Lund University, Faculty of Engineering
Thesis for the degree of Master of Science

PV module type qualification

A review of different technologies from a reliability perspective

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Abstract

More solar power plants are being built than ever, and the number only seems to be increasing for every year. The photovoltaic modules used in these plants are manufactured and installed today with an estimated lifetime of a minimum of 25 years; 25 years of constant exposure to various weather conditions and 25 years of expected power production. As 90 % of all installed PV modules are less than 10 years old, it is impossible to know how today's technology will perform after 25 years. To ensure that the modules can endure time and field exposure to produce as much energy as possible during their lifetime, it is important to consider reliability and durability when designing PV modules.

The aim of this thesis was to compile knowledge about and analyse how different technologies used in PV modules affect their reliability. Additionally has a prequalification process that assesses the reliability and durability early in a project been evaluated. This was through a literature review where scientific articles, test results, and field reports were compiled and the combined information analysed. The module properties of back cover, cell technology, frame, interconnections, module and wafer size, and encapsulant were concluded to affect the module reliability. All properties have different design alternatives that can be used, which all have advantages and disadvantages concerning reliability that can be further assessed through tests. Additionally, some technologies are more compatible with each other and perform better in certain conditions. To be aware of and minimise reliability problems with PV modules, reliability and durability should be a factor when deciding on PV module type for a PV power plant, and this could be evaluated through tests and a technology assessment.

Sammanfattning

Det byggs fler solenergianläggningar än någonsin, och det är en utveckling som ser ut att fortsätta under de kommande åren. Solcellsmodulerna som används i dessa solparker produceras och installeras idag med en beräknad livstid på minst 25 år; 25 år där de förväntas producera elektricitet och samtidigt vara konstant utsatta för varierande väderförhållanden. 90 % av alla installerade solcellsmoduler är idag mindre än 10 år gamla, vilket gör det omöjligt att veta hur dagens teknik kommer att prestera om 25 år. För att solcellsmoduler ska producera så mycket elektricitet som möjligt under sin livstid är det viktigt att de kan stå emot slitage, ett sätt att arbeta för detta att designa för tillförlitlighet och beständighet.

Syftet med detta examensarbete var att sammanställa kunskap om och analysera hur olika tekniker som används i solcellsmoduler påverkar deras tillförlitlighet. Vidare har en kvalificeringsprocess som undersöker tillförlitlighet och beständighet tidigt i ett projekt utretts. Detta genom en litteraturstudie där vetenskapliga artiklar, testresultat och driftrapporter har sammanställts och den sammanlagda informationen analyserats. Följande attribut hos en solcellsmodul fastställdes påverka modulens tillförlitlighet; baksida, typ av celler, ram, sammankoppling av celler, storlek på modul och cell, och inkapslingsmaterial. Alla attribut har olika designalternativ som används i industrin idag, vilka alla har olika för-och nackdelar som kan undersökas ytterligare genom olika test. Vidare är vissa tekniker mer kompatibla med varandra och fungerar bättre i vissa förhållanden. För att vara medveten om och minimera problem med tillförlitligheten hos solcellsmoduler borde tillförlitlighet och beständighet vara en faktor när beslut tas om typ av solcellsmodul för en solcellspark, och detta kan undersökas genom olika test och utredning av olika tekniker.

Nomenclature

a-Si Amorphous Silicon

BOM Bill of Material

c-Si Crystalline Silicon

CdTe Cadmium telluride

ECA Electricallty Conductive Adhesive

EL Electroluminescence

EPE A three layer encapsulant of EVA-POE-EVA

EVA Ethylene Vinyl Ecetat

FEM Finite Element Method

GWp Giga Watt peak, maximum power output

HIT Heterojunction with intrisic thin layer

HJT Heterojunction

IBC Interdigitated Back Contact

LETID Light and Elevated Temperature Induced Degradation

LID Light Induced Degradation

MBB Multi busbar

NREL National Renewable Energy Lab (USA)

PERC Passivated Emitter and Rear Contact

PID Potential Induced Degradation

POE Polyolefin Elastomer

PV Photovoltaic

PVEL Photovoltaics Evolution Labs

RETC Renewable Energy Test Center

SJH Silicon heterojunction

TCO Transparent Conductive Oxide

TOPCon Tunnel Oxide Passivated Contact

TPO Thermoplastic Polyolefin

UV radiation Ultraviolet radiation

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1 Introduction

Photovoltaics is a field under fast development as the interest in electricity production through solar power is large and rapidly increasing. While new technologies are being developed and launched it is necessary to ensure their quality to maximise their performance. The PV modules should be able to produce power for a lifetime of over 25 years while enduring the effects of time and varying weather conditions, which requires reliability and durability (IEA 2017). This is beneficial for the module owners, the electricity users, and also from a climate perspective as longer lifetimes mean less module production, though it is not necessarily prioritised by manufacturers (Gottschalg 2019).

All technology ages, and in the datasheet for a PV module are its expected annual degradation in power output specified. However, as the large scale PV industry is relatively new and constantly developing new technologies, are these degradation rates only assumptions; the manufacturers can only estimate how their modules will perform 10, 20, or 30 years from their production date. Therefore are tests and research crucial for making these estimates as reliable as possible, as well as a thorough quality assurance process to investigate the quality of the modules throughout their lifetime by finding signs of failures before they occur. (ibid.)

Before this quality process starts however must a module be chosen to perform the tests on; a module type qualification should be executed to make a first choice of module type. This is done in part by controlling the supplier and their quality process and experience with different technologies. Another part is deciding on module type, in which many factors play and reliability should be a major one, though that is not always the case. There is a need to know early in the development of solar power plants if a PV module type has the capacity to reach the quality requirements, this to evaluate which technologies are an option for the plant. (RWE 2020)

1.1 Aim

The aim of this thesis is to

- Compile knowledge of PV modules, field experiences, and test results to give an overview of the reliability and durability of different PV module technologies in a technology assessment.
- Evaluate the necessity of and develop a prequalification process to assess the reliability and durability of a technology in a systematic way early in the project development.

1.2 Research questions

The following questions will be evaluated in this thesis:

- How is the reliability of a PV module affected by its design, and which technologies are the most durable?
- What is the necessity of a prequalification process and how can it be formed?

1.3 Limitations and definitions

This thesis is limited to studying photovoltaic modules used in utility scale power plants, and only the module itself is considered; ways of mounting, connecting, or in other ways designing the power plant are excluded. As a first step in the methodology will relevant aspects of the module be selected for further evaluation. In the comparison between different technologies is only the impact on the module reliability of importance, other aspects like efficiency, costs, and climate impact are not considered.

The following terms are central in the thesis and defined as follows in the context of PV modules

- Reliability: The ability to perform as close to the original capacity as possible; the lower the power loss the higher the reliability.
- Durability: The ability to last over time and withstand external circumstances; to have sustained reliability when subjected to different conditions.
- Quality: A module of high quality is designed and produced in a way that ensures its reliability and durability.
- Failure: A specific type of degradation, not a binary concept as the module can still produce power when degraded but not at full capacity.

1.4 Copyright

All figures are either created using information from the stated sources or are provided by RWE in which case it is stated. The exception is figure 15

1.5 Report structure

In section 2 is the broad background of photovoltaic modules introduced, and the theory is further explained in section 3. Here are all the parts of the PV module presented together with the different technologies that are an option for the parts today and in the near future. Section 4 contains the methodology used in the thesis. Section 5 presents a compilation of tests performed by different labs and failures that can occur, as well as an example of a mechanical stress test. The results of the literature review can be found in section 6, divided by six properties of a PV module. In the following section 7 are the results analysed in the same structure. Finally, the result, methodology, and other aspects of PV modules are discussed in section 8, and the conclusion is presented in section 9.

2 Background

2.1 Cell

To extract energy from sunlight and convert it to electricity a photovoltaic cell is required. The general structure of a PV cell is shown in figure 1 where the majority of the cell consists of a semiconductor material, generally silicon doped with other elements. The upper silicon layer is n-doped which means there is an excess of electrons, and the bottom layer is p-doped; there is an absence of electrons. This difference in charge creates an electrical field. When the cell is exposed to light are photons with a certain amount of energy absorbed by the silicon, exiting electrons. These free electrons move through the semiconductor in the direction of the electric field and are collected by the conducting electrodes creating an electric current. (EIA 2023)

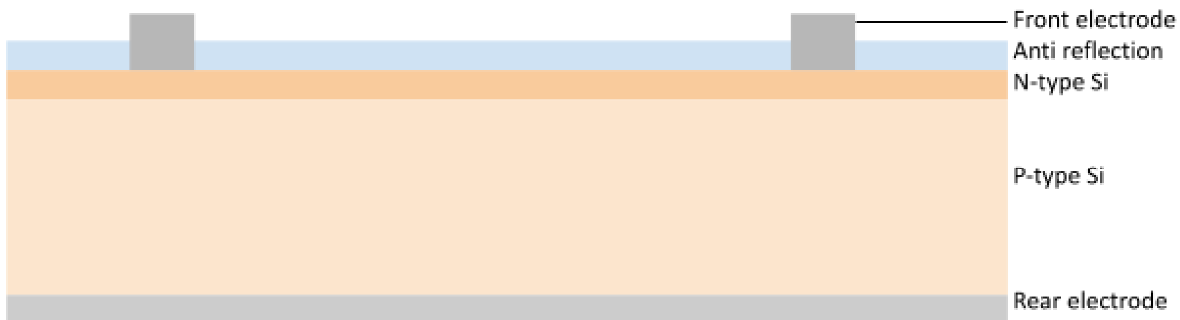


Figure 1: Schematic structure of a traditional solar cell

2.2 Module

A basic example of a PV module is shown in figure 2 presenting all the major parts. The frame is used for mechanical reinforcement, to mount the module, and provides some protection from moisture and physical impact. Glass covers the front of the module allowing light to pass through while protecting the cells. The glass is covered with an anti-reflection coating to increase the amount of light that reaches the cells. The cell layer consists of PV cells on wafers that each produce power and are connected to each other in series, and connected to the module in a junction box. The backsheet protects the back of the module and provides stability. All these parts are assembled with different encapsulants and adhesives. (PVEL 2023a)

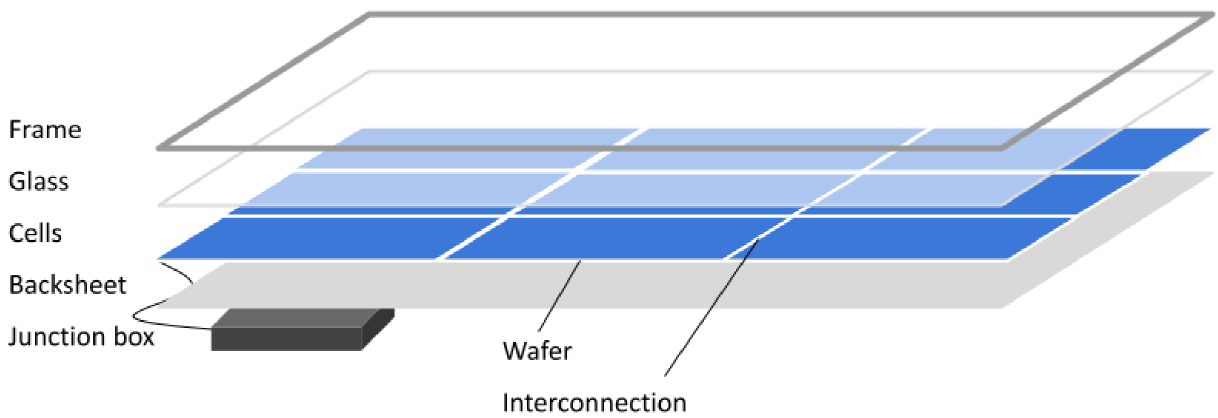


Figure 2: Schematic structure of a PV Module

2.3 Market

The PV industry is growing fast; the technology is evolving, new power plants are being built and more solar power is being generated every year. In 2022 were in total 1185 GWp of PV capacity installed while in 2017 the number was 407 GWp. The installed capacity has almost tripled in 5 years, and since 2012 has the capacity increased more than 10 times from 100 GWp. This means that 90 % of installed PV are less than 10 years old, and 65 % less than 5. (IEA 2023)

The PV market consists of different kinds of PV systems, where utility scale power plants are the largest at around 65 % and roof-top systems the second largest at 30 %. The remaining 5 % are building integrated, floating, and agricultural PV systems. (Fischer et al. 2023)

While PV modules are being installed all over the world are the vast majority being produced in China, either the whole module or key parts. China is dominating almost every aspect of the PV market as illustrated in figure 3, and as they continue to increase their manufacturing capacity this is predicted to continue. However, there have been efforts to support local production in USA, India, and Europe for political reasons. Trade conflicts between USA and China have led to expanded solar cell production in unaffected countries like Vietnam and Thailand as chinese PV companies have invested in manufacturing there. In Malaysia are the South Korean polysilicon (the base material used to make monocrystalline for PV) producer OCI planning to increase the production with the country's current total capacity every year for the next five years. In addition, Norway has some polysilicon production and India is planning on investing in it, along with a quickly increasing wafer and module production.

Germany and USA have also announced wafer production in the near future, in addition to their polysilicon production, and there are initiatives to start more production in the EU for more sustainable PV modules. (IEA 2023)

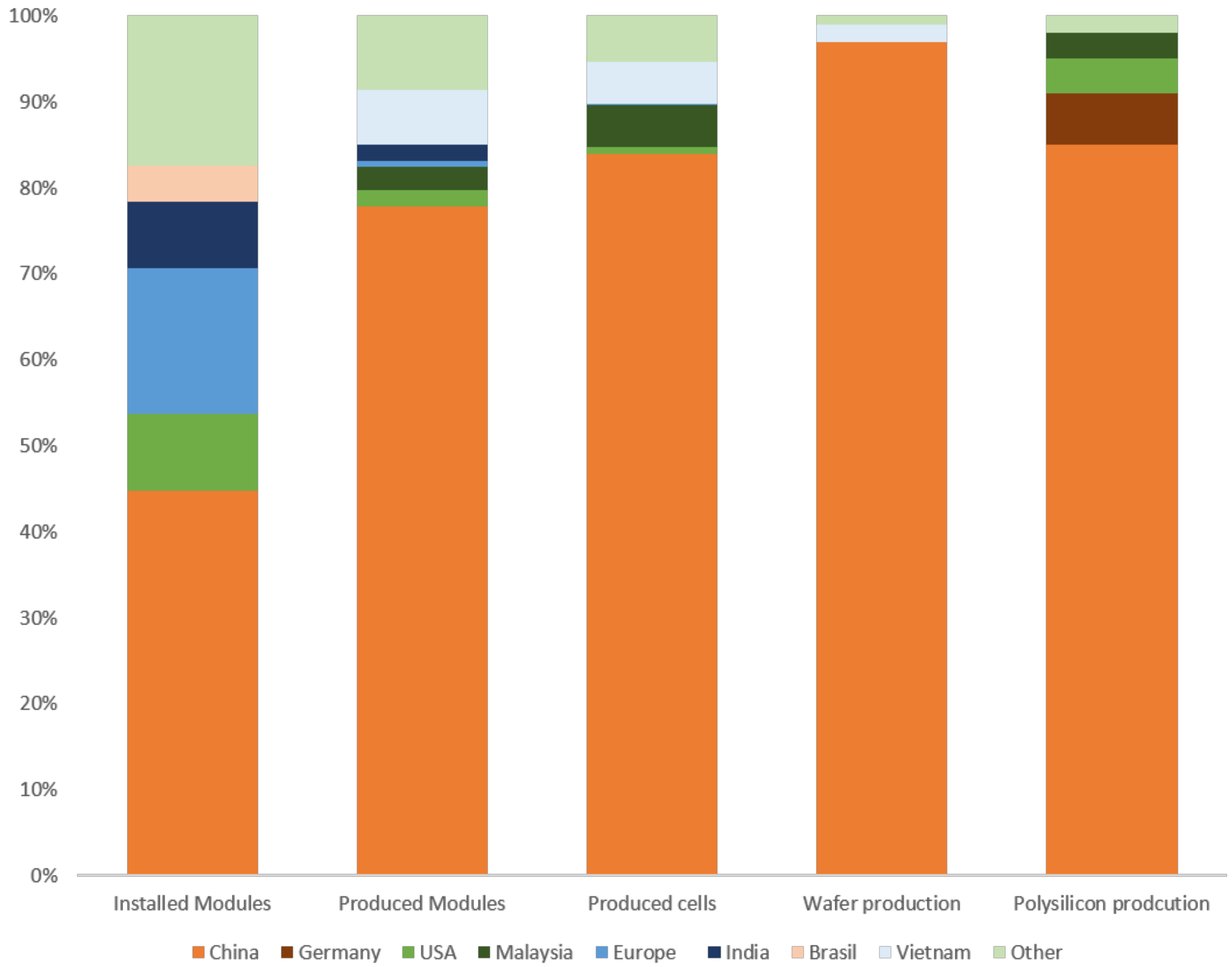


Figure 3: The PV market in 2022, polysilicon production includes non-PV production of 5 % (IEA 2023)

One area where China is not dominant is thin-film cells; the american company First Solar is the largest manufacturer of thin-film CdTe modules, and produces them in USA, Malaysia, and Vietnam. Additionally are thin-film modules produced in Japan, Germany, and China. (ibid.)

The top 6 PV module manufacturers are responsible for 75 % of the 275 GWp shipped PV modules in 2022, all presented in table 1 (Santos 2023) (IEA 2023).

Table 1: Shipped PV modules 2022 in GW by the largest manufacturers (Santos 2023)

Manufacturer	Country of origin	Shipped PV modules [GWp]	% of total shipment
Longi Solar	China	45	16.4 %
Trina Solar	China	43	15.6 %
Jinko Solar	China	42	15.3 %
JA Solar	China	40	14.5 %
Canadian Solar	Canada	21	7.6 %
Risen Energy	China	15	5.8 %

2.4 Quality

The quality of PV modules is regulated by standards like IEC 61215, IEC 63342, IEC 63202 and IEC 61730 which describe tests and minimum requirements for PV modules (IEC 2021). Test labs for PV modules often perform these tests as IEC certification of modules can be a part of their services. Additionally, these test labs can perform more extensive tests of PV modules as part of their own certification or as a service to customers. This is to test the modules in ways that mimic real conditions to a larger extent than the minimum IEC requirements.

The quality process is regulated by ISO 9000 but can be implemented in different ways. Table 2 shows an example of a quality chain for PV modules (RWE 2020).

Table 2: Example of quality process for PV modules

1. General	Details of the quality chain below depend on the selected Module and the conditions (e.g. sea climate, humidity, dust, wind exposure, etc.) on site. It shall be adjusted in accordance with the Employer's specific requirements if there are relevant new findings on module quality.	
2. Prequalification	Basic selection after decision in project	2.1 Supplier qualification 2.2 Module type qualification
3. Fabrication	Before production	3.1 Factory audit 3.2 Module quality check with contract BOM
	During production	3.3 Factory monitoring
	Before first transport	3.4 Pre-shipment tests
4. Transport	During transport	4.1 Cargo safety management
	After transport	4.2 Material quality control at project site
5. Operation	After installation	5.1 Mechanical completion tests and EL-imaging
	During operation	5.2 In operation tests if relevant

3 PV module technologies

3.1 Cell technologies

There are several different ways of constructing PV cells, some are well-established in the market and some have recently started to rise in popularity. The cell technology mainly affects the efficiency of the solar module but also influences the overall reliability. In this section, different technologies that are predicted to be present in the market in the next years are described.

In 2021 95% of the produced PV cells silicon based, while the remaining 5% were thin film technologies where CdTe cells make up the large majority (Fraunhofer ISE 2021). Of the silicon based cells were PERC cells the dominant technology, as seen in figure 4, though the PERC dominance is predicted to decrease in favour of TOPCon and heterojunction (HJT) technologies. This is because those technologies have a higher energy conversion efficiency which means higher power output, see table 3 (Fischer et al. 2023)

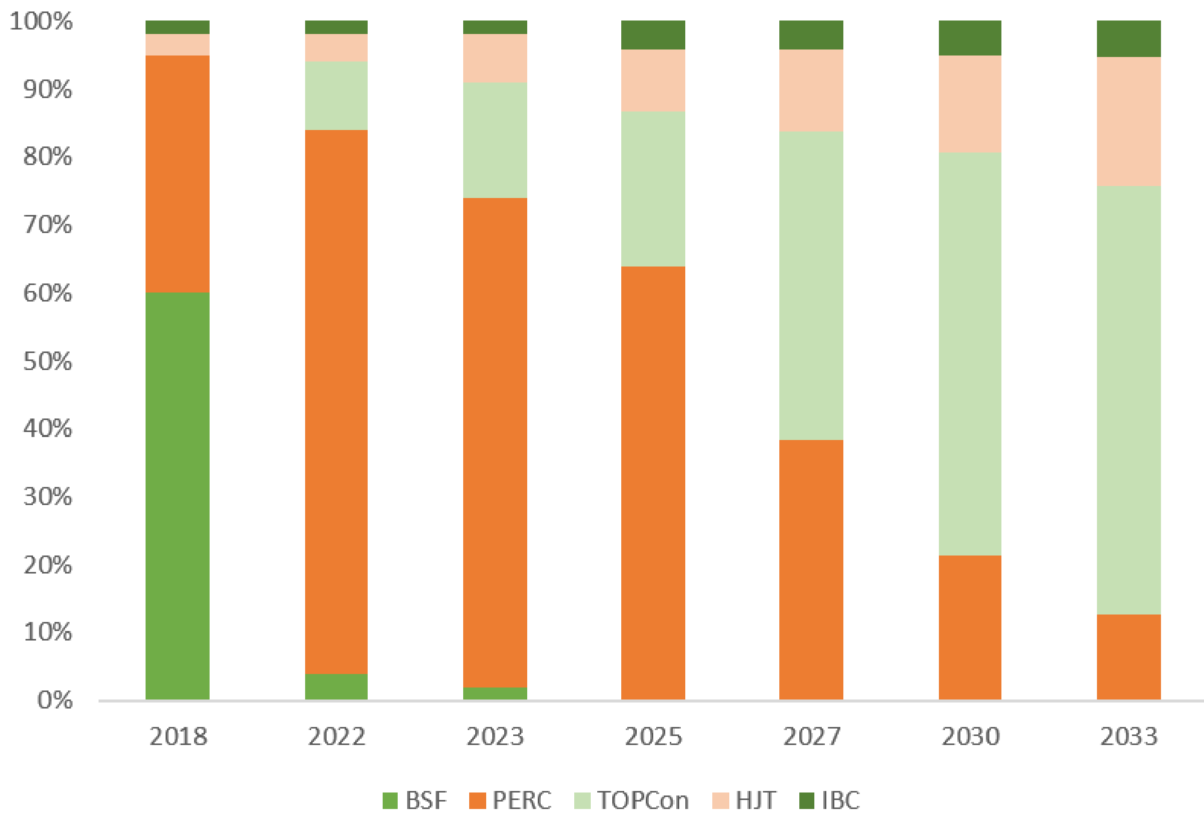


Figure 4: Market shares for different silicon based cell technologies, 2018 and 2022 are measured data, and the rest predictions (Fischer et al. 2023)

Table 3: Average stabilised efficiency values for mass produced silicon PV cells (Fischer et al. 2023)

Technology	**Average stabilised efficiency**	
	2022	2030 (prediction)
P-type mc-Si (PERC)	21.2 %	22.7 %
P-type mono-Si (PERC/TOPCon)	23.2 %	24.2 %
N-type mono-Si (TOPCon)	23.9 %	25.8 %
N-type mono-Si (HJT)	24.0 %	26.0 %
N-type mono-Si (IBC)	24.8 %	26.0 %
Tandem cells	-	29.5 %

3.1.1 Passivated Emitter and Rear Contact

PERC solar cells are traditional PV cells with an extra insulating layer at the bottom of the cell, see figure 5. This passivation layer has two functions that leads to higher power output; it decreases the free movement of electrons in the cell which reduces the probability of free electrons recombining with an atom before moving to create the current. Additionally, the internal reflection increased by this technology. (Ayoub et al. 2017)

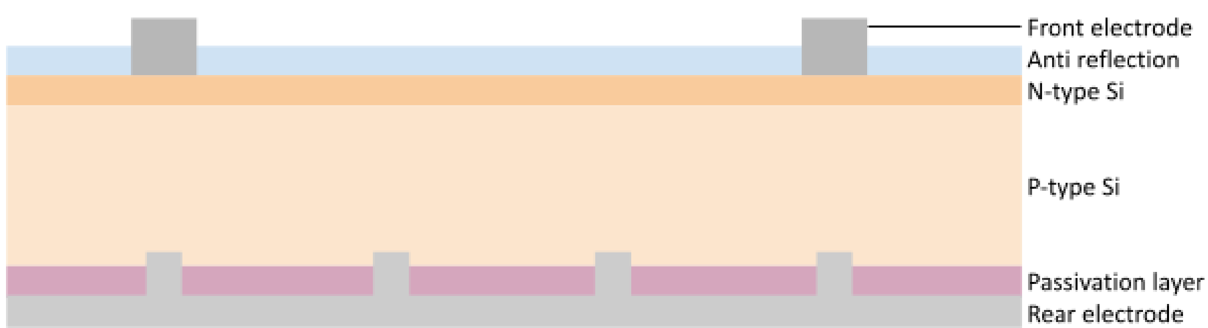


Figure 5: Schematic structure of a PERC solar cell

3.1.2 Tunnel Oxide Passivated Contact

TOPCon is similar in structure to PERC. An extremely thin silicon oxide layer is placed at the bottom of the cell, allowing current to flow through it. On the bottom of this layer is a layer of doped silicon, mostly with phosphorous, as seen in figure 6. This achieves the same positive effect of reduced recombining as PERC, though with full rear contact instead of partial. This makes the cell more effective and as the manufacturing is similar to PERC are they more easily produced than other technologies. (Ghosh et al. 2022)

Figure 6: Schematic structure of a TOPCon solar cell

3.1.3 Heterojunction

Another method of reducing the recombining in the cell is to use heterojunction technology, abbreviated HJT or HIT, as opposed to homojunction which previously described technologies are classified as. Two layers of amorphous (non-crystalline) silicon, one p-type and one intrinsic (non-doped), are added to the top of the n-type silicon core. On the rear side are another two amorphous silicon layers added; one intrinsic and one n-type. This is illustrated in figure 7. The intrinsic layers work as passivation layers and are very effective in lowering the surface recombination which increases the efficiency of the cell significantly. (Chuchvaga et al. 2023)

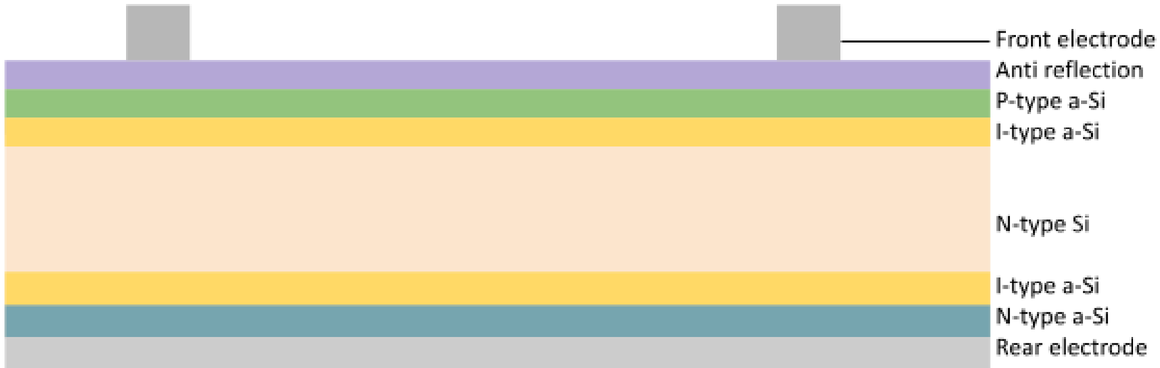


Figure 7: Schematic structure of a heterojunction solar cell

3.1.4 Interdigitated Back Contact

Another silicon based PV cell technology is Interdigitated Back Contact (IBC) which has reported high efficiencies. IBC cells have all electrode contacts on the rear side, see figure 8 which means that no grid on the front of the cell shades the cell. This does however create some problems with the passivation of electrons, and there are multiple ways of improving this, among them combining IBC with HJT. (UNSW 2017)

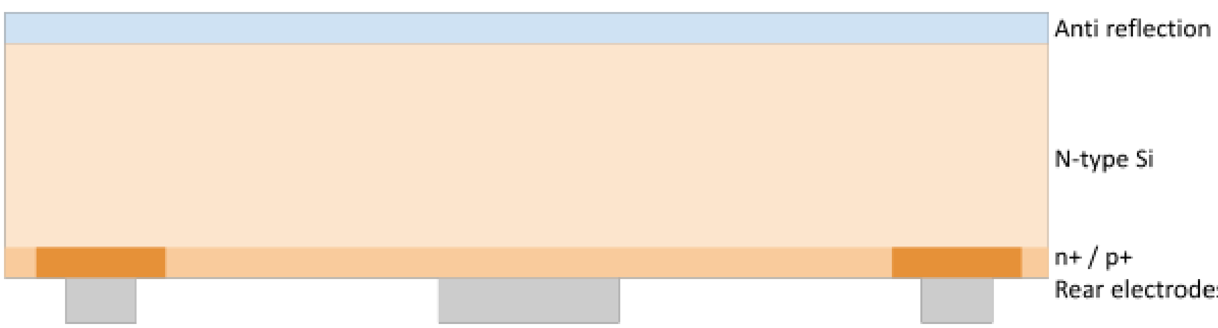


Figure 8: Schematic structure of a basic IBC solar cell

3.1.5 Cadmium telluride

The vast majority of solar cells used today are silicon based, though other materials are being used as well. One of these that are present in the market is solar cells made from cadmium telluride (CdTe). This technology does not use wafers as its base; it is a so called thin-film solar cell which is significantly thinner, lighter, and more flexible than silicon based ones. The basic structure of CdTe solar cells is shown in figure 9 with a top layer of Transparent

Conducting Oxide (TCO), a layer of n-type CdS, and a base of p-type CdTe. However, there are variants of this with more layers of different compounds with different properties to increase the power output. (Scarpulla et al. 2023)

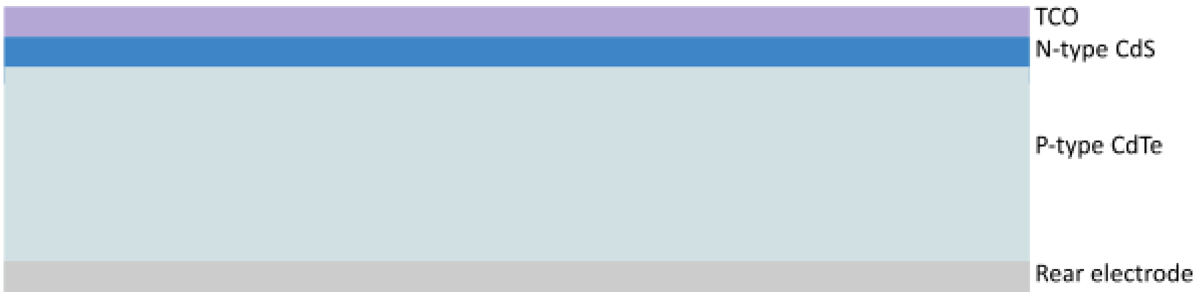


Figure 9: Schematic structure of a basic CdTe solar cell

3.2 Interconnections

A way to make PV modules more area efficient, i.e. more power output per m^2, is reducing the space between the cells, which conventionally is 2-3 mm. This can be made in different ways; from placing the cells a little closer to one another, to them overlapping, see figure 10. The connections between the cells collect the power generated by each cell to the module and are therefore a crucial part of the module structure. At the same time, they are vulnerable to thermal and mechanical stress that causes the module to bend.

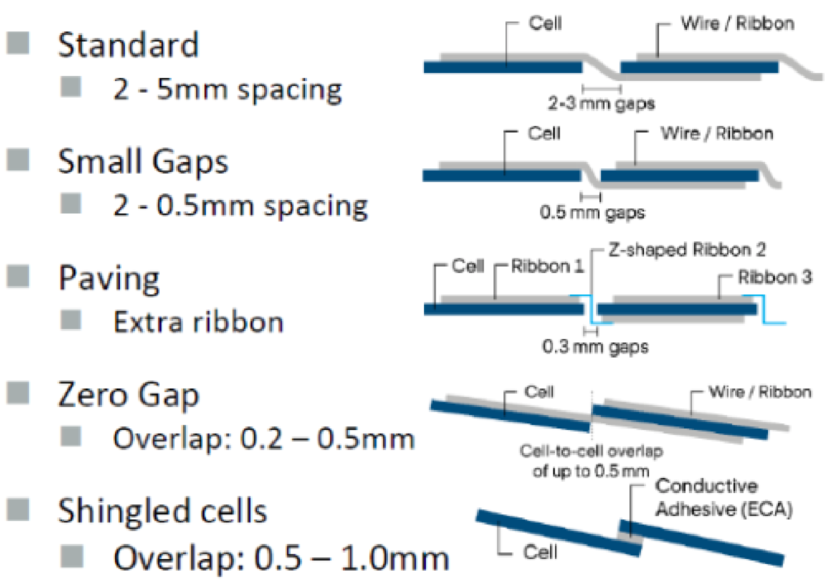


Figure 10: Illustration of different interconnection technologies (RWE 2020)

The interconnection between the cells which has been most commonly used is ribbons made out of copper, though now thinner copper wires are dominant as they are used to connect half cells and in multi busbar connections. This domination is predicted to continue as seen in figure 11 (Fischer et al. 2023)

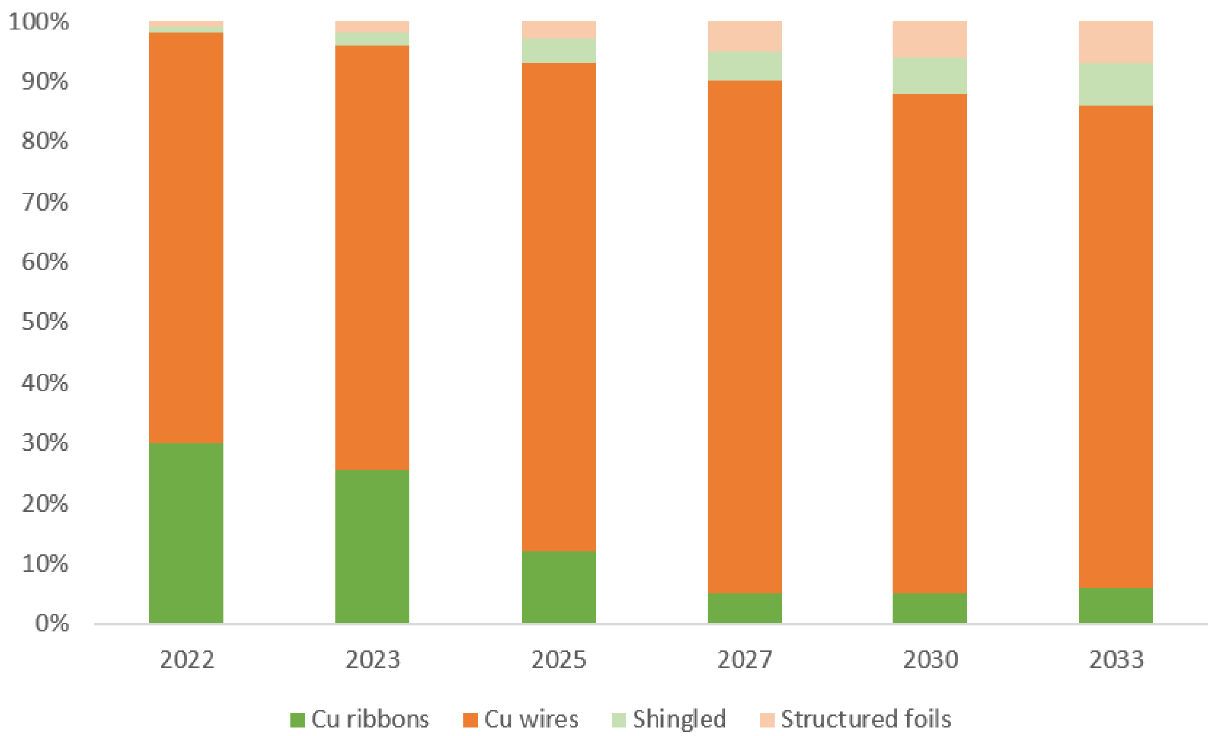


Figure 11: Expected market shares for different cell interconnections (Fischer et al. 2023)

3.2.1 Small gap and paving

There are different methods used by different manufacturers to make the cell gap 0.3-0.5 mm. Trina Solar has a high-density interconnection technology (Trina Solar 2021) and JA Solar has a gapless flexible interconnection which has a buffer treatment in the cell gap that can endure mechanical stress (JA Solar 2022). Paving or tiling ribbons between the PV cells can make the gap between them as small as 0.3 mm. This can be achieved by using differently shaped ribbons for the front and back connections (UNSW 2019b) or with z-shaped ribbons (RWE 2020). However, the distinction between paving, tiling, and shingles is not clear as different manufacturers use different terminology.

3.2.2 Shingles, tiling and zero gap

When shingling the PV cells are the edges put on top of one another like rooftop shingles or tiles. This has several positive effects on the efficiency of the PV module as the space between the cells is eliminated and the busbar is covered by the neighbouring cell reducing shading losses. To connect the shingled cells can different techniques be used; an Electrically Conductive Adhesive (ECA) (Baliozian et al. 2019), aluminium foil strings (Paschen et al. 2021), soldered ribbons (Longi 2019) or alternating flat and round tiling ribbons (Jinko Solar 2020).

3.2.3 Multi busbar

The number of interconnections (busbars) per cell has increased drastically and is predicted to continue to do so, see figure 12. When the number of busbars increases does the width decrease to allow for the same power but less shading and power loss (Panda et al. 2022).

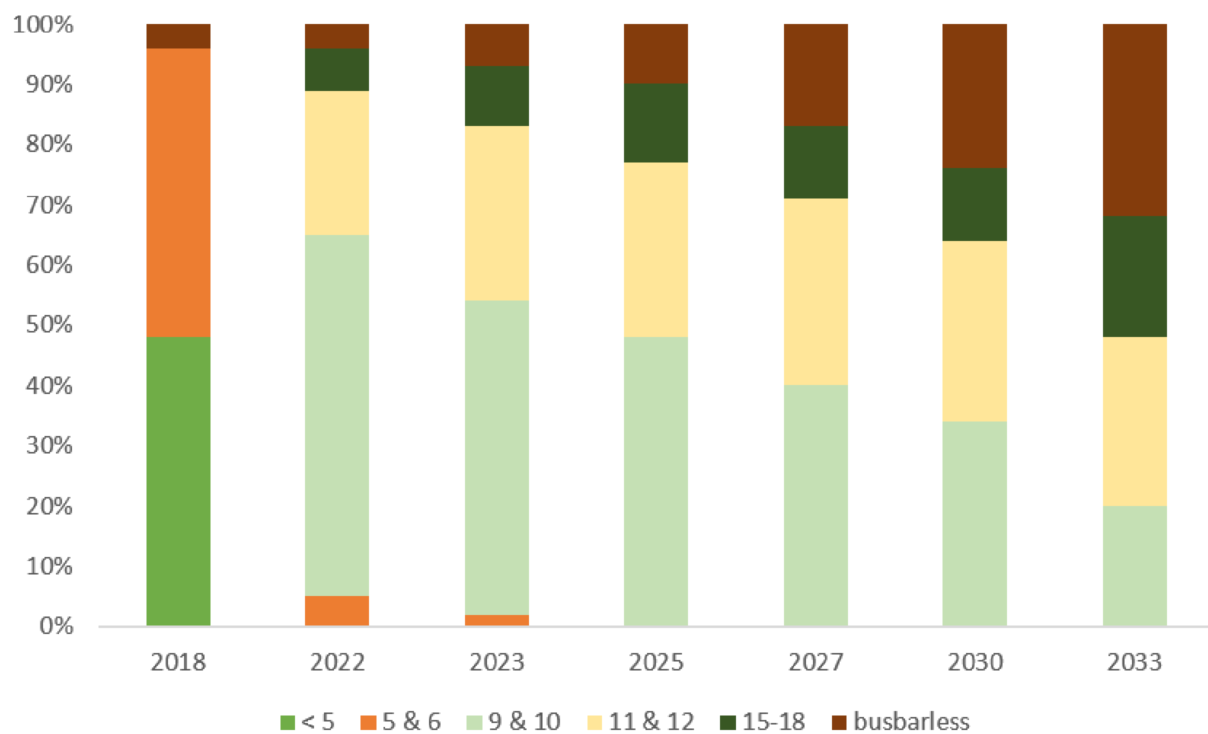


Figure 12: Expected market share for different busbar technologies for cells in M10 format, all formats in 2018. 2023 and later are predictions, 2018 and 2022 measured data(Fischer et al. 2023)

3.3 Size

Another way to make PV modules more area efficient is increasing the area. This is made by either increasing the size of the cell wafers or the module itself. Larger sizes mean that less related equipment and materials are needed for the same power output. This is something PV manufacturers have taken advantage of to increase the power of a single module.

3.3.1 Large wafers

The size of solar cell wafers differ as seen in table 4. M3/G1 was for a long time the standard size but was later replaced by M6 which is now leaving room for even larger wafers. Larger wafer sizes increase the cell sizes which leads to either fewer cells in a module or larger modules with the same amount of cells. (Fischer et al. 2023)

Table 4: Wafer size labels, their width and market share (Fischer et al. 2023)

Label	Width [mm]	Share 2022	Share 2030 (prediction)
M3/G1	158.75	5 %	0%
M4	161.7	5 %	0 %
M6	166.0	28 %	0 %
M10	182.0	45 %	52 %
M12/G12	210.0	17 %	42 %
>M12	>210.0	0 %	6 %

The size of the wafer has a large impact on the output power of the cell, though because the current increases with wafer size so do the electrical losses. (M. Mittag, Pfreundt, and Shahid 2020)

3.3.2 Large modules

When wafer sizes are getting larger so are the modules if the number of cells does not decrease, which is not happening. Figure 13 shows how module areas are increasing, the mid-size of 2.5 to 3 m^2 are about 2.4 x 1.1 m. When the modules are getting larger they are also getting heavier (Fischer et al. 2023).

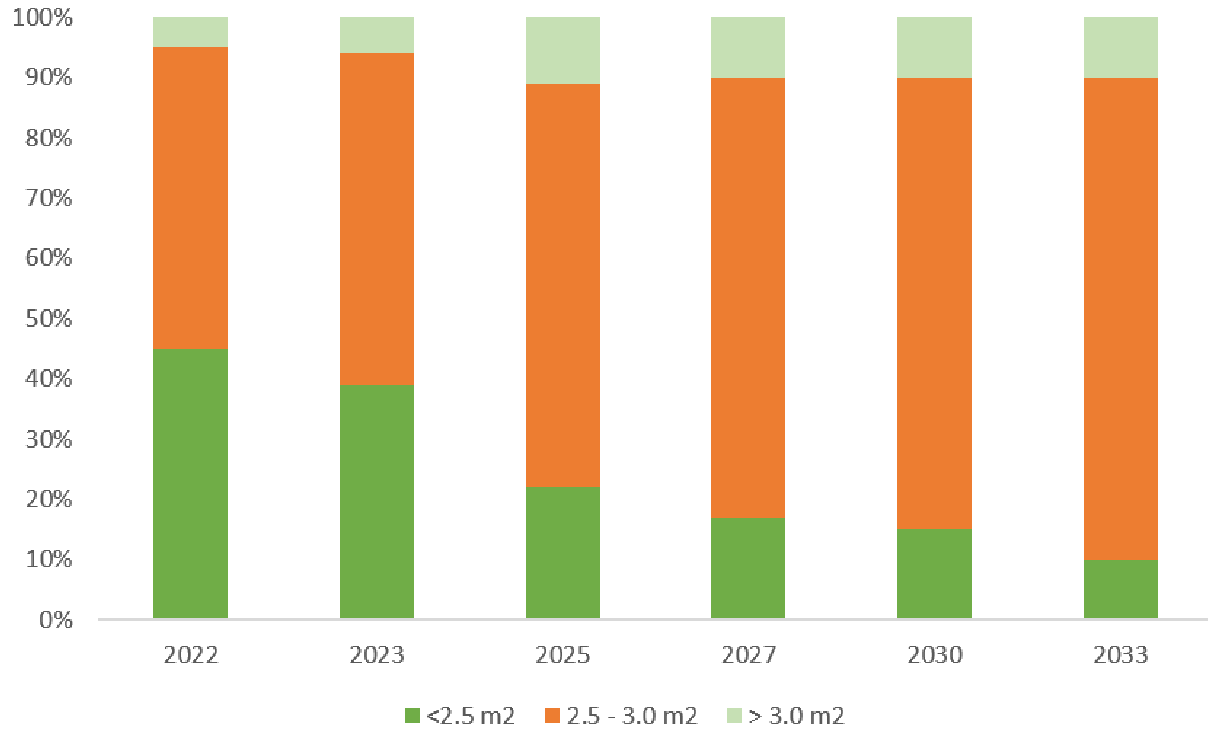


Figure 13: Trend of module size for power plant applications (Fischer et al. 2023)

3.4 Module material

3.4.1 Back cover

The rear side of the PV module can be covered by a glass sheet similar to the front cover to allow for light to enter through both sides, which is often referred to as a glass/glass (g/g) module. The back can also be covered by a backsheet made out of variants and layers of polyvinyl fluoride, polyvinylidene fluoride, PET, polyamide, and others (Buerhop-Lutz et al. 2021). These are often called glass/backsheet (g/b) modules regardless of their material, and can be opaque or transparent. These two different types of back covers have different properties which affects the durability of the PV module. In 2022 a third of PV modules glass/glass, and that is predicted to increase to about 60 % in the next 10 years. The remaining modules then having a non-glass backsheet (Fischer et al. 2023).

3.4.2 Frame

The frame can be an important part of the module design to increase module durability. The most common frame is made out of aluminium, though there are also frames made from steel and plastic, and frameless modules, see figure 14. Metal frames have the same basic design shown in figure 15.

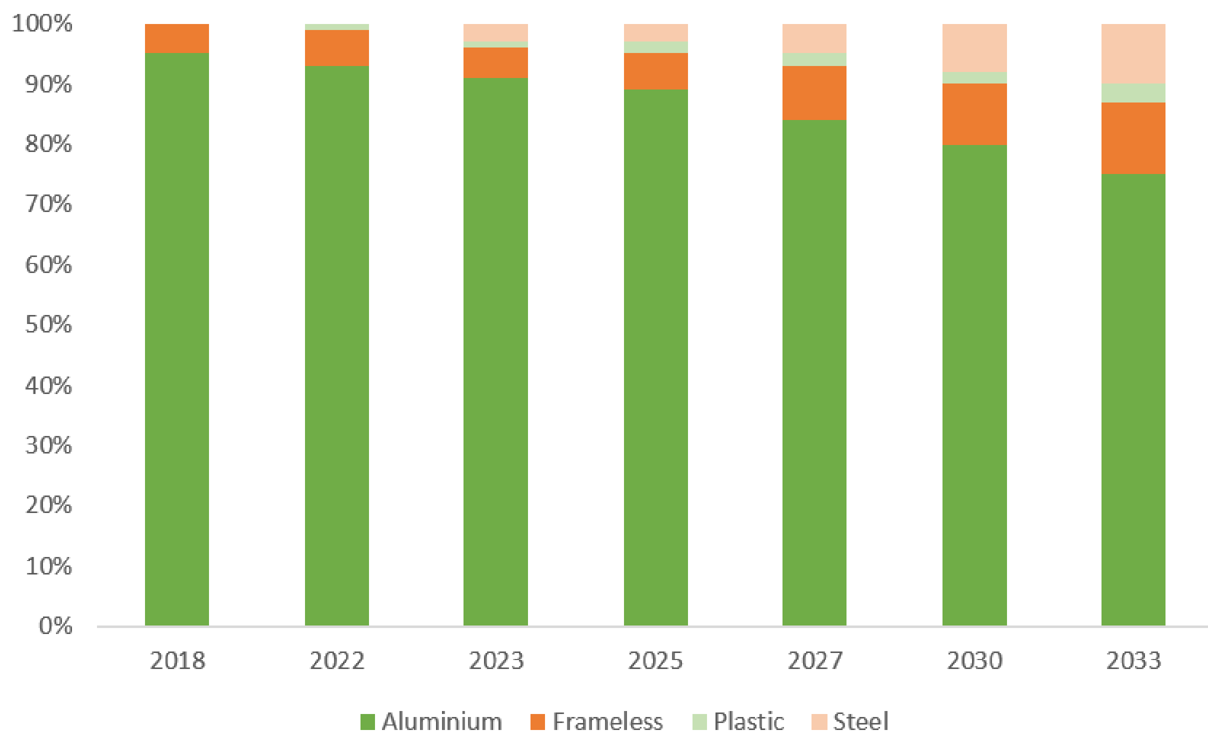


Figure 14: Expected market shares for frame materials of c-Si modules. 2018 and 2022 are measured data and the rest are predictions. (Fischer et al. 2023)

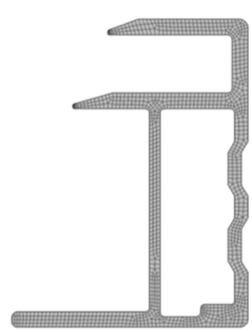


Figure 15: Example of a typical frame design, where the module is attached between the two top edges (Tummalieh et al. 2022)

3.4.3 Encapsulant

The encapsulant in PV modules has three main purposes; to protect the cells from the impact that affects the glass or backsheet, to isolate the cells and connectors to prevent short circuits, and to not absorb the photons intended for the PV cell (IEA 2017). The most common encapsulant today is Ethylene Vinyl Acetate (EVA), and it has been dominating for a time, though there are other options like polyolefin encapsulants as seen in figure 16. Two common polyolefin-based encapsulants are polyolefin elastomer (POE) and thermoplastic polyolefin (TPO), which have some different properties than EVA, though there are variations in each category (Uličná et al. 2023). A combination of different encapsulants can be used, for example, one material on the module front and another on the rear side, or EPE which is a three layer encapsulant of EVA-POE-EVA.

Figure 16: Expected market share for different encapsulation materials. 2018 and 2022 are measured data and the rest predictions (Fischer et al. 2023)

3.5 Module features

3.5.1 Half cell

Half cells, or dual cells, are conventional PV cells that are cut in half to create two smaller cells. The halves generate the same voltage as a full cell but half the current, which results in less resistive losses in the busbars as the power is dependent on the squared current (UNSW 2019a). Half cells also reduce losses from shading. This makes the technology very popular; in smaller cells than M10 half cells are dominating in 2022 with almost 90 %, and that number is predicted to increase in the next 10 years. For larger wafer sizes the percentage about the same in 2022, however, the half cell share will probably decrease in favour of third and quarter cells, though still be in the majority. (Fischer et al. 2023)

3.5.2 Bifacial

Bifacial cells can absorb energy from light on both the front and rear sides. These are dominating the PV market but can be used in both mono-and bifacial modules. The characteristics of the module, mainly the back cover of the module, and the electrical design decide the ability to absorb light from the back side as well. However, the front and rear sides do not have the same efficiency, and this ratio is expressed as a bifaciality factor and differs between different cell technologies. PERC has a bifaciality factor of 70 %, TOPCon 80 %, and HJT 90 %. (ibid.) Today the share of monofacial modules is greater than bifacial, and this is predicted to change as seen in figure 17. Though, these numbers are for all kinds of PV modules, and bifacial are to be used mainly in utility scale power plants.

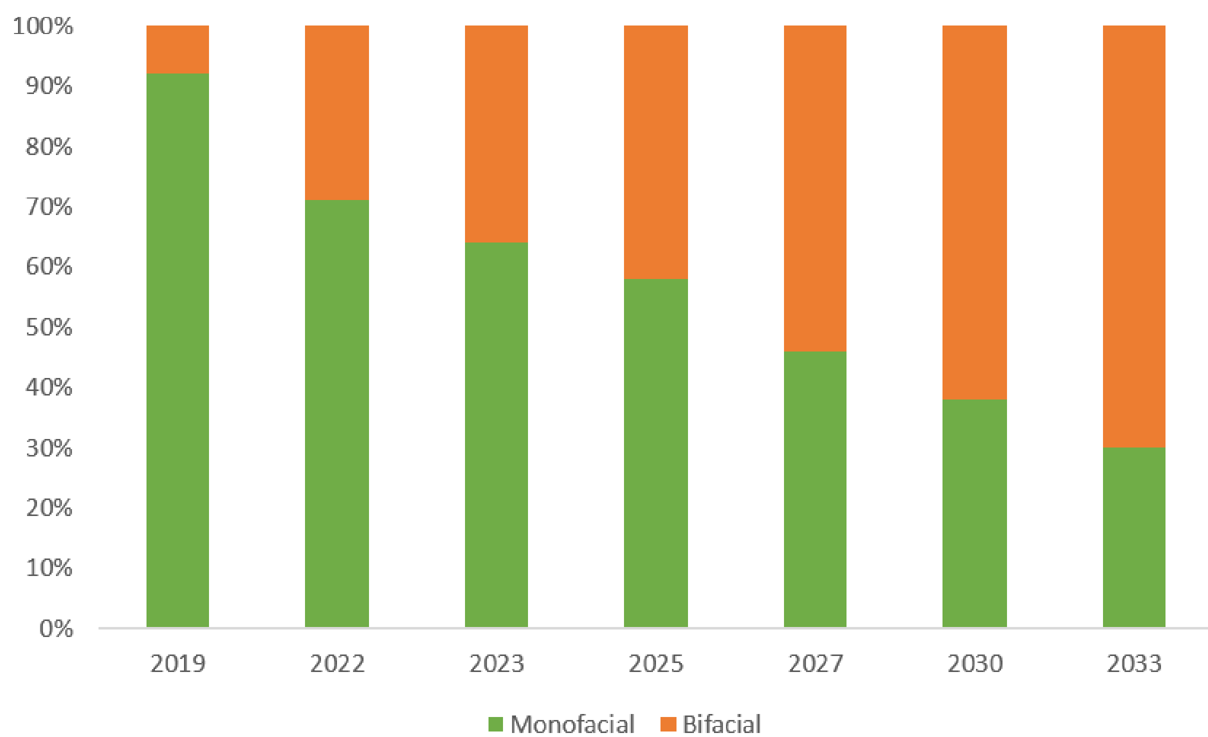


Figure 17: Expected market share for bifacial modules. 2019 and 2022 are measured data and the rest are predictions. (Fischer et al. 2023)

4 Method

The main methods used in this thesis are a literature review, a compilation of the gathered data, and an analysis of this data where the reliability and durability of PV technologies have been concluded.

The following properties and their corresponding technology alternatives of PV modules presented in section 3 were considered to be the most relevant for the qualification of PV modules from a reliability perspective. This based on which technologies will be present in the next years and which attributes have the largest influences on the reliability of a PV module.

- Back cover material
- Cell technology
- Frame
- Cell interconnections
- Module and wafer size
- Encapsulant

4.1 Literature review

For each property were a systematic information search conducted where all of the main sources listed below in 4.1.1 were studied. After this was a database search using LUBSearch performed. The keywords were both broad, i.e. "PV cell reliability", "PERC reliability", and technology degradation specific, i.e. "PERC PID". The found articles sources and citations were examined to find other relevant research. Inclusion criteria were

- Articles concerning the technology in question and reliability, durability, or degradation
- Field studies where the results concerned reliability, durability, or degradation
- Lab tests of reliability, durability, or degradation
- Articles that compared technologies, or were conducted in a way that the results can be compared to other
- Articles concerning technology for PV power plants or can be applied to that context

- In English
- Published at the earliest in 2017

In addition to this, whitepapers and product datasheets from the six largest manufacturers were examined to see what research they conduct and what technologies are used in the industry.

4.1.1 Main data sources

The main data sources used in the literature review are the following

- Reports from IEA's Photovoltaic Power Systems Program. Primarily *Assessment of Photovoltaic Module Failures in the Field* (IEA 2017), but also other reports.
- PV Evolution Labs' scorecard (PVEL 2023b), an annually released compilation of test results from their Product Qualification Program where multiple modules from different manufacturers are being tested.
- Renewable Energy Test Center's annual PV Module Index Report (RETC 2023) where trends and results from their module tests are presented.
- International Technology Roadmap for PV (Fischer et al. 2023), an annual report released by VDMA predicting technology trends in the PV industry.
- The Fraunhofer research database (Fraunhofer n.d.), a german group of institutes of which one does PV research and tests.
- The National Renewable Energy Laboratory's research database (NREL n.d.), an american research laboratory where PV is being researched.
- TÜV, a group of third party companies that performs quality tests and inspections. They do not have a database, but to find available reports from tests that they have performed, published by them or a partner, one can do a Google search of TÜV together with a PV technology.

The main sources outside the literature review were material provided by RWE; inspection reports, root cause analyses of failures in RWE's PV power plant, and a previous technology assessment for PV module technologies (RWE 2020).

4.2 Analysis

The data obtained in the literature review were compiled, compared, and examined to make a comparison of the reliability of different technology alternatives to use for the properties presented in the beginning of this section.

Based on this compilation and a technology assessment and quality chain proposal from RWE (RWE 2020) were an overall process for module type qualification formulated, including how to keep informed with technology advancement and publication of new research.

5 PV quality testing

5.1 Failures

In table 5 are common PV module failures listed and their causes, effects, and involved parts of the module. Though some failures need a more in-depth description:

- Snail trails are discolouration of the front side metallisation of the cells, which assembles snail or worm trails and typically follows cracks in the cell.

- Different types of Potential Induced Degradation (PID) appear in different types of PV cells, but have the common cause of the voltage difference between the cells and the grounded frame. Shunting-type PID-s is ionic (Na+) leakage from glass, encapsulant, or cell surface to the cell causing shunts in the pn-junction. There is also Na-penetration-type PID-Na which is the same phenomenon but without the shunting. The cause for polarisation-type PID-p is still unknown but is believed to be due to the accumulation of charge in insulation layers. Corrosion-type PID-c is caused by electrochemical processes that affect the TCO layers, dielectrics, or metallic contacts. (Molto et al. 2023)

- Light Induced Degradation (LID) has for long been a problem in boron-doped PV cells (Markevich et al. 2019), though recently has gallium-doping become more common which has highly reduced the effect of this failure (PVEL 2023b).

- Light and Elevated Temperature Induced Degradation (LETID) is a cell-level phenomenon where the charge carrier lifetime reduces under illumination and high temperatures, which leads to power loss. This state is not permanent; the cells can recover if in the right conditions, however, both the degradation and regeneration process can span over the course of years. This effect has been observed in the majority of silicon-based cells; both p-and n-type, homo-and heterojunction, mono-and multicrystalline, and for different dopants. (Karas et al. 2022)

Table 5: Overview of failures based on IEA 2017 and IEA 2021, and results in failure frequency from Moser, Jahn, and Richter 2017.

Failures	**Affected parts**	**Cause**	**Effect**	**% of failed modules***	**% of total modules**
Discolouring	Encapsulant, backsheet	Thermal stress, humidity, corrosion, degradation of encapsulant	Reduced photocurrent due to absorption of light, cracking in backsheet.	13,17	3,84
Glass breakage	Glass	Bending stress, glass breakage, mechanical load	Moisture ingress, increased reflection	5,61	1,63
Snail trails	Cells	Cell cracks, humidity	Discolouring	4,83	1,41
Defect backsheet	Backsheet	Bending stress, mechanical load, humidity, delamination	Moisture ingress	3,31	0,96
Delamination	Encapsulant, backsheet	PID, bending stress, thermal stress, UV exposure, degradation of EVA, insufficient adhesion, air bubbles	Moisture ingress, increased reflection	2,68	0,78
Interconnect failure	Interconnections	Thermal stress, mechanical stress, cell swimming during lamination, corrosion, burn marks, hot spots	Complete or partial power loss in cell or module, hot spots	0,82	0,24
Cell cracks	Cells	Thermal stress (cold), mechanical load	Snail trails, moisture ingress, increased resistance, electrical separation of cell part, recombination current across crack, hot spots	0,15	0,04
PID-s	Cells, encapsulant	Humidity delamination, low volume resistivity of encapsulant, humidity, corrosion, delamination, hot spots	Lower power output	–	–

Table 5: Overview of failures based on IEA 2017 and IEA 2021, and results in failure frequency from Moser, Jahn, and Richter 2017.

Failures	**Affected parts**	**Cause**	**Effect**	**% of failed modules***	**% of total modules**
Corrosion	Frame, inter-connections	Humidity, delamination	Increased resistivity, discolouration	–	–
Burn marks	Cells, inter-connections	External heat, hot spots	Increased resistivity, discolouration	–	–

*Including failure causes like soiling, improper installation and shading which accounts for 70 % of all failures but are not module dependant. Other failure causes like theft and fire damage are also included in these numbers but account for less than 1 % of failures

5.2 Testing

Table 6 presents some test procedures that part of IEC 61215 and other tests that are performed by four test labs; PV Evolution Labs (PVEL), Fraunhofer ISE, TÜV Rheinland, Renewable Energy Test Center RETC and U.S. National Renewable Energy Lab (NREL). For a full list see Annex 1.

Table 6: Common tests performed to evaluate the quality of PV modules

Test	**Purpose**	**Desciption**
Visual Inspection*	Detect visible defections	Exterior inspection of all parts of module
Outdoor exposure test	Initial exposure of module to real conditions	Mount the module outside for 60 kWh/m_2
UV-exposure	Identify which materials are susceptible to UV radiation	Expose the module to UV irradiation 15-60 kWh/m_2
Thermal cycling test	Test ability to withstand thermal stress	Alternate temperature between -40 and +85 °C for 200 cycles, one cycle is $\sim$4 h. Accelerated thermal cycling has cycles of $\sim$1 h.

Humidity-freeze test	Test ability to withstand high temperatures and humidity followed by cold	Thermal cyling in 85 % relative humidity for 10 cycles
Damp heat test	Test ability to withstand hot and humid conditions	Subject the module to 85 °C and 85 % relative humidity for 1000 h
Wet leakage current test*	Test insulation under wet conditions.	Connect a DC voltage source to module while immersed in liquid
Static mechanical load test	Test ability to withstand static load	Subject the module to a load of 1.5 times x the design load (minimum 2400 Pa) on both front and back side.
Hail test	Test ability to withstand hail	Shoot ice balls of variying size and weight at vulnarble parts of the module
Cyclic mechanical load test	Test ability to withstand dynamic load	Subject the module to an alternating load of ±1000 Pa for 1000 cycles
PID test	Measure ability to withstand degradation from applied voltage system	Subject the module to 85 °C, 85 % relative humidity and maximum voltage for 96 h
LID test	Measure the Light Induced Degradation in modules	Subject a number of modules to light until the power has reached LID-stability
LETID test	Measure the Light and Elevated Temperature Induced Degradation	Modules that have been LID-tested are subjected to 75°C and low current for 162-486 h.
PAN performance	Simulate module performance	The performance in different operating conditions are used to simulate performance in PAN files for 2 locations

*Tests that are performed initially and after other tests to evaluate if the module is faulty

5.3 Example of quality testing of a PV module

To evaluate whether a specific PV module was of sufficient quality for usage in a power plant the following tests were performed and reviewed by Fraunhofer ISE on request of RWE. Twelve modules of the same model and bill of material (BOM) were subjected to the following tests, some to multiple, some to one but at least two modules per test.

- Initial characterisation (Flash test, Electroluminescence (EL) imaging, visual inspection, wet leakage test, insulation test)
- Mechanical load test, 2400 Pa and 5800 Pa.
- Backsheet peel and thickness tests
- Encapsulation crosslinking
- Initial stabilisation (LID) and nameplate verification
- Determination of temperature coefficients
- PID test
- LETID test
- Accelerated aging test

All tests were passed according to the specified criteria, except the last accelerated aging test where the power loss was greater than 5 % in both tested modules, which is outside the limit. The modules were therefore determined as insufficient.

Figure 18 shows the mechanical load test of 5800 Pa and 19 the effect. The EL images show the electrical conductivity of the cells, where lighter colour indicates higher voltage. In figure 19 are cracks visible in three cells, and the dark colour shows that they are disconnected from the rest of the module, not producing any power. Other things that can be shown with EL-imageing is micro cracks, forked cracks from impact, black spots, burn marks, shaded portions in soldering area, and dead or disconnected cells.

Figure 18: Mechanical load test of 5800 Pa, can be made both in this way with weighted bags or with a machine that applies the pressure. Picture from RWE.

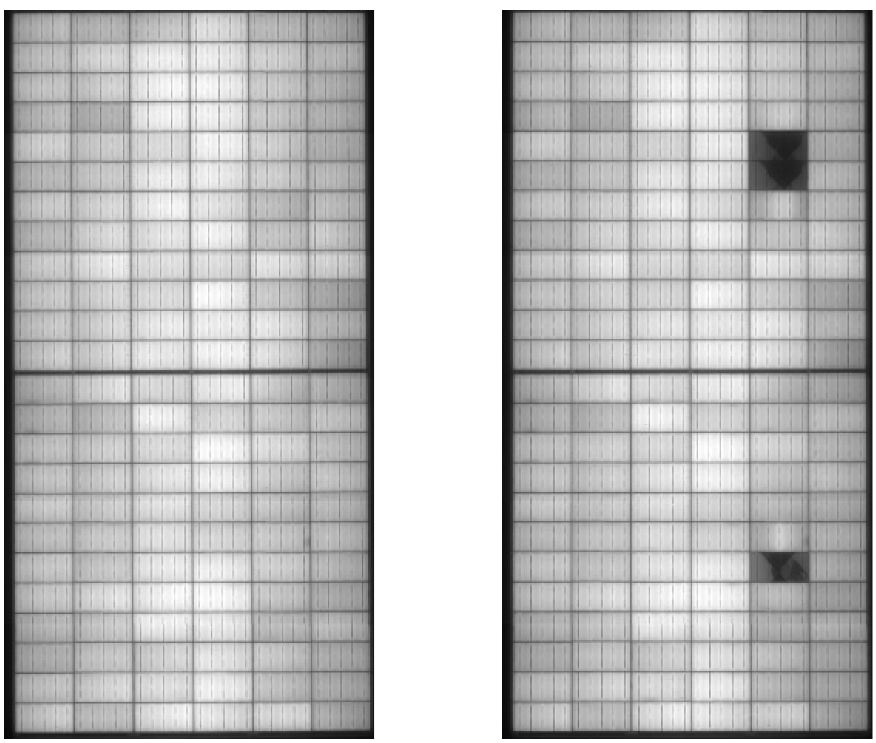
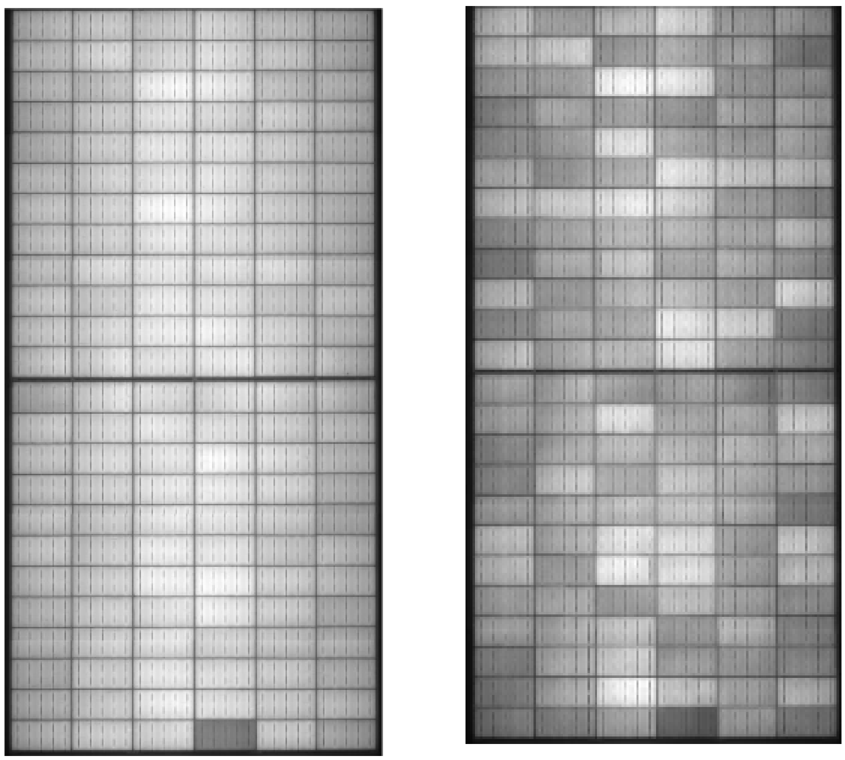


Figure 19: EL images of the module before and after mechanical load test of 5800 Pa. Picture from RWE.

The only failed test was the accelerated aging test, and figure 20 shows one of the tested modules before and after the test. Initially are one cell darker than the others, indicating

that this one cell is not producing the same power as the others. This is still the case after the test, but now are more cells darker and are together making up a power production of 5 % less than before the test. When comparing 19 and 20 are the difference between singular faulty cells and general degradation clear.
-micro cracks -forked cracks (impact) - u cracks like branch - black edge/black corner - black spot -shaded portions in soldering area -dead cells



(a) Before **(b)** After

Figure 20: EL images of the module before and after accelerated aging tests. Picture from RWE.

6 Results

In this section are the results from the literature review presented, divided by module property. The results are presented in tables where the performance of different technologies in different studies is compared. Additionally are results from studies that are less comparable in terms of technologies studied or measurable results presented.

6.1 Back cover

Both glass/glass and glass/backsheet are alternatives for PV modules. In table 7 are test results presented; g/g and g/b respectively perform better in some tests and worse in some. Though, some results can be linked directly to the absence or presence of glass and backsheet; in hail tests are the glass twice as likely to break in g/g modules which have double the amount of glass as g/b modules, and only g/b modules can have backsheet delamination.

Table 7: Results in tests of modules with different back covers, PVEL 2023b, RETC 2023, A. Kumar et al. 2022

Test	**Glass/Glass**	**Glass/Backsheet**	**Source**
Thermal Cycling	0.5 % median degradation	1.8 % median degradation	PVEL Score card
Damp Heat	1 % median degradation	1.9 % median degradation	PVEL Score card
Mechanical stress	No cell cracks, lower power loss, glass twice as likely to crack	Higher power loss, glass half as likely to crack	PVEL Score card
Hail test	Glass twice as likely to crack. Thickness of 3.2 mm survives impact from 55 mm, 2 mm glass survives 45 mm hail.	Glass half as likely to crack	PVEL Score card RETC Index
Backsheet durability	–	No cracks in backsheet, moisture leakages.	PVEL Score card
Thermal cycling, damp heat and UV exposure	Severe edge browning and grid finger degradation. Less ion migration and adhesion loss.	Ring browning (medium severity). More ion migration and adhesion loss.	NREL
In-field UV exposure	Intense browning of EVA everywhere causing power loss	Browning of EVA in cell centers, yellowing in other parts, causing less power loss	Patel et al. 2020

In addition to these test results, IEA 2023 presents that g/g modules have lower moisture ingress and are therefore less prone to corrosion. On the contrary are they more prone to delamination in the EVA due to bending stress during production, which RWE 2020 also concludes as the most delicate step for g/g modules; the lamination process requires a homogeneous temperature distribution of the whole module for a correct lamination.

The g/b modules have a higher diffusion of oxygen in a module which prevents discolouring to a certain extent, which is supported by the results from Patel, Sinha, and Tamizhmani 2020. Though, the different reactions to thermal stress in the different back and front materials will cause a peeling force in the module.

Liu et al. 2021 concludes in their paper that g/g modules degrade less in hot and dry climates, while in semi-desert and alpine conditions are there no clear difference. R. Kumar et al. 2022 concludes from their tests that the series resistance increases substantially in g/b modules when they are operating in humid conditions, while this is not the case for g/g. They also saw that disconnected fingers in the cells appeared faster in g/g modules and in drier conditions.

6.2 Cell technology

Newly developed or old enhanced cell technologies are being introduced to the utility PV market for their high efficiency, however, it is still unknown how they will perform after years of operating in the field. In table 8 are five technologies and their results in various tests presented.

Table 8: Results from simulations and tests by PVEL 2023b, Sinha et al. 2022 and Molto et al. 2023.

Test	PERC	TOPCon	HJT	CdTe	IBC	Source
Thermal cycling 600h	Good	Good	Some problems		–	PVEL
Damp heat	1.2-1.7 % average power loss	1.2-1.7 % average power loss	1.2-1.7 % average power loss	1.2-1.7 % average power loss	–	PVEL
PID test	1.1-1.6 % median power loss	1.1-1.6 % median power loss	1.1-1.6 % median power loss	Good	–	PVEL
LID + LETID	0.7 % average and median power loss	0 % average and 0.2 % median power loss	0 % average and 0.2 % median power loss	0 % average and 0.2 % median power loss	–	PVEL
UV 2000h	1-7 % power loss	–	11% power loss	–	Inconclusive	Sinha et al. 2022
PID types	PID-s, PID-p, PID-c, PID-Na	PID-p, PID-c, PID-Na	PID-c, PID-Na,	–	PID-s, PID-p, PID-Na	Molto et al. 2023
Accelerated damp heat with NaCl	10 % power loss	75 % power loss	50 % power loss	–	–	Sen et al. 2023

LETID affects the silicon-based technologies PERC, TOPCon, and HJT, though in slightly different ways; for instance are n-type cells (TOPCon and HJT) shown to be degrading slower than p-type (Ning, Song, and Zhang 2022). CdTe cells are not silicon-based and are therefore not affected by this phenomenon.

All assessed cell technologies are affected by PID which causes power loss, though table 8 shows that PERC and IBC are the only si-based technologies in which PID-s occurs, and PID-p is not a problem in HJT cells (Molto et al. 2023). HJT cells have shown to be more resistant to PID than other technologies in certain conditions, but the effect is irreversible and it is mainly the short-circuit current density that is affected, which means that one degraded cell lowers the power output of the whole string (Yamaguchi et al. 2018). The degradation of n-type IBC modules in outdoor conditions during six years was tested by Ishii et al. 2020. The total average degradation in power output was 3 % and was concluded to be caused by PID-p, and this effect was likely saturated with time. A difference in degradation depending on the polarity of the voltage was also shown; positive potential caused up to 6 % power loss while negative caused a maximum of 2 %. In CdTe modules have PID-Na been reported in dry conditions with some shunting tendencies, and in humid conditions can PID cause corrosion and delamination of the TCO layer (Luo et al. 2017).

Exposing cells to salt (NaCl) before an accelerated damp heat test causes significant power loss in HJT and TOPCon cells, and minor degradation in PERC cells, see table 8. The cause for the power loss is primarily increased resistivity, and also due to migration of Na+ ions. (Sen et al. 2023)

As also seen in table 8 UV exposure can cause degradation of the PV cells, and the power loss varies with cell technology. The study was conducted on unencapsulated cells, and it was concluded that glass and anti-reflective coatings protect from UV damage. To further avoid UV induced degradation can UV-blocking encapsulants be used, though they are more prone to discolouration (Sinha et al. 2022). Ye et al. 2023 studied UV degradation in HJT cells and concluded that the a-Si layer is susceptible to degradation from UV light, and also mentioned encapsulant as a protectant.

PAN performance tests simulate module performance in different locations based on module performance data and characteristics, and bifacial HJT and TOPCon modules perform the best. This is because they have high bifaciality factors and good temperature coefficients; the output power decreases less per increased degree. (PVEL 2023b)

6.3 Frame

Beinert 2022 presents two design rules that concern frame design; *The higher the frame stiffness the better* and *Frame design has to be adapted to specific module design.* The first of these rules is based on that the stress in the module centre depends on the deflection of the frame. Though, the same tests show that this does not affect the probability of cell fractures. The results are presented in table 9 together with results from a test performed by Truthseeker 2022 where modules with a 40 mm aluminium frame and 35 mm steel frame were subjected to downforce and upforce mechanical load.

Table 9: Results from simulations and tests by Beinert, Leidl, et al. 2017 and Truthseeker 2022.

Test	**Aluminium**	**Steel**	**Source**
Mechanical load 2400 Pa (Sim)	50 mm deflection 275 MPa stress in cells	45 mm deflection 270 MPa stress in cells	Beinert 2022
Downforce mechanical load 2400 Pa	3.8 mm deflection	2.5 mm deflection	Truthseeker 2022
Downforce mechanical load 7180 Pa	-5.6 mm deflection 6 new cracks, 2 propagated	1.7 mm deflection 1 new crack, 0 propagated	Truthseeker 2022
Upforce mechanical load	Break at 3830 Pa	Break at 6460 Pa	Truthseeker 2022

In figure 21 are results from two FEM simulations of mechanical load on PV modules shown, where framed and frameless modules are compared. Both Beinert, Leidl, et al. 2017 and Papargyri et al. 2019 conclude that frameless mounting is mainly suitable for glass/glass modules because there is no significant difference in the amount of stress in cells, while there for glass/backsheet modules is a large increased stress in the absence of frame. However, increased stress was found in the cells that the mounting clamps were attached to. This is in line with the assessment from RWE 2020 which states that for a module to be suitable as frameless must the module itself be rigid enough to withstand mechanical stress. There the frame as a protection against moisture is also discussed, and the side sealing must be examined in quality tests.

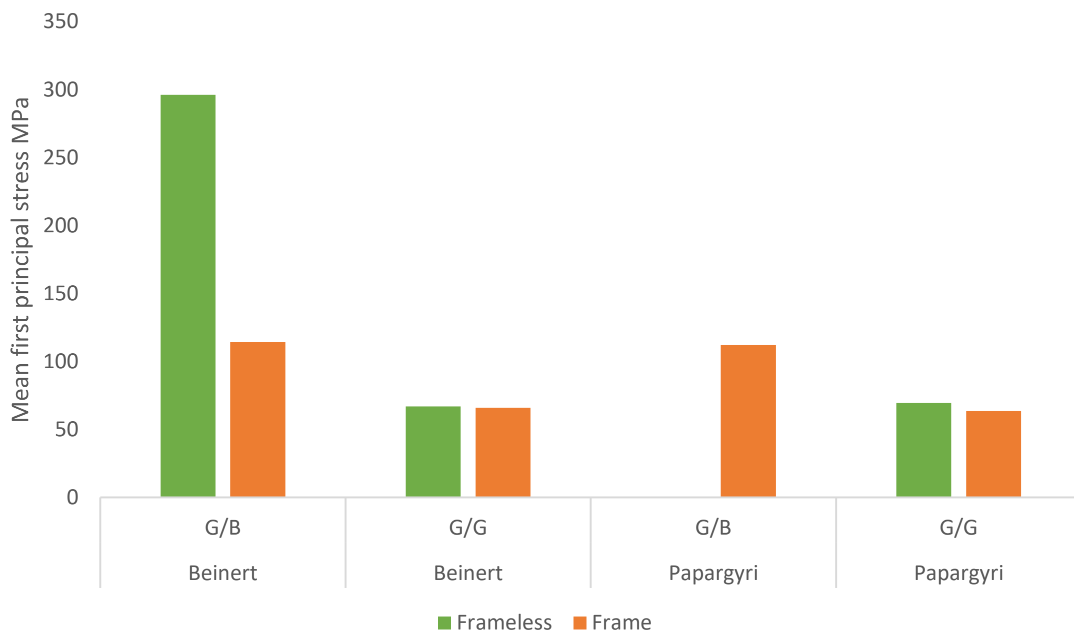


Figure 21: Results from simulations and tests by Beinert 2022 and Papargyri et al. 2019. The latter one did not contain tests on frameless g/b modules

The presence or absence of a frame can have different effects on module coverage by snow, sand, soil etc. Build-up of soling along the edges of the module is more likely in framed modules, which can lead to hot spots (Kazmerski et al. 2017). In snowy environments with a module surface temperature of around 0°C snow can slide off frameless modules faster than framed, which can lead to an energy gain of over 10 %. However, if there is a build-up of snow below the modules, this faster slide-off effect can lead to a larger build-up covering the frameless modules. For module surface temperatures below 0°C are the snow not sliding down the modules, and there are no large differences between framed and frameless modules. (Riley et al. 2019)

The frame is a main source of PID as the potential difference between the grounded frame and the high voltage in the cells causes the degradation. This indicates that frameless modules may reduce the PID in a module. (Luo et al. 2017)

The design of the frame affects its durability and stabilising effect on the PV module, regardless of material. A wider frame causes less deflection in the module, as does also a wider cavity in the design. (Tummalieh et al. 2022)

6.4 Interconnections

Degradation and failures of the cell interconnections are often an effect of other properties of the PV module than the interconnections themselves. A main cause of interconnect degradation is corrosion. One source of this is the acetic acid that is created when EVA is degrading. This acid deteriorates the ribbons or wires, which causes discolouring of the encapsulant and increases the resistance in the conductor. Moisture also accelerates interconnection corrosion, which means that defects in the lamination, glass, and backsheet of the module increase the risk of interconnect failures. (IEA 2017)

Something that decreases the power loss due to interconnection failures is the multi busbar trend, the number of busbars and therefore the connections between the cells are increasing as stated in section 3.2.3. This is because the higher redundancy makes an interconnection failure affect a smaller cell area (Walter et al. 2017). Majd et al. 2022 presents an increased thermo-mechanical reliability of up to 15 % with multi busbar interconnections. Though, more interconnecting busbars means thinner wires and soldering area, which might increase failures in the soldering process (RWE 2020).

Decreasing the gap between cells creates a higher stress in the interconnections when subjected to bending stress, from both external load and thermal stress, which the design of them must take into account. Some designs change the shape of the ribbons which can make the soldering process and result more unreliable. (ibid.)

Shingled cells and conventional ribbons perform differently in thermal cycling tests, see table 10. Klasen et al. 2022 reports cracking of ECA shingled PV cells after thermal cycling tests, caused by bending in the overlap due to thermal expansion and contraction. To avoid cracks must the ECA and encapsulant have similar thermal contraction properties. The power was not severely affected by the cracks, but in outdoor conditions might the small cracks lead to more degradation of the module which can lead to power loss.

ECA shingled modules used in an RWE PV plant showed degradation of ECA in tests made before construction, resulting in power loss. The cause was concluded to be vibration in transportation in combination with performed stress tests, which strained the ECA causing interconnection failures.

Table 10: Results in tests of modules with different cell interconnections, Schiller et al. 2019, C. Kutter et al. 2020

Test	ECA shingels	Conventional ribbons	Source
Thermal Cycling 200 h	0.7 % power loss	1.8 % power loss	Schiller et al. 2019
Accelerated thermal cycling 200 h	0.7 % power loss	1.6 % power loss	Schiller et al. 2019
Accelerated thermal cycling 200 h, glass-free module	1.0 % power loss	3.7 % power loss	Kutter et al. 2020

The PVEL scorecard does not report any performance differences for modules with different interconnection technologies, even though many different modules of different types are tested with varying results. (PVEL 2023b)

6.5 Module and wafer size

Both the size of the module and the cells affect a PV module's resistance to stress. In table 11 are results from a test of two modules of different sizes where the larger was more affected by external loads.

Table 11: Results from test by Longi and TÜV Nord (Longi 2020)

Test	2.26 x 1.13 m	2.38 x 1.30 m	Source
Dymanic load – wind tunnel	Max. vibration speed ± 1.5 m/s. Max. vibration strength 0.025 at 44 Hz	Max. vibration speed ± 2 m/s Max. vibration strength 0.030 at 33 Hz	Longi and TÜV Nord 2020
Thresher test – wind tunnel	Passed at 60 m/s	Failed at 45 m/s	Longi and TÜV Nord 2020
Static load – 2400 Pa	38.5-43.5 mm deformation, 5 cracked cells	63-67 mm deformation, 30 cracked cells	Longi and TÜV Nord 2020

Figures 22 and 23 show the resulting module stress from simulations of thermal and mechanical stress tests. Increasing the number of cells does not affect the thermal impact on the module, but larger cells react better to colder temperatures and slightly worse to hot conditions. The mechanical load simulations show that an increased number of cells and larger cells result in higher stress, though this is primarily in g/b modules.

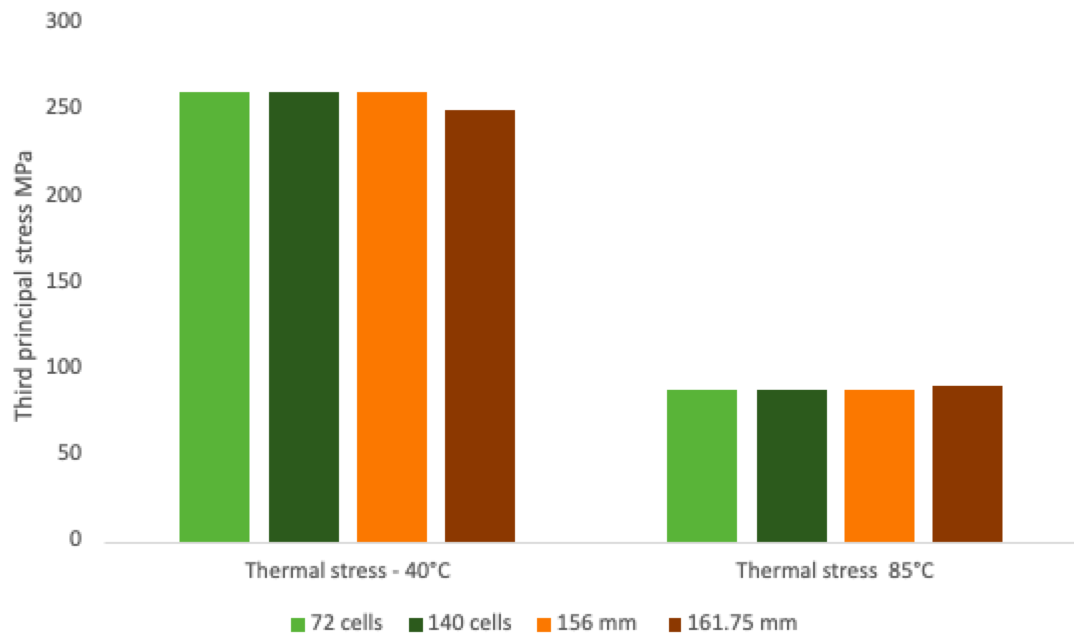


Figure 22: Results from thermal stress simulations by Beinert, Romer, et al. 2020. Changes in the number of cells in green, change in cell size in orange

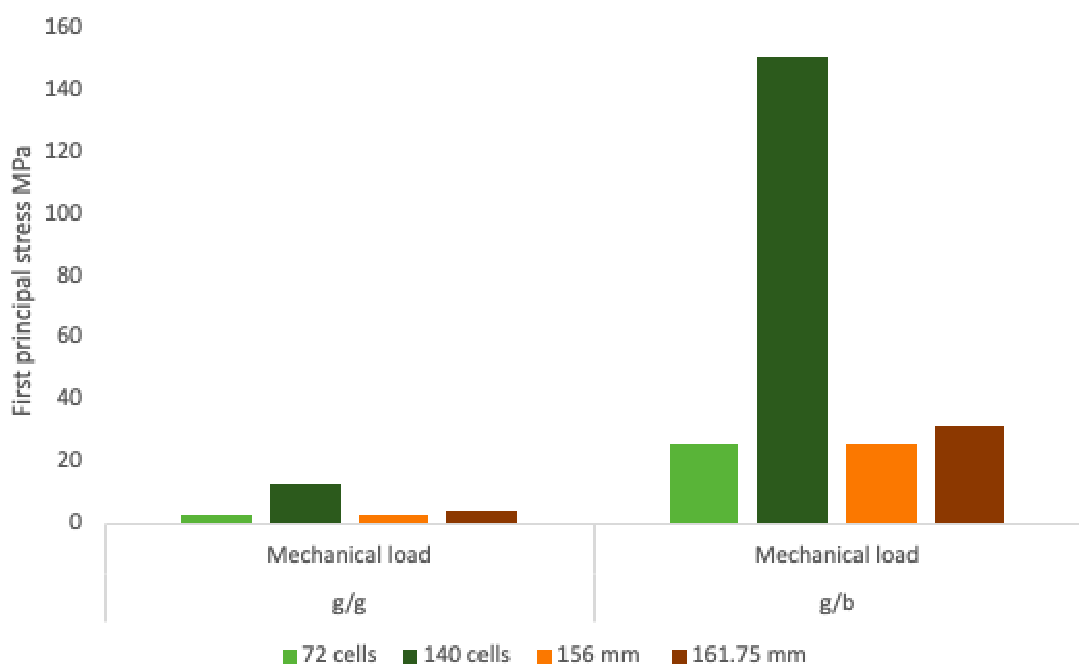


Figure 23: Results from mechanical stress simulations by Beinert, Romer, et al. 2020. Changes in the number of cells in green, change in cell size in orange

Beinert 2022 presents 15 thermomechanical design rules for PV modules based on FEM simulations. Some of them are regarding module and cell size; stress is decreased by smaller module area and longer rather than wider modules. They also conclude that half-cells that are portrait-aligned instead of landscape-aligned reduce the stress significantly when static mechanical load is applied. This is supported by Bosco 2022 who shows that in addition to increased stress is there a probability of fractures of 99 % in the centre of the landscape-oriented cells compared to 39 % for portrait aligned. Romer, Pethani, and Beinert 2023 develops this by concluding that *The short side of the cell should be aligned along the highest expected curvature of the PV module* which can vary with the type of load.

6.6 Encapsulant

The encapsulant in a PV module has a large impact on its reliability. Table 12 presents results on how well EVA, POE, and EPE encapsulants perform in PID tests and a combined increased stress test.

Table 12: Results in performance tests by PVEL 2023a, Mahmood and TamizhMani 2023 and A. Kumar et al. 2022.

Test	**EVA**	**POE**	**EPE**	**Source**
PID test	Four times higher median degradation. 0-9 % power loss depending on backsheet material.	No power loss regardless of back-sheet material.	No power loss regardless of back-sheet material.	PVEL 2023. Mahmood and TamizhMani 2023.
Thermal cycling, damp heat and UV exposure	Severe grid finger degradation	Minor grid finger degradartion		Kumar et al. 2022

PID is a major factor in encapsulation reliability as seen in table 12. The encapsulant can influence the PID-s in Si-based PV cells as high polarity, volume resistivity, and water vapour transmittance rate increase the ionic leakage current. These are properties that are usually high for EVA while lower for POE. A low degree of crosslinking (bonding of polymer chains) in the encapsulant can result in higher volume resistivity, and hence PID, and increased discolouration at interconnections. (IEA 2017)

The back cover-encapsulant combination also influences the degradation of the encapsulant. In an increased stress test study by A. Kumar et al. 2022, a g/g module with POE did show more yellowing but less finger degradation than one with EVA. A module with a transparent backsheet showed equal yellowing regardless of the encapsulant, but POE led to more finger degradation. Patel, Sinha, and Tamizhmani 2020 observed that g/g modules with EVA showed significantly more browning than g/b modules with the same encapsulant when exposed to UV light in the field for several years. The browning was concluded to be a cause of power loss, and the difference between the modules to be an effect of the photobleaching that non-glass backsheets allow.

When UV light and heat react with EVA is acetic acid produced, which is an acid that can cause degradation of the EVA itself and other parts of the module in the form of corrosion of interconnections and PID. Also in this case, the back cover and encapsulant pairing does matter; a backsheet lets the acid escape from the module while the glass traps it. (IEA 2017)

Figure 24 shows the result of a study by Romer, Pethani, and Beinert 2023 where simulations of inhomogeneous loads were applied to PV modules with different encapsulants. At below -20°C are EVA most cell-stress resistant, while for temperatures warmer than -20°C is it POE. POE is also the most protective of the glass at all temperatures.

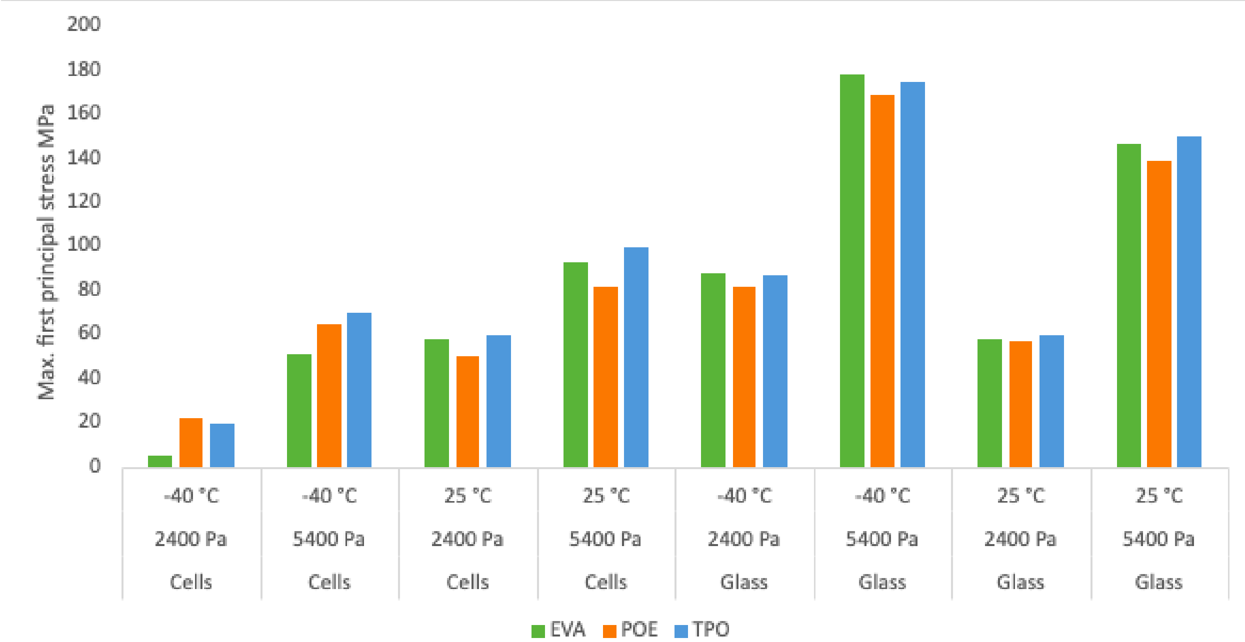


Figure 24: Performance in stress tests by Romer, Pethani, and Beinert 2023

Even the same type of encapsulant can have different effects on the module reliability. PVEL 2023b reports a case of two models identical in everything except the encapsulation suppliers but the power loss in a PID test was 1.1 % and 4.5 % respectively. Uličná et al. 2023 shows supporting results as the degradation of the encapsulants tested does not correlate to the type of encapsulant but components in each variant of encapsulant.

7 Analysis

In this section are the results presented in the previous section 6 summarised, compared to one another and it's evaluated when the different technologies are advantageous. In section 7.7 are the result and analysis summarised to a technology assessment, and a proposal for keeping this up to date is presented, together with how module prequalification plays a part in the quality assurance process.

7.1 Back cover

The main advantages of glass/glass compared to glass/backsheet modules are that they protect the module from moisture to a larger extent, and are generally more durable in heat and humidity. The g/g modules also perform better in mechanical stress tests, and double glass sheets give the module the same stability as a frame gives. However, they are more likely to cause discolouration of the encapsulant over time, which can reduce the photocurrent causing power loss. G/g modules are also more vulnerable during production as the lamination process requires more precision and results in more bending stress.

A backsheet will make the module less likely to be discoloured, or for cracks to occur on the rear side when exposed to mechanical stress and physical impact. On the contrary, they do degrade more in hot conditions, and the different thermal expansion of front and back creates stress during temperature changes. One main disadvantage with a backsheet is that it does not fully protect the module from moisture leading to increased moisture ingress in the module. This can cause accelerated degradation of the cells and their interconnections, resulting in power loss and increased series resistance in the module.

Accordingly should be choice of material to cover the back of the module be dependent on the environmental conditions of the location of the PV modules. In an area with a high risk of hail or other impacts on the module back might there be a benefit of a backsheet, while in a hot and/or humid area or somewhere with fluctuating temperature a rear glass side would be more protective of the module. That would also be the case in environments where the mechanical stress consists of snow load, heavy wind, or similar.

Though, there are attributes in each technology that can affect the durability of the back of the module. Thicker glass (3.2 mm instead of 2 mm) increases the resistance to hail, and different compositions of a polymer backsheet and different glass treatments have separate characteristics. The back cover must also be paired with a suitable encapsulant, otherwise will the durability of both the back cover and encapsulant be affected.

7.2 Cell technology

PERC cells are the most widely used cell technology and have been established for a few years which means that it has been extensively studied and its weaknesses are known. The cells are susceptive to LETID and multiple forms of PID, but generally resist heat well. Previous light induced degradation from boron-doping has been eliminated by instead using gallium, this is an example of how a well established and researched technology is being developed for increased reliability.

On the contrary, TOPCon and HJT as they are constructed today are relatively new in the mass production market and might degrade in unforeseen ways. Both technologies degraded critically when exposed to salt in combination with damp heat, which can make them less suitable for certain environments, for example close to the sea. Though, both TOPCon and HJT are generally less affected by PID and LETID compared to PERC cells. Additionally, while their main advantage is that they have higher efficiency than PERC cells they also keep this efficiency at high temperatures and low light.

One example of the uncertainty of new technologies is that UV exposure caused significant power loss in HJT cells in a recent study. The cause of this is tied to the a-Si layers in HJT cells, and to protect from this can a UV-blocking encapsulant be used. The UV-absorbing additives do however increase discolouration and other degradation of the encapsulant, which also causes power loss. These two degradation causes must therefore be compared to see which affects the module the most, as well as assessment of other methods for UV-protection.

IBC cells are susceptible to multiple forms of PID, mainly PID-p which appears at all voltages but with time and increased voltage reaches saturation. The PID effect is more prominent at positive potential differences, which is something to consider when doing the electrical design of the PV arrays. In UV exposure tests of IBC cells have the results been inconclusive, as cells tested showed both a slight increase and decrease of power after UV exposure. Further testing and field exposure is needed to investigate how UV resistant the technology is.

CdTe has a similar novelty as the other technologies except from PERC; its recent development has made it more efficient which has led to increased market share. It is now the only widely used technology that is not silicon-based, and this has both advantages and disadvantages. While the technology shows good resistance to PID and LETID in some tests there are also degradation tendencies which only future field exposure data can show the extent of.

7.3 Frame

Aluminium frames have for a long time been dominant for solar modules, and while the track record has been good are there now two alternatives on the market; steel frames and no frame at all. Steel frames are constructed in the same way as aluminium ones, but are more durable. Though, this comes with a higher weight which has its disadvantages in production and construction that can lead to quality issues.

The frameless technology is primarily an alternative for glass/glass modules, whose resistance to mechanical load is not affected by whether the module has a frame or not. However can the stress increase in the places where mounting clamps are attached to the module, which might lead to fractures in the cell or glass. The benefits of a frameless module are less material cost and weight, reduced PID, and in certain conditions less power will be lost due to snow or soil coverage because the frameless design allows the snow/soil to slide off.

Making wider frames, regardless of material, increases the module stability. This does however require more material, leading to larger costs, weight, and environmental impact, which often leads to manufacturers wanting as thin frames as possible. Changing the frame design in other ways that do not need more material and don't decrease the frame width is preferable.

7.4 Interconnections

Interconnection failures are often caused by corrosion which is an effect of degradation of other parts of the module which allows for moisture or acid to collect in the module. This emphasises that it is crucial for the reliability of the whole module that all parts work as intended. One part that fails in a non-detectable way can cause another part to fail in a way that causes major power loss. The main failure protection in interconnection technology is to increase the number of busbars for higher redundancy and thus minimise power loss at a failure. However, more busbars involve more soldering points that can fail and are something that must be monitored in production.

The interconnections are vulnerable to temperature changes as the metal in them has a different thermal expansion and contraction than the rest of the PV module. This makes thermal testing important to the interconnection reliability. Cells shingled with ECA have shown less power loss in thermal cycling tests than conventional ribbons, but are more prone to cracking and disconnection in some cases. Shingling using shaped ribbons might not have these traits, but there are not many tests done in that area.

There are not many studies comparing the reliability of different interconnection technologies, the focus is mostly on power optimisation. Different manufacturers often have their own type of cell interconnection, which might be a reason why there are not many third party studies. Though, PVEL who tests modules from different manufacturers with different interconnection technologies does not state any findings regarding interconnections. This lack of studies makes quality testing all the more important for finding and fixing weaknesses in cell interconnections.

7.5 Module and wafer size

A larger module area leads to higher mechanical stress in the module, during both dynamic and static mechanical load. Though there are factors that can decrease the stress; glass rear protection protects a larger module from stress more than a backsheet as the stability increases. The ratio between the module's sides also has an effect; longer rectangular modules are more durable, and extra reinforcement to protect the module and increase stability is also an option. However, with increased module size comes increased module weight, something that is not beneficial in production, transportation, and installation of modules and thus a heightened risk of breaking the module. Therefore might not extra weight from reinforcement be welcome, the result can in some cases be the opposite; to decrease the total weight of a large module might manufacturers make module parts like frame and glass thinner which as previously stated might impact the durability.

The size of cells and wafers is also a factor in this. In very low temperatures, larger cells contribute to stress relief while it is the opposite for very high temperatures. Based on this can the most beneficial cell size be decided depending on in which climate the modules are operating; and which temperatures will be the most frequent. The study that showed this used cells with widths of 156 and 161.75 mm respectively, when increasing the size more the effect should increase as well. The same goes for the number of cells.

Additionally, the dimensions and alignment of the cells are something to consider. Rectangular half cells are more resistant to mechanical load than square full cells, which is great as the vast majority of PV modules now have half cells. However, the vast majority also have landscape-aligned half cells, which is not as beneficial as portrait-aligned from a mechanical stress point of view.

7.6 Encapsulant

The main advantage of EVA is that it has for a long time been the industry standard encapsulant, and has consequently been tested and used in various conditions, and been developed to be durable along the way. Additionally is it stress resistant at very low temperatures. There are however several weaknesses with EVA. The acetic acid production when reacting with UV light is only a factor with this encapsulant, and it is generally more susceptible to PID than others. For temperatures over -20 °C, which is where the vast majority of PV modules are operating, is EVA not the most resistant to stress.

Polyolefins like POE or TPO are a broad group of encapsulants and are fairly new to the PV market. They have been shown to protect the module from PID and mechanical stress in a successful way compared to EVA. POE is especially stress resistant. Though, as with all new technologies, might they degrade in ways that are now unknown.

Still, it is difficult to make conclusions about encapsulation materials on this level as studies show that the composition of the individual encapsulant highly affects its reliability properties.

7.7 Prequalification

7.7.1 Technology assessment

To make a module type qualification for which type of PV modules to use in a solar power plant, the summary of the above results and analysis in table 13 can be used. The main advantages and disadvantages of each technology are stated for comparison, as well as which technologies are compatible with one another. A full version of the assessment can be found in annex 10.2, which includes compatible conditions and additional testing that might be relevant for each technology to make sure that it performs well. One thing to consider and assess further is the frequency and severity of different failures, when compromises are being made between technologies should the overall reliability be as high as possible.

Table 13: Technology assessment: summary of results and analysis

Module technology	Alternatives	Advantages	Disadvantages	Compatible with
Back cover	Glass	Moisture protectant, mechanical stress resistant	Browning of encapsulant, vulnerable during production	Frameless
	Backsheet	Hail resistant	Vulnerable to thermal stress, moisture ingress	
Cell technology	PERC	Widely used and tested	Susceptible to LETID and multiple forms of PID	
	TOPCon	Slow LETID, low temperature coefficients	New technology, possible power loss after UV exposure	
	HJT	Slow LETID, low temperature coefficients	New technology, possible power loss after UV exposure	
	CdTe	No LETID and good resistance to PID		
	IBC		New technology, possible power loss after UV exposure	
Frame	Aluminium	Widely used and tested		
	Steel	Stiff and durable	Heavy	
	Frameless	Reduces PID and soiling	Not suitable for g/b modules, increased stress in clamped cells	G/g modules
Inter-connections	Small gap			
	Shingles	Performs well in thermal cycling tests	ECA vulnerable to cracking and degradation	
	Multi busbars	Increased redundancy	More and smaller soldering points	

Table 13: Technology assessment: summary of results and analysis

Module technology	Alternatives	Advantages	Disadvantages	Compatible with
Module and wafer size	Smaller wafers	Fairly stress resistant in warm temperatures		
	Larger wafers	Fairly stress resistant in cold temperatures		
	Smaller modules	Less mechanical stress		
	Larger modules		More mechanical stress in mainly g/b modules, heavy	G/g modules
Encapsulant	EVA	Widely used and tested	Forms acetic acid when degrading, susceptible to PID	G/b modules
	POE	Stress and PID resistant		
	TPO	PID resistant		

7.7.2 Process

An update of the technology assessment should be included as a part of the process as new research and test results are continuously being presented, the technologies are developing and new alternatives appears on the market. To do this the following annually released reports, used as main sources for this review, can be used

- PVEL's annual scorecard
- RETC's annual PV module index
- Reports from IEA's PV power systems program. A variety of reports are released every year, but there is a summarising annual report, along with annual national reports and a trend report.
- International Technology Roadmap for PV is released every year predicting PV trends.

Research and tests performed by institutes like Fraunhofer ISE, NREL, and many others should also be assessed, but as a broad variation of studies are performed by them might this be more challenging.

The quality tests later in the process are necessary to evaluate the technologies and catch possible failures. All results should be noted for future module type qualifications and quality work. The same applies to operation reports from producing PV power plants. Technology tests are good but are only imitations of the conditions that the modules are operating in during their lifetime. Therefore are field reports a more reliable source of how reliable the modules actually are, and the information must be analysed. How the prequalification and quality process can be integrated in a PV power plant project is shown in figure 25. The steps related to the prequalification process in light green are further described below.

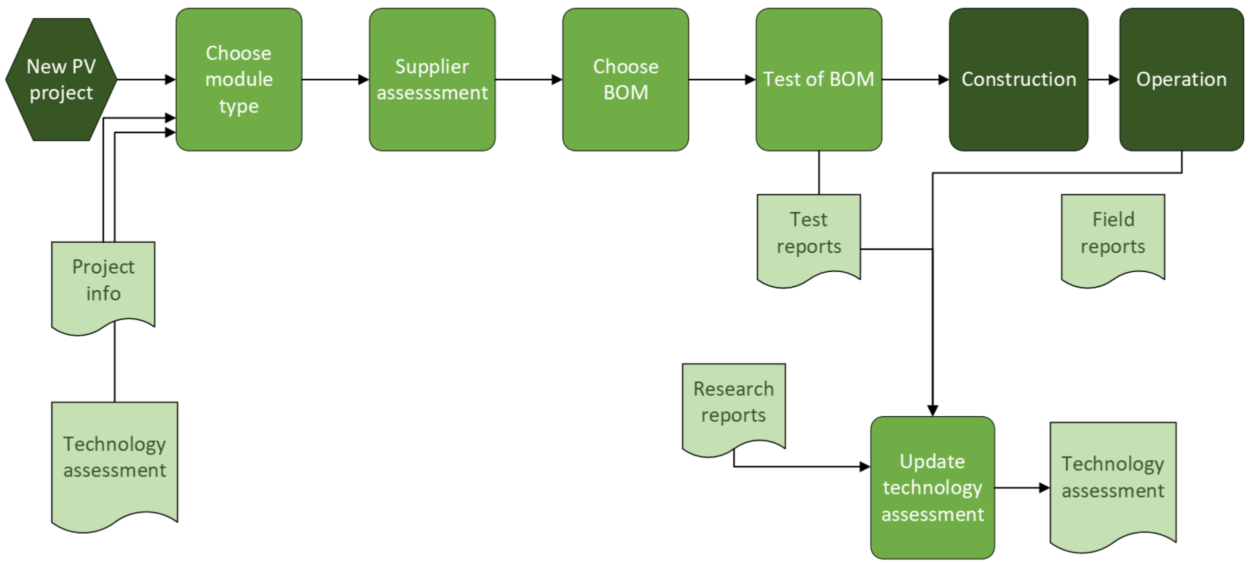


Figure 25: Prequalification process

- **Choose module type:** Based on the project details, available suppliers and the technology assessment is a module type chosen. This can be iterative with the supplier assessment.

- **Supplier assessment:** The supplier should provide documents stating their experience and quality work, for example, IEC certification and third party audit reports (see annex 10.1 for full list). In this stage should factory audits be performed and risk management the assessed to evaluate the supplier.

- **Choose BOM:** When a supplier has been chosen the specific bill of material can be decided. This in dialogue with the supplier, and it is important that the previously shown certification and experience cover the technologies used in the BOM.

- **Test of BOM:** When the complete modules have been decided they should be tested at random; approximately 20 serial numbers are to be chosen and sent to a test lab. Which tests to be performed depends on the technology assessment and the project; what reliability risks are there that must be investigated?

- **Update technology assessment:** When new information is gathered should the technology assessment be updated, as stated in the previous section

8 Discussion

Below are the results and methodology discussed, followed by a broader look at other aspects that affect the choice of module technologies.

8.1 Result and analysis

8.1.1 Technology dependency

The presented result and analysis are divided by technology in a broad sense, for actual modules the reliability depends on the individual bill of material. Aspects like the type and treatment of glass, the composition of the encapsulant, the exact materials in the backsheet, the design of the frame, the dopant in the cells, the width of interconnections etc. plays a large role. Likewise, the combination of all the parts must be compatible with one another. The production is a crucial part of quality assurance as well, as faults easily can appear in one product batch that affects the reliability, though this comparison has assumed that everything has been performed in an ideal way. Therefore are tests of individual modules when the BoM has been decided very important.

8.1.2 Field conditions

While there are general things that affect the reliability of the PV modules are there multiple location specific things to consider when deciding on module type. Module design is a consideration and compromise between different factors, and neither an unreliable nor overly reliable (expensive) module is wanted.

Moisture is one of the main causes of PV module degradation over time, leading to corrosion and PID. Modules in almost all locations are being subjected to moisture, whether it is through rain or humidity, and it causes particular damage in combination with heat. Therefore, the damp heat tests are of great importance, and for all areas, except perhaps the particularly dry, a module that resists moisture is a recommendation.

PV power plants are being built in places with high solar radiation, which often means high operating temperatures. Though, when there is no sun during the night or winter can the temperatures drop significantly and fast, creating thermal stress which some technologies handle better than others. All materials must have similar thermal expansion to not create stress leading to cracks or disconnections, though that is difficult to achieve with metal interconnections. They are therefore of extra importance to test for fluctuating temperatures.

External chemical impacts like that from seawater, industries, cars, or agriculture are also important conditions to consider for the PV modules. Apart from soiling the modules, chemicals can degrade both the outside and inside of the module causing power loss, and is also important to consider in tests in the module qualification process. For sea adjacent PV power plants are salt mist testing crucial, and for those close to agricultural areas, the tests should ideally investigate the reaction to the exact chemicals used.

As extreme weather has become more common and will continue with increased frequency in the future, PV modules must be able to handle storms, heat, snow etc. to be called reliable. This does not mean that all modules should be resistant to 45 mm hail, but that the risk in the intended area should be evaluated for the whole lifetime of the power plant. If there is a risk in the near or far future the modules should be tested and adapted to this. There are several examples of PV power plants being damaged by hail storms, and as presented earlier there are well developed tests for assessing the hail resistance of a module. Thicker glass and a backsheet have been shown to protect the modules from hail breakage, though there are also other solutions where the modules are attached to a movable tracker that can be tilted to reduce the damage.

Additionally are there numerous weather conditions and environmental factors that can not be classified as extreme weather, but still can make a large impact on the PV modules. Strong winds create a large force on the modules, in deserts sand abrasing of the modules is a problem, and heavy rain can make the ground unstable. Things like lightning strikes, and animal or human interference are also things that can happen but are more difficult to protect from on a module level.

8.1.3 Prequalification

All this information and research are of no use if it is not used when building PV power plants. Therefore are some kind of prequalification process needed to ensure reliable modules effectively. Presented in section 7.7 is one broad suggestion that should be specified and altered to the conditions it is applied to.

8.2 Discussion of methodology

The PV industry is growing fast; new modules are being released, power plants built and research made all the time. This means a lot of uncertainty when it comes to reliability;

previous degradation causes like light induced degradation have been developed away, while new weaknesses in technologies are being discovered. When comparing previous International Technology Roadmaps for PV with the most recent are the difference between the predictions often large; the industry is moving forward more quickly than anticipated.

8.2.1 Literature

Because of the fast development, the literature used as a source in this thesis was published at the earliest in 2017, though one could argue that even work from 2017 is outdated. This depends on which type of information is gathered from the work; an evaluation has been made that the information presented in an older source is still relevant for today's modules. Or, in some cases has no more research been published in the area which makes the most recent source the most adequate. And while the development is fast; the technologies that were being researched 6 years ago are now reaching the mass production market.

The main sources used in the literary review are reports and articles published by associations, institutes, or third party laboratories, which have been evaluated to be reliable sources. Other sources used are published articles in scientific magazines, or by universities or industry associations, which also should be reliable. However, the PV research community is quite small, as some authors appear in multiple articles. In some areas are some people doing the majority of the research which might be a source of error as more diversity in studies leads to more secure results.

The sources used have all been in English, though as the majority of all PV modules are being manufactured and developed in China might there have been an advantage to use sources in Chinese as well, in particular from the China Photovoltaic Industry Association. Though, as companies account for the development and production would most information be difficult to acquire as it is their property. Manufacturers are averse to presenting information that is not beneficial to them. One study performed by the manufacturer Longi is used as a source, and its results are that the Longi module is more stable than the other tested one, which is not further presented. Though, as the subject of the test was the size of the module and no similar test had been published the result was in line with simulations, was the test evaluated to be suitable as a source.

8.2.2 Data sources

Tests, simulations, and field data are the data sources that are the basis for the presented result. Out of these are field data the most accurate as that is documentation of actual performance and degradation of PV modules. However, the field data are from modules manufactured up to 10 years before the publication of the results as field exposure takes time. How modules produced today perform in long-time exposure to outside conditions is impossible to know; tests are the best way to estimate that. While tests are made to mimic real conditions and impact on modules are they only tests, and can therefore miss some things and overestimate the importance of others. Simulations can give good indications of how modules react but should be compared to tests and field data as many factors can impact the results.

In section 5.3 are tests of a specific module made by a laboratory presented; all tests are passed except an accelerated aging one causing the module to be labeled as insufficient. One can discuss if the accelerated aging test is necessary and a cause for that labeling as it mimics aging conditions at a rate that won't happen in the field. However, as the module did not pass the test and some modules do, those modules have a higher durability. The question is if this is needed durability or if the modules that pass the test are overly qualified.

8.3 Other aspects

One main limitation of this thesis has been to only take reliability into consideration, which is not the case when making decisions on development and investment in PV modules. Two main factors are the cell efficiency, which differs between technologies, and the cost, which can vary a lot between alternatives for all parts of the module. Other factors to consider are the recyclability of different materials, emissions in production, material availability, country of origin, volume, and weight, health and safety, and the module's impact on transportation and construction.

Another aspect is production, which has a direct effect on reliability; a module that is produced faulty from the beginning is more prone to fail during its lifetime. Therefore is tests of the production line very important to ensure reliability and that the modules reach the necessary requirements. Inversely, the reliability design of modules must consider the production to also make the production as reliable and easy as possible.

Standardisations of PV modules would make some things easier in terms of reliability; comparisons would be more easily made, system parts would be more compatible, and more general requirements could be had. Though, as standardisation can impact the developers and manufacturers negatively are they not likely. However, regarding module size has there been initiatives from manufacturers to create a standard for mid-size modules to increase efficiency in production. IEC presents standards and test requirement continuously which manufacturers follow, though these are the minimum requirements for quality, and as the process is slower than the development can they easily be outdated.

China is dominating the PV industry, and it is percentage-wise likely to continue as large investments are being made both inside and outside of China. Though, the increased production and development in the rest of the world can create a more broad and diverse industry which enables more development and research, perhaps in a more reliable direction. There might also be a chance of increased transparency in the industry when the development and manufacturing spread to more countries as international organisations like IEC will have more impact on an internationally diverse industry.

9 Conclusion

From a strict reliability perspective, the following module would perform the best in most conditions; glass/glass, PERC, any frame, multiple busbars and conventional gap between cells, small module but any wafer size, POE or TPO encapsulant. Though, compromises are required to lower costs and increase power output, and there are advantages and disadvantages to all technologies that must be considered.

As PV modules are developing rapidly, there is a need to evaluate the emerging technologies. The modules will during their entire lifetime be subjected to varying weather conditions which makes reliability and durability a major factor in their performance. A prequalification process based on a technology assessment is one way of doing this, provided that the assessment is continuously updated based on new research and experiences.

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10 Annex

10.1 Tests

Test	Purpose	Desciption	IEC	PVEL	Fraun-hofer	TÜV	RETC	NREL
Visual Inspection*	Detect visible defections	Exterior inspection of all parts of module	x		x	x		
Insulation test	Control that the module is electrically insulated	Connect a DC voltage source to all parts of module	x		x	x		
Outdoor exposure test	Initial exposure of module to real conditions	Mount the module outside for 60 kWh/m2	x		x	x		
Hot spot endurance test	Ensure that hot spots due to reverse bias aren't created	Expose the module to radiation and shadow cells to determine worst-case scenario in terms of generated heat.	x		x	x		
UV-exposure	Identify which materials are suscepticle to UV radiation	Expose the module to UV irradiation 15 kWh/m2	x		x12	x	x3	x40
Thermal cycling test	Test ability to withstand thermal stress	Alternate temperature between -40 and +85 degrees for 200 cycles, one cycle is ~4h. Accelerated thermal cycling has cycles of ~1h.	x	x3	x3	x	x3	x3
Humidity-freeze test	Test ability to withstand high temperatures and humidity followed by cold	Thermal cyling in 85 % relative humidity for 10 cycles	x	x	x	x	x3	
Damp heat test	Test ability to withstand hot and humid conditions	Subject the module to 85 degrees and 85 % relative humidity for 1000 h	x	x2	x2	x	x2	x2
Wet leakage current test*	Test insulation under wet conditions.	Connect a DC voltage source to module while immersed in liquid	x		x	x		
Static mechanical load test	Test ability to withstand static load	Subject the module to a load of 1.5 times x the design load (minimum 2400 Pa) on both front and back side.	x	x	x	x		
Hail test	Test ability to withstand hail	Shoot ice balls of variying size and weight at vulnarble parts of the module	x	x	x	x	x	
Bypass diode testing	Test the functionality of bypass diodes		x		x	x		
Cyclic mechanical load test	Test ability to withstand dynamic load	Subject the module to an alternating load of ±1000 Pa for 1000 cycles	x	x	x	x	x	
PID test	Measure ability to withstand degradation from applied voltage system	Subject the module to 85 degrees and 85 % relative humidity and maximum voltage for 96 h	x	x2	x	x	x2-5	
LID test	Measure the Light Induced Degradation in modules	Subject a number of modules to light until the power has reached LID-stability. (IEC 63202)	x	x		x	x	
LETID test	Measure the Light and Elevated Temperatur Induced Degradation	Modules that have been LID-tested are subjected to 75 degrees and low current for 162-486 h. (IEC 63342)	x	x2	x	x	x	
PAN performance	Simulate module performance	The performance in different operating conditions are used to simulate performance in PAN files for 2 locations		x			x	
Backsheet durability	To test the durability of the backsheet	1000 h DH, (UV exposure, 50 TC, 10 HF cycles) x3		x				
Combined UV and DH test	Test the durability to damp heat and higher UV radiation	Expose the module to > 15 kWh UV irradiation and damp heat			x			
Extended mechanical load test EML	Test ability to withstand high mechanical load	Subject the module to a max load of 10 kPa, temperature from -40 °C to 60 °C, dynamic load frequency up to 0.2 Hz			x			
Salt mist test	Test ability to withstand corrosion	Subject the module to salt mist			x	x		
PTC conditions	Test module in conditions that might be more realistic than standard test conditions (STC)	Cell temperature of 45 °C, ambient temperature of 22°C, wind speed 1 m/s					x	

*Tests that are performed initially and after other tests to evaluate if module is faulty

10.2 Assessment

Module technology	Alternatives	Advantages	Disadvantages	Compatible with	Important tests	Compatible conditions	QA process*	QA process
Back cover material	Glass	Moisture protectant, mechanical stress resistant	Browning of encapsulant, vulnerable during production	Frameless	UV exposure, hail tests	Heat and humidity, heavy load		
	Backsheet	Hail resistant	Vulnerable to thermal stress, moisture ingress		Damp heat, Thermal cycling	Hail		
Cell technology	PERC	Widely used and tested	Susceptible to LETID and multiple forms of PID		PID and LETID tests	Salt		
	TOPCon	Slow LETID, low temperature coefficients	New technology, Possible power loss after UV exposion		PID and LETID tests, UV exposure	Heat		
	HJT	Slow LETID, low temperature coefficients	New technology, Possible power loss after UV exposion		PID and LETID tests, UV exposure	Heat		
	CdTe	No LETID and good resistance to PID			PID tests			
	IBC		New technology, Possible power loss after UV exposion		PID and LETID tests, UV exposure			
Frame	Aluminium	Widely used and tested			Mechanical stress			
	Steel	Stiff and durable	Heavy		Mechanical stress	Heavy load		
	Frameless	Reduces PID and soiling	Not suitable for g/b modules, increased stress in clamped cells	G/g modules	Mechanical stress	Snow and soil/sand		
Interconnections	Small gap				Thermal cycling, mechanical stress			
	Shingles	Performs well in thermal cycling tests	ECA vulnerable to cracking and degradation		Thermal cycling, mechanical stress			
	Multi busbars	Increased rendundancy	More and smaller soldering points		Thermal cycling, mechanical stress			
Module and wafer size	Smaller wafers	Fairly stress resistant in warm temperatures						
	Larger wafers	Fairly stress resistant in cold temperatures			Mechanical stress			
	Smaller modules	Less mechanical stress				Heavy load		
	Larger modules		More mechanical stress in mainly g/b modules, heavy	G/g modules	Mechanical stress			
Encapsulant	EVA	Widely used and tested	Forms acetic acid when degrading, susceptible to PID	G/b modules	Damp heat			
	POE	Stress and PID resistant				Humid		
	TPO	PID resistant						

*Based on RWE's assessment in 2020