal of testing the module's resistance to moisture ingress over time. The test was carried out in conjunction with the ongoing 1000h encapsulation tests, and ran for about 750 hours. In this module, the above-mentioned soldered FBC interconnection technique was used where the wires are soldered together at the space between neighboring cells. After the DH heat test, the minimodule showed

no visible discoloration of the cell metallization (indicating oxidation) nor discoloration of the desiccant, which has the property of turning green after saturation with moisture. In figure 12 the EL images of the modules can be seen. After the stringing of the module, a slightly darker area can be seen on the bottom-right cell, indicating a contact with higher resistance. After assembly, this dark area became more pronounced, indicating that the quality of the contact had reduced. After 750 hours of damp heat, the contact was fully disconnected. In addition, two contacts between the bottom left and top left cell were compromised. This may have occurred due to the thermal expansion of the module's components or due to shocks and vibrations inflicted during transportation.

*Figure 12: EL imaging of a 4-cell minimodule, using soldered FBC interconnections. Left; the module before the final assembly, Middle; the module after final assembly. Right; the module after 750 hours of damp heat testing.*

In figure 13, the I-V curve of the minimodule before and after pressing can be seen. Short circuit current was measured to be slightly lower after the assembly. However, as mentioned, measuring the current at such low voltages is difficult and leads to inaccurate results. Since multiple contacts in the module turned out to be disconnected at the final EL test, an I-V curve of the module after DH was not measured since the result could not be used to compare the performance of the minimodule before and after the DH test.

*Figure 13: Top; I-V characteristics of the minimodule with soldered FBC connections before pressing. Bottom; I-V characteristics of the minimodule with direct FBC connections after pressing.*

Sprint 3 showed that the soldered FBC interconnection technique, as applied here, is too unreliable for use in open-source PV modules. Moreover, even when reliable solder joints can be created, the modular interconnection technique introduces another failure mode at an already vulnerable part of the PV module (Kutter et al., 2018; Schiller et al., 2019; Ndiaye et al., 2013).

## Sprint 4: Full scale module

For the execution of sprint 4, which consisted of the construction of a full-scale module, some of the original design choices as described in the morphological chart were altered (see table 4).

First, the method of using 1mm-thick spacers at the corners of the pseudo square cells as used in the second attempt of assembly was used. This is because it has the benefit of using less plastic than when a plastic pad is added underneath the cells spanning the whole module area.

Second, the spacers were not used to hold the oxygen and moisture scavengers, as was the case in the minimodules. Instead, the scavengers were added in sachets at a non-active area of the module, namely the 15mm-wide space on the top of the module where the bus wires connect the cell string to the junction box. Separating the scavengers from the spacers reduced the complexity of module assembly and part production.

Third, as with the minimodules constructed as a second iteration in sprint 2, the cells were held onto the front glass by small pieces of foam rubber placed on the back of the cells. However, as opposed to the minimodules, the 24-cell module was assembled with the cells facing



downwards, which allowed for a more straightforward placement of the rubbers, as well as making the soldered interconnection between the cells and the bus wire easier to make as the vertical space between the wire and the glass had been eliminated. The small pieces of spacer rubber were placed at both corners and in the middle of the cell, at the position of the tabbing wires, similar to the placement of cell holders by Mittag et al.(2015) and Mittag et al. (2017) (see figure 14)

*Figure 14: small pieces of foam rubber were added on the rear side of the PV cells to press them against the front glass and hold them in place.*

Fourth, the soldered FBC interconnection method tested in sprint 2 and 3 was abandoned in the creation of the large-scale module, as too many interconnection failures were observed over the course of sprint 2 and 3. Due to the limited temporal scope of this research, no other modular interconnection methods were tested. Instead, the 24-cell module was interconnected using conventional FBC stringing.

Finally, a JB was added to this module. Rather than adding holes to the back glass, the bus wires were passed through the edge seal. Since an edge-mounted JB was difficult to find commercially, a normal, back-mounted JB was used. A shrink wrap was added around the external bus wires (sticking through the edge-seal) and these were folded around the rear glass inside the frame so as to stick out of the frame on the back side of the module. Two small slots were made on the side of the JB so the bus-wires could pass through the side of the rear-mounted JB. These slots were then potted together with the potting of the entire JB (see figure..)

The construction of the 24-cell module took around 16 hours. The full process of build is described in appendix 1 as part of the open-source documentation of the circular PV module. In summary, the construction consisted of

1. Pre-soldering the cells
2. Preparing the front glass with spacers
3. Stringing the cells
4. Testing the string for cracks and failed connections
5. Adding the rubber pieces on the back of the cells (see figure 14)
6. Adding the desiccant and oxygen absorber sachets
7. Applying the butyl tape seal
8. Mounting the back glass
9. Pressing to create a complete seal
10. Applying the frame and silicone blocking seal
11. Mounting the JB
12. Final testing

Some of the challenges observed in the manual assembly included the breakage of multiple cells and unreliability of various solder joints. For example, when a tabbing wire twisted or bent during handling, it became very difficult to solder properly. These faults were resolved after preliminary tests, during which EL was repeatedly carried out before the module was sealed to indicate and repair failures or cracks in cells which needed to be replaced to create a high-quality module.

Testing using EL prior pressing of the module indicated no cracks nor failures in any of the cells. However, testing using EL following the pressing showed one cell with cracks, and one cell area with slightly less luminescence, likely as a result of a failed solder joint (see figure 15). It should be noted, however, that a dark area in the cell does not automatically mean a

lower yield, rather it indicates that the charge carriers are drawn to the neighboring cell areas. These failures can be either a result of the pressing process, or the result of shocks and vibrations inflicted during the transportation and handling of the module between subsequent tests.

*Figure 15: Top; EL image of the 24-cell module, before pressing. Bottom; EL image of the 24-cell module, after pressing. After pressing, one crack and one failed contact occurred*

Another unforeseen problem that occurred after the closing of the module is that some of the Fe grains in the oxygen absorber sachet leaked onto the active area of the module. Therefore, makers should be careful to perforate the sachet in a way that prevents leakage of the sachet contents.

The results of sprint 4 mainly highlight that the manual assembly of PV modules is a highly labor intensive process, which will remain the case even after learning, task division and batch production lines. Moreover, manual assembly introduces many inaccuracies which can be prevented through the use of machines. Therefore, besides the development of open-source circular PV module concepts, the development of supplementing open-source turnkey equipment is needed, as also highlighted by Buitenhuis & Pearce (2012). Further work on the module should include experimentation with other modular interconnections, that ease dis- and reassembly without cell breakage. Furthermore, module size should be further increased to the more conventional 60 and 72 cell architectures. In this case, bypass diodes should be added which can fit within the vertical space between the front- and rear glass, or this space should be enlarged.

## 5. Analysis

Based on the results presented in the previous chapter, this chapter will analyze to what extent the presented design meets the research objectives, namely a high module efficiency, a low LCOE, good quality, high circularity, and high suitability for open-source

### Module Efficiency

According to the I-V curve measured in sprint 4, the 24-cell module has a total efficiency of 13.5% (see Appendix 2). According to the datasheet of the cells used, their efficiency is 20.4% (see Appendix 3). This equates to a CTM efficiency of 66%. This is very low compared to the CTM efficiency of conventional PV modules. This low CTM efficiency can be attributed to a range of factors, which will be discussed here.

First and foremost, as can be seen in the EL imaging, the 24-cell module showed one crack and one disconnected contact. The resulting power dissipation, especially in the last cell of the string will have a significant negative impact on the output power, which is further exacerbated by the fact that the module does not have any bypass diodes. The benefit of the module design is that these failures can be repaired by opening the module and replacing the broken cell and resoldering the failed contact. However, improvements to the design and production method are needed to avoid such failures during transportation and pressing.

Related to the last point, the manual soldering of cells may introduce inconsistencies and low-quality contacts which may result in a higher shunt resistance than usual. In this module a shunt resistance of 240 ohm per cm<sup>2</sup> was measured, resulting in a FF of 71.7%.

Once a design and production method are available that yield reliable module quality, the issue of reflectance and refraction at the front of the module should be addressed to further increase CTM efficiency. Solar glass with an ARC should be used to reduce reflectance. In addition, with glass-glass modules, the thickness of the front glass can be further reduced from 4 to 2 mm. Furthermore, as explored in the morphological chart. Edge-sealed module designs are needed that achieve better optical coupling between the front glass and the cells to reduce refraction losses, without giving up on circularity.

Another factor that may have played into the low CTM efficiency, is the age of cells used. The datasheet of the cells warns the user to avoid exposing the cells to the air, and using the cells ASAP after unpacking. However, the cells used had been unpacked for an unknown period of time at the moment of assembly (see Appendix 3). Therefore, to obtain a more accurate number for CTM efficiency, the I-V measurement should have been performed on the cell string without the front sheet.

## LCOE

To evaluate the effects of the redesign on LCOE, a couple of major factors of the LCOE calculation are evaluated. These are, the investment expenditures or capital expenditures needed to build the module, the operations and maintenance expenditures, and the expected lifetime. Another important factor is energy generated yearly, but this has already been covered under module efficiency.

By summing the price indications of the BoM, a total material price of €110.87 is reached (see appendix 1, see Figure 16). This excludes value added taxes. The main cost drivers are the glass, cells and metal frame at 44%, 30% and 12% of the total price respectively. To save costs, as well as module weight and material, thinner glass should be chosen. Currently the glass thickness of both the front and back-sheet is 4 mm. This can be reduced to 2 mm as shown by Mittag et al. (2017). The reason why 4 mm glass was chosen for this prototype is because it was the only low-iron tempered glass available within the temporal scope of the study. After the glass, the cells are the main material cost, which can be slightly lowered when ordering in large quantities, but will remain the largest cost driver when all else has been optimized. Although this module used an aluminium frame, work towards a frameless module could reduce the costs even further.

*Figure 16: material cost breakdown for one 24-cell open-source PV module, based on price indications for all components (see appendix 1)*

Besides material costs, labor cost will be a major cost driver. As mentioned, the construction time could be somewhat reduced through learning, task division and batch production, but labor will remain a major cost. Rather, work should go towards outsourcing or automating part of the production process. For example, the cell presoldering, which takes up the largest part of the assembly process could be outsourced by purchasing pre-soldered cells. However, the commercial availability and choice of pre-soldered cells is much lower than that of unsoldered cells. In terms of automation, work could go towards open-sourcing some of the turnkey equipment needed to produce PV modules, as also suggested by Buitenhuis & Pearce (2012).

Based on the DH tests performed, it is expected that the module will have a functional lifetime of >25 years in humid climates, and a longer lifetime in dry climates. However, more testing is needed to examine the exact effect of the observed level of oxidation on the degradation of the cell performance. During the assembly process, it was observed that a

small-scale production method with little automation leads to inaccuracies and flaws in the production, which could lead to premature failure of the module. The benefit of this module design is that a failed module could be repaired if this would be the case, but the production process should be further developed to minimize faults as to reduce the operations and maintenance expenditures over the lifetime. The benefit of the module design is that the lifetime can be extended through refurbishment. However, it is uncertain whether the components used and the overall design will still be relevant at the module's EoL. Therefore, it is important for future iterations of the design to take into account the predicted future developments in the PV industry. If components turn out to be obsolete at the module's EoL, they may perhaps yield some salvage value through recycling, which would further lower the LCOE.

## Quality

As mentioned, the DH test showed that the encapsulation is likely to be adequate for a lifetime of >25 years in humid climates. As no TC test was performed, it is difficult to say with certainty whether the encapsulation would withstand TC. However, since both the front- and backsheet are made of the same material, these expand and contract at the same rate. Furthermore, the integrity of the edge seal over a long lifetime with many thermal cycles has been shown both by the insulating glass industry, as well as by Mittag et al. (2015) and by Depuis et al. (2010) in their edge-sealed PV modules.

Furthermore, the conventional FBC connection used in the 24 cell module has been tried and tested in TC tests throughout the PV industry. If, in future iterations of the open-source circular PV module a more modular interconnection technique besides the soldered FBC technique tried in this research will be applied, TC will be the most critical test to validate its integrity.

Other tests, such as mechanical load and hail testing should be no problem for the 24cell module as it has a front- and back- sheet of 4mm tempered and hardened glass.

## Circularity

To evaluate the module's circularity, the results are analyzed with a focus on the module's ease of dis- and reassembly, the ease at which components and materials can be separated from one another and re-used, and the amount of different materials used. Furthermore, according to the circular design strategies proposed by Bakker et al. (2019), circular PV modules should be evaluated according to design for product attachment and trust, standardization and compatibility, and upgradability and adaptability.

During the research, the encapsulations built were opened and closed multiple times. The opening of the module is fairly easy when the edge seal is heated. The recommended method for breaking the edge seal is to cut it using a hot knife. Once the module is opened, cells or wires can be replaced by desoldering them at their front- or back contact. The FBC interconnection method has the disadvantage that the adjacent cell also has to be desoldered, which is not ideal since desoldering- and resoldering it may result in breakage of the cell. Thus, in future iterations of the circular PV module, more modular interconnection techniques such as those proposed in the morphological chart (plugs, magnets, clips) should be explored. The ease of separation of the spacers, scavengers and junction box from the glass will depend on the strength and amount of adhesive used to fixate these parts. For these parts, an optimal glue strength and amount should be found to adequately fixate them during the module lifetime, while still making them easy to remove during disassembly. For the

junction box the level of adhesion needed will be more. The rubber pieces holding the cell are not fixed, meaning they are the easiest to replace if needed. Holding the cells in place without adhesives makes this module design unique in literature, as cells can be removed through desoldering only.

Material separation will be easiest for those isolated materials which are not adhered to other materials. Difficult to separate materials are the glue used to fixate components to the glass and the butyl rubber and silicone sealant used which adhere to each other, to the glass and to the aluminium frame. This adhesion is good for module durability as it renders mechanical stability, but it complicates material separation. This complexity also entails that the resulting material flow will be difficult to re-use without preprocessing. Metal separation from the module will also be difficult as all metals are soldered together or deposited onto the cells as BBs and fingers. Thus, specialized recycling processes are needed to extract the metals from EoL modules and wafers. Besides metal, these recycling processes could yield PV-grade Si as the cells have not been polluted with EVA or other adhesive encapsulant plastics.

The open-source circular PV module uses a range of materials, similar to those used in conventional PV modules. To reduce the amount of different materials and thereby facilitate recycling, the plastic parts of the module could be made of the same plastic, for example PE or PP. Furthermore, a frameless design would further reduce the amount of materials needed. Finally, the glass requirement could be reduced by switching to thinner glass.

In terms of the circular design strategies for products in the growth stage, as proposed by Bakker et al. (2019), mainly design for dis- and re-assembly, standardization and compatibility, as well as upgradability and adaptability are applied. Design for dis- and re-assembly has been covered above. Besides this, the module uses standard components which are widely available today. Given the future developments of the PV industry, as covered in the literature review, some components could become outdated and unavailable during the module lifetime. For example, the M2 wafer size is seeing less and less use (VDMA, 2020). To ensure that spare parts will be available over the module lifetime, future iterations of the open-source circular PV module should take into account predicted future developments. Using such state-of-the-art parts however, is limited by the commercial availability of such parts. In terms of design for upgradability and adaptability, the module could, for example, easily be upgraded with a new string of cells, when the current cells become outdated. In addition, an active semi transparent cell layer (e.g. perovskite or dye sensitized PV) could be added to the front glass, creating a 4T multijunction module. Design for product attachment and trust was less of a focus in this research, because the functional aspect of the product was prioritized over the form and user experience. However, taking experience from the examples named by Bakker et al. (2019), a timeless design, using basic forms and shapes, and a uniform look should be aimed for in the future iterations of the open-source circular PV module.

## Suitability for Open-Source

Finally, the suitability for open-source according to the standards set by OSHWA (n.d.). In terms of design, these standards mainly lay focus on the accessibility of materials and components, and the amount of specialty equipment needed. In the design of the module it was made sure that all components are commercially available worldwide by checking whether they are listed on alibaba.com. However, this research does not recommend any specific merchant and recommends to use locally sourced or even reused materials and components where possible.

Moreover, all the tools used in the construction of the 24-cell module should be available to makers worldwide, or commercially available at low capital cost. The large press is a more niche tool, but a press could easily be improvised using, for example, wooden boards and a heavy weight.

The requirement for tools and components to be commercially available was the main constraint in the design. As can be seen in the morphological chart, in some cases a sub-ideal design choice was made because the more ideal design choices were not suitable for open source. For example, butyl tape was chosen although extruded desiccant-filled PIB may have formed a better seal, because the extrusion equipment needed for hot-melt PIB is not commercially available at a low capital cost.

## 6. Limitations, Discussion & Conclusion

### Limitations

This research was limited by multiple factors, which explain the missing information needed to fully answer the research question. First and foremost, there is the limited capabilities, limited knowledge, and any unconscious bias on behalf of the author, which may have influenced the results to some extent. Therefore, repeated reproduction of the research methods is needed to increase the legitimacy of the results. Second, the research was carried out under a limited temporal scope which did not allow for a repair of the 24-cell module, carrying out a TC test with minimodules using the climate chamber previously used for the DH test, or exploring any of the other aforementioned directions for further research. Third, the research was limited by the availability of material and test equipment such as magnesium, functioning climate chambers, climate chambers large enough for the 24-cell module or spectrometers. That being said, a great deal of manufacturing equipment was available for use at the university. However, the research aim of suitability for open-source limited the use of manufacturing equipment and components to those commercially available at low capital costs only.

### Findings

This thesis has presented a redesign of the conventional PV module that incorporates both circularity, and open-source with low-capital, local (re)manufacturing. The fixation method of the cells using rubbers and spacers only makes this design for repair and remanufacturing unique, as previous work mostly focuses on design for recycling. The results show that simultaneously incorporating low LCOE, high efficiency and high quality is very challenging. Especially manual soldering introduces difficulties as it leads to inconsistencies, faults, impurities and cracked cells. In addition, it greatly increases the labor time which increases LCOE. Therefore, where available at a reasonable price point, pre-soldered cells should be used in this design. Based on the results and the research objectives, multiple other design adaptations have been suggested.

First, the results suggests reconsidering the frame as part of the module design. The benefit of the frame is that it protects the glass edges (as well as protecting people from the glass edges) and that it ensures mechanical stability at high temperatures, since these temperatures make edge seal materials become viscous. The downsides of a frame are that it increases module costs, increases the use of virgin material, can cause soil buildup on the module, and leads to

a less uniform look. The last point is important for circularity, given the design requirement of design for attachment and trust. In addition, previous work on edge-sealed glass-glass modules has shown the virtues of a frameless design.

Second, the research suggests using more modern cells, such as the M6 size, and PERx architectures since it will facilitate the availability of suitable spare parts over the module lifetime. Other benefits of modern cell designs are increased cell efficiency and larger active area. In addition, the glass-glass design warrants the use of bifacial cells to further increase efficiency.

Third, the research suggests using a modular interconnection technique that allows for easy replacement of single cells without the need for desoldering the cell, as well as the adjacent cell, as is the case with the conventional FBC interconnection technique. The soldered FBC interconnection technique explored in this research was found to be unsuitable due to its high susceptibility to failure. However, as explored in the morphological chart, other modular interconnection techniques are possible that would allow for the easy replacement of a single cell.

Fourth, the research suggests adding an EPDM o-ring as a third edge-seal. EPDM is an often used rubber for outdoor applications and it can stop the horizontal flow of the butyl rubber, which requires a significant margin around the edge to prevent pollution of the cells. The EPDM would also act as an extra barrier to oxygen and moisture, and is easy to remove as it is a solid, non adhesive material.

Fifth, focus should be on the front of the module, in improving the absorption of light into the front glass and overcoming the issue of refraction losses in the interface of glass-gas inside the module. To reduce reflection, commercially available ARCs could be applied, such as those found on television screens and shopping windows. However, their long-term durability in outdoor environments is questionable. In addition, this newly introduced material will in some cases be difficult to separate from the module, and in most cases be difficult to recycle at a high value.

Sixth, the results suggest using a thinner glass of 2 mm for the front- and backsheets, as this reduces weight and costs and does not compromise the mechanical integrity of the module to a critical extent.

One of the main additions to PV module research presented in this paper is the use of vertical spacers between the front- and rear sheet of the module. The benefit of such spacers is that they create a direct connection between the front- and back sheet, theoretically transferring the force of a frontal impact, directly to the backsheet rather than onto the cells. This could be especially beneficial when using more flexible, lightweight materials as a front sheet. However, the effect of mechanical impacts such as falling hailstones needs more testing to verify this theory. Moreover, the space between the cells and the rear glass creates an added level of thermal insulation, leading to potentially high internal module temperatures which reduce module efficiency. Thus, when continuing the development of such vertically spaced modules, methods should be found for thermally coupling the cell rear and the module back/front sheet. Perhaps such thermal coupling could even be achieved in conjunction with optical coupling through the use of, for example, an electrically insulating liquid inside the module, as was suggested in the morphological chart. Alternatively, the waste heat from the cells could be actively reused in a PV-thermal configuration.

With these considerations in mind, it is theoretically possible to come to a design that makes trade-offs between the different research objectives, reaching an open-source circular PV module that also has a high quality, low LCOE and high efficiency. However, besides improving design, attention should also be paid to improving the production process.

Out of the research objectives, suitability for open-source turned out to be the main technical constraint in the design, since many design choices were limited by the commercial availability of parts and equipment. Moreover, it is still uncertain what the added benefit is of open-sourcing PV module technology on the level of the energy system. As PV modules are subject to increasingly high requirements on price and quality, a highly labor-intensive production process is certainly not suitable for a commercially competitive PV module design. However, the open sourcing of such a design may have other benefits, as it can stimulate learning and innovation in the field of PV energy. Besides this, the open-sourcing of a PV module design can be an end on its own, to advance technological sovereignty, as described in the introduction. Finally, the design could be further developed into something that is commercially competitive, in conjunction with a highly automated production process that can be easily scaled to produce larger volumes of PV modules. As with the module design, this production process and accompanying turnkey equipment could be open-sourced as well, to further advance technological sovereignty and stimulate fast innovation in the field of PV energy.

## Discussion and Directions for Further Research

Besides the aforementioned, multiple other directions for further research have been identified throughout this research. First of all, the effect of thermal cycling on the module design proposed here needs to be investigated to gain certainty about its durability in outdoor environments over an extended period of time. Second, further research should put more focus on the form factor of the design, rather than purely the functional aspects, as form was found to be an important circular design requirement for products in the growth stage. Third, the effectiveness of the moisture absorber and oxygen scavenger in creating an inert atmosphere should be further explored, for example through gas spectrometry. Third, the potential for upgrading the module during the module lifetime should be further explored, both from a technical feasibility standpoint, as well as from an economic feasibility standpoint.

In addition, further research could be carried out into plastic encapsulations, which have the benefit of generally having a lower cost, a lower weight and a lower carbon footprint. Plastic encapsulations could be welded at the edges, creating a monocoque encapsulant, existing of one single material. This would also give the designer more freedom to work with alternative shapes and forms. The downside of using plastic is that the material is generally less resistant to outdoor conditions than glass, but some plastic types exist with excellent UV-resistance, high impact resistance and low moisture and oxygen transmissivity.

## Conclusion

This research set out to present a way in which the cost, environmental impact and social impact of PV energy production could be reduced. An encapsulation method was developed that can contribute to reducing PV waste and closing the material loop on PV, as it allows for recovery of intact PV cells and other components. Moreover, the construction of the presented PV module can be carried out by anyone with access to basic skills, components and tools. This allows for the development of a more distributed manufacturing system which



reduces dependency on carbon-intensive and exploitative PV module manufacturing. As mentioned, more work is needed to reach these objectives, but this research can be viewed as a first building block, upon which many more can be laid.

## Appendix 1: Open-Source Documentation

### How-to

Welcome to the instruction for building the second prototype of the circular PV module. This how-to will cover all of the steps required to build the module, and go over some improvements and lessons for the next prototype. This version is a working prototype, but still needs improvements in build quality and production method. The prototype has 24 cells, which should amount to around 12V.

### Materials Needed

Category	Description	Price Indication
Front Sheet & Spacing		
Glass	2* Low iron, high transmittance tempered glass. 4*1038*698 mm (2 or 3 mm glass is also possible)	€48.50
Spacers	1*120*70mm PETG sheet	€0.50
Electronic components		
Cells	24 FBC cells, 157*157mm.	€32.81
Wiring	About 1.30m of bus wire, 60m of tabbing ribbon, 10cm of 4 mm shrink wrap, lead-free solder and a flux pen	€5.00
Junction Box	PV junction box with one diode	€5.00
Seal		
Primary Sealant	Silicone blockseal caulk tube for use with glass and butyl	€2.10
Secondary Sealant	Butyl tape roll 20*2 mm	€2.65
Glue	Glue suited for glass and plastic	€0.05
Inert atmosphere		
Moisture absorber	10g of silica gel ground to a powder	€0.17
Oxygen absorber	20g of Fe grains	€0.40

Grip seal bags	2*, about 10*20 mm	€0.04
Frame		
Frame Metal	Aluminium 15mm U profile, about 3.6m	€13.60
Frame Spacers	Plastic spacer rings of various sizes between 0.5 and 3mm	€0.05
	Total Price Indication	€97.22

Keep in mind that the price is indicative and varies highly based on where you order components from and to and the quantity of the order.

## Tools Needed

To build the module, you will need access to a laser cutter or jigsaw; a saw suited for aluminium; a soldering station with a soldering iron, pliers, wire snippers, a heat gun, a multimeter and a benchtop power supply; a caulk gun; a large press; and a camera with an infrared filter.

## Construction Method

### Step 1: Pre-soldering the cells

Use the pliers to stretch the tabbing wire while unrolling it, and cut wires large enough to cover the front contacts of the cell, as well as back contacts of the adjacent cell, with a 4mm space in between (308 mm). Solder these wires onto 20 cells. While soldering, hold the cell flat and be careful not to crack the cells with high pressure or heat. Four cells will have shorter front contacts, as they are connected to the bus wires on the top and bottom of the module.

*Pre-soldered solar cell.*

### Step 2: Preparing the front glass

Cut the spacers out of PETG according to the svg file attached, clean one of the glass panes and glue the spacers at the intersections on the following grid:

*Laser cutting pattern for the spacers*

*Grid Layout for placing the spacers*

### Step 3: Stringing

String your cells according to the following circuit diagram, laying them face down on the glass pane. Have the bus wires stick out in the middle at the top of the module. The bypass diode will be added later when the module is connected to the junction box.

*Circuit Diagram of the PV module*

#### **Step 4: Preliminary Test**

Once all cells are connected in series, test the module for cracks or disconnected contacts using electroluminescence. I placed the glass on supports and photographed the cells from underneath in a dark room. Carry out repairs if needed and repeat the test.

*One of the EL pictures taken from underneath the module to test for cracks or disconnections*

#### **Step 5 Adding the rubbers**

Lay down pieces of rubber on each cell at the corners and in the middle, on the tabbing wire.

*Small pieces of rubber placed on the back of the cell to hold the cells against the front glass*

#### **Step 6: Adding the oxygen and moisture scavengers**

Glue the sachets of oxygen and moisture scavenger onto the glass at the top of the module, in the spacing between the butyl tape and the cells, where the bus wires connect to the junction box.

#### **Step 7: Adding the secondary edge seal**

Add butyl tape around the edge of the module. At the bus wires, lay the butyl tape under the wire and stick a bit of butyl rubber over the top, so the wire is covered with rubber on all sides

*The bus bar wires going to the junction box, surrounded by butyl rubber on all sides.*

#### **Step 8: Adding the back glass**

Clean the other pane of glass, perforate the moisture and oxygen scavenger sachets and lay the glass on top of the assembly, carefully aligning the two sheets of glass

#### **Step 9: Pressing**

Once the top glass is on, press it down to create a tight seal all around. I used an industrial press, but you can also use heavy weights for example. It is a good idea to use foam blocks or wood on both sides of the module to protect the glass from damage. Pressing works best if left for a couple of minutes, letting the rubber slowly flow out. Check whether a full seal is achieved all around. Otherwise, repeat the pressing step. If a full seal cannot be achieved, extra rubber can be added by pushing it in from the side.

#### **Step 10: Adding the frame**

Cut a frame out of the aluminium U-profile by cutting it at an angle of 45°, with about 3 mm extra on all sides. Add shrink wrap to the two bus wires sticking out of the top of the module. Fold the bus wires around the back glass to the back of the module. Fill the pieces of U-profile with silicone sealant and apply it to the edge of the module. Jam spacer rings between the U-profile and the back glass at each corner to cover the leftover space. Besides acting as a primary seal, the silicone also adheres the frame to the glass.

*Left: Silicone sealant added to the inside of the frame. Right: the frame stuck to the module, with spacer rings between the frame and the module rear.*

### Step 11: Adding the junction box

Cut two small grooves in the side of the junction box to let the bus wires in.

*Grooves added to the junction box, for passing the wires through*

Feed the bus wires through the grooves, glue the junction box onto the glass and solder the bus wires onto the contacts of the junction box. I used a weight to hold down the junction box while the glue was setting. If you are not sure which bus wire is positive and which is negative, you can use a multimeter and check the voltage. Finally, add silicone sealant around the edge of the junction box.

*Left: Bus bar wires fed through the slots in the junction box and soldered to the contacts.*

*Right: A weight placed on top of the junction box while the glue is setting.*

### Step 12: Final Test

Once the glue and the silicone sealant has set, add some connector wires to the junction box and close it. Next, carry out the electroluminescence test again to verify the module is in good working order.

## Appendix 2: 24-cell Module I-V Parameters

## Appendix 3: Datasheet of the PV Cells Used

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