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A COMPARISON OF DIFFERENT SOLAR CELL TECHNOLOGIES FOR INTEGRATED PHOTOVOLTAICS

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ABSTRACT: The dominating solar cell technology for PV power plants is the Si based solar cell. However, solar cell technologies such as chalcogenide, organic, III-V or perovskite solar cells, all have their own niche markets or potentials. The aim of this work is to provide an overview and comparison of the different solar cell technologies for the application in integrated photovoltaics. The current statuses of the technologies are reviewed. Characteristics relevant for integrated photovoltaics are defined and each technology is discussed regarding those key influencing factors. The results of the comparison are compiled in a concise table summarizing strengths and weaknesses of the different technologies in respect of their application for integrated photovoltaics.
Keywords: Building Integrated PV (BIPV), Vehicle Integrated PV (VIPV), Fundamentals

1 INTRODUCTION

The integration of solar cell technology in different applications such as at buildings (BIPV) [1–4], vehicles (VIPV) [5–7], roads (RIPV) [8, 9] or electronic devices (DIPV) [10, 11] establishes a set of requirements for the used solar cell technology that differs to those applied in photovoltaic (PV) power plants. Design aspects, such as variable size and form or aesthetic variety, are possibly more important than achieving lowest levelized cost of electricity (LCOE). Additionally, many different types of solar cell technologies exist and are currently explored in the market and in research. Each one of them offers unique advantages and, while the crystalline Si solar cell may be the dominating solar cell technology for PV power plants, it is far from settled which technology is the best choice for an individual application or integration case.

The aim of this work is to provide a concise comparison of the different solar cell technologies for their use in integration applications. It is based on similar approaches performed for assessing the potential of solar cell technologies and for BIPV applications [1, 12]. We have reviewed a vast number of publications for each individual solar cell technology and combined the knowledge of the authors in the respective field to achieve a fair and scientific comparison between each technological approach. While the comparison provides a current perspective, we tried to explore the future potential to be able to provide an outlook for the next years. The comparison is considering technologies at different stages in their development; some technologies are already well established, while others are still under development. Therefore, the comparison needs to be looked at very carefully since some technologies may potentially not be able to achieve technical goals in the end, or unexpected hurdles could be still discovered during development.

In the next section the requirements for the integration of solar cell technologies in integrated applications are reviewed, and the criteria for comparison are derived and defined. The third section discusses the different solar cell technologies individually. In the fourth section, the comparison is carried out and the last section reviews and concludes this work.

Within this work the terms “solar cell technology” or “solar cell” describe the active element converting light into electricity. These solar cells are usually encapsulated by glass, foils or other materials to form a “module” or “PV-module” which is then integrated into the application (see Fig. 1). This work aims to compare the solar cell technologies independent of the module technologies. In certain cases a solar cell technology may offer an easier application or integration of beneficial module technologies. These cases are mentioned and discussed for the respective requirements in Sec. 2 and in Sec. 3, individually.

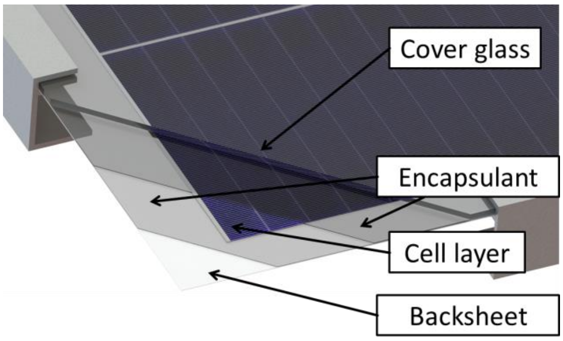

Figure 1: Standard module setup with the cell layer, which is encapsulated by the encapsulant, a backsheet and the cover glass.

2 REQUIREMENTS OF INTEGRATED PV

While each application of integrated PV or even each specific setting or device may have different requirements, this work aims to provide a general overview of such requirements. Therefore, a broad perspective on potential requirements is discussed and criteria for comparison are derived. Afterwards the criteria for comparison are defined in detail.

2.1 Requirements

Integrated PV applications usually provide a delimited area where solar cells can be integrated. The current and voltage output needs to be adjusted for the application. Depending on the application, a maximum power output might be required, or should fit precisely to the used power system [10]. Therefore, the efficiency is a criterion as well as the adjustable electric parameters (i.e. current and voltage output).

While the overall cost is usually one of the major concerns for PV power plants, the cost for solar cells for integrated PV may not be as relevant. In many cases the cost of integrating the solar cells in a suitable module technology for the application is far more expensive [1] such that a small difference in solar cell costs may not be as relevant as for PV power plants. Still it is a requirement since a large cost difference may be a criterion for exclusion in certain applications.

For some applications (notably BIPV) the long term stability is a crucial factor and modules should offer a guaranteed power output, lifetime and non-degrading visual appearance, exceeding even the requirements of PV power plants [4]. In addition, regional building regulations must be fulfilled. For other applications (notably VIPV) the requirements contemplate more severe conditions, such as added vibrations or more prolonged exposure to chemical compounds (i.e. oil, salt). However, the lifetime may be not as long lasting as for BIPV [5]. Even further, some applications (notably DIPV) may not require a life time of more than 10 years and conditions may not be as harsh as for BIPV or VIPV [10]. Additionally, long term stability is majorly influenced by the module technology and can be adjusted. Nevertheless, there are some solar cell technologies which are inherently more stable than other. Long term stability can be considered under the aspects of power output stability, electric safety and stability of visual appearance. Since these aspects are usually observed in combination, they are considered together in the factor “long term stability”. The added vibration requirements are discussed in regards to flexibility.

Integrated photovoltaics is usually applied under non-ideal conditions, such as a non-optimal angle to the sun [13, 14], lower irradiations, diffused light [4], or elevated temperatures [4]. The non-optimal angle reduces the irradiation on the solar cells. If the module has a curvature, this effect is even worse and additional measurements on module level (i.e. usage of bypass diodes or different interconnections) need to be taken into account to minimize power losses [14]. Therefore, performance under lower irradiation and elevated temperatures are considered as criteria.

The design variability and design freedom is a major concern for most integrated PV applications. Criteria are the variability in shape (including curvature) and size, mechanical flexibility of the technology (bending), homogeneous appearance, colored appearance, and transparency. The colored appearance is a module technology [15, 16] (except for certain organic solar cells and c-Si solar cells) that requires a homogeneous appearance and therefore, it is included in the discussion of homogeneous appearance. Additionally, weight and (e.g.) fracture strength of a module, are usually also part of design requirements for integrated photovoltaics. However, these characteristics are mainly defined by the used module technology and are therefore not considered for the cell comparison.

The life cycle assessment (LCA) is becoming more and more important for most application cases in industry. Therefore, the cell technologies need to be compared regarding the impact in different LCA categories such as climate change, particulate matter, resource use or ecotoxicity. Since this topic is vastly complex and current research is performed regarding these effects, this work limits itself to a very rough overview on hazardous materials used during manufacturing or within the device.

As a final requirement category, the future potential of the cell technologies are examined. It will be discussed regarding a view from the market penetration perspective and from the current research activity to account for the different time scales of possible implementations into products.

2.2 Comparison criteria

The comparison criteria are categorized as: criteria influencing the levelized cost of electricity (LCOE); design criteria, which provide an overview on the creative leeway of each technology; and future potential, which is described by the market size and research interest to show maturity as well as development perspective. Additionally, the design criteria contain a brief assessment on used hazardous materials.

LCOE criteria:

Efficiency: If possible, a currently achieved efficiency range of publicly available modules is considered. Otherwise a module efficiency is estimated based on current research results and used as main evaluation criteria. Additionally, a lab record efficiency of the cell technology as provided in [17, 18] is considered as well.

Cost: If possible, the market price range in $\$/W_p$ is considered or a market price range is estimated based on current research and industrial roll out plans.

Long term stability: The long term stability is largely influenced by the module setup, since a module acts as a barrier to the environment. However, some cell technologies are requiring additional measures for environmental protection compared to others. Therefore, long term stability is evaluated on cell level. It considers how fast degradation occurs under regular conditions such as humidity, thermal cycles, and UV-radiation.

Performance under lower irradiation: This criterion considers how the solar cell performs under lower irradiation (e.g. 100 W/m²) relatively to standard testing conditions (STC, 1000 W/m^2, 25°C). This relative change needs to be observed in regards to the efficiency of the cell. A low performance under low light may still provide a comparable high power output to other cell technologies with better performance under low light if the power output at STC is already higher.

Performance under elevated temperature: Similar to the previous criterion, it is evaluated how the solar cell performs under elevated temperatures (e.g. 60 °C) relatively to STC conditions.

Design criteria:

Size variability: The size of the standard element and the smallest element is considered as well as the additional efforts to achieve non-standard sizes. The scalability to larger sizes is also considered, e.g. if additional measures need to be taken into account to achieve larger modules starting from the standard size.

Adjustability of electric parameters: The adjustability of electric parameters is considered on module level. Therefore, not only the possibility to vary the cell output voltage and current is considered but also the interconnection variability. Solar cells can be interconnected in parallel or in series to adjust the current or voltage output of the module. The size of the smallest current or voltage increment is usually determined by the smallest cell size. The standard cell size, the reasonable possible smallest cell size and the additional effort to achieve smaller than standard cells are considered.

Variability in shape: It is considered if complex and non-rectangular shapes in 2D (flat modules) can be achieved and how complex the methods or adjustments are. A possible curvature in 3D is also considered within a reasonable curvature range, since larger curvatures may reduce the power output significantly [14] and prevent usage of such modules.

Mechanical flexibility of the technology: This criterion considers the vulnerability of the cell technology in regards to repeated bending. Aspects are piecewise or continuous bending, or if single time or frequency bending is possible.

Homogeneous appearance: The homogeneous appearance can also be considered a module technology; nevertheless, some cell technologies are inherently better suited to provide a homogeneous appearance than others. Therefore it is considered how difficult it is to achieve a homogeneous appearance.

Transparency: It is assessed whether a cell technology can be transparent or semi-transparent in the visible spectrum range. Translucency is also considered. It is not considered if module segments can be without cells to achieve local transparency since this applies to all technologies.

Hazardous materials: The mainly used hazardous materials during production and within the device are considered.

Future potential:

Market penetration: The market penetration is described by the current number of manufactures and manufactured volumes worldwide for a given technology.

Research activity: The research activity considers the number of different research groups working on a technology.

3 SOLAR CELL TECHNOLOGIES

Over the years, an assortment of different solar cell technologies has emerged, and the technologies are investigated in the market and in research on different levels [19–23]. This work limits itself to currently actively discussed technologies in research and with a clear industrial perspective. Therefore, previously actively discussed technologies such as amorphous Si [24] or dye-sensitized solar cells [25, 26] are excluded. As an emerging technology we specifically included Perovskite-Si tandem cell concepts [27, 28] since it is currently very active in research and a clear perspective in the market is shown by current ramp-ups for industrial scale production [29].

An important consideration for design aspects is the differentiation between thin-film based technologies and wafer based technologies (see Fig. 2). Thin-film based technologies consist of coatings that are applied onto a substrate. These films can cover larger areas homogeneously and interconnection between cells is included in the films. The substrate may already be a module part. Wafer based technologies are built around alterations of or on a material slab. The slabs (wafers) need a separate interconnection and encapsulation.

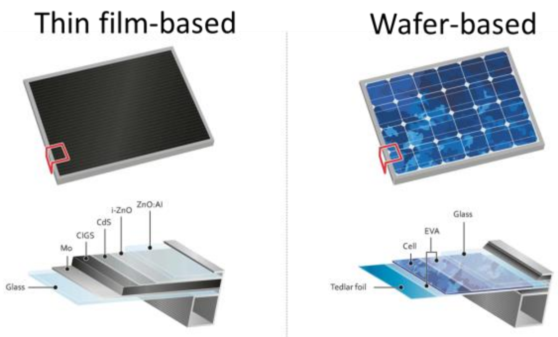

Figure 2: Overview of thin-film- and wafer-based technologies on the example of CIGS solar cell technology and c-Si solar cell technology.

Thin-film based technologies are chalcogenic, organic and perovskite solar cells. Wafer based technologies are crystalline-Si and the considered hybrid tandem cell concept. III-V solar cells are a thin-film based technology, which is usually applied onto wafers [30] or small (metal) foils [31, 32], which need an external interconnection. Therefore, III-V solar cells are considered as wafer based technology for this comparison.

3.1 Crystalline Si cells

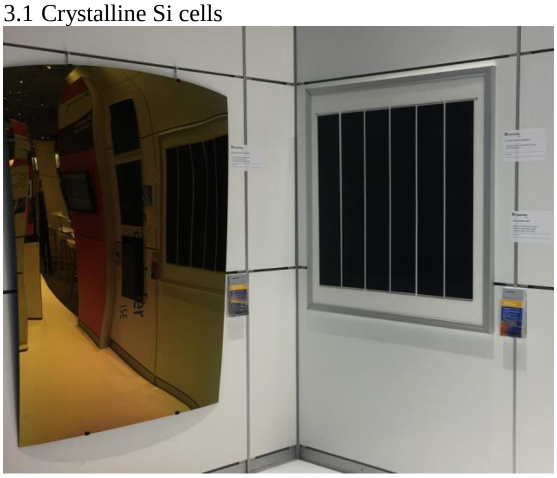

Figure 3: Curved vehicle roof with matrix-shingled [33] crystalline Si solar cells behind a golden color layer (left) and flat truck box body panel with series-shingle crystalline Si solar cells (right).

Crystalline Si (c-Si) cells offer an available module efficiency of 20.5%-22.8% [34]. The current lab efficiency record of a cell is 26.7% [18]. Figure 3 shows two developed prototypes for vehicle integration using crystalline Si solar cells.

The cost of a standard cell is currently around 21 €/m² (11.5 €ct/W_p) and of a module around 40 €/m² (21.4 €ct/W_p) [35].

Regarding long term stability, the cell need to be protected from humidity, this is easily solved by encapsulation in a module. Different thermal expansion coefficients of the cells and the encapsulation and interconnection materials may degrade the module under frequent temperatures changes. The c-Si cells may crack under mechanical load. Nevertheless, a guaranteed power output over 30 years can be observed in the market [36, 37].

The performance under lower irradiation and temperature strongly depends on the specific cell technology but usually higher temperatures reduce the cell output power by around 0.5% relative per K. As an example a module with 21% efficiency at STC may have an efficiency of 17.3% at 60 °C [38]. For different c-Si solar cell technologies, this effect is drastically reduced [39]. Similarly, the efficiency for low light conditions is also reduced to around 90% at 100 W/m² irradiation [40, 41].

As a wafer based technology, the standard size of a cell is 15.6 x 15.6 cm² and the voltage at maximum power point (MPP) is at around 0.5 V per cell and the current just below 10 A. Variation in current is only possible through varying cell size usually done by laser cutting. This is already an established industrial process [42] but a cell size below 1 x 1 cm² is not realistically feasible. The layout of complex flat modules with standard wafer based Si cells may be not optimal and many inactive gaps will be observed. Only the cutting of cells and a more complex interconnection scheme may be able to facilitate a good module efficiency of complex structures. Regarding 3D shapes, a stepwise linear curve of a module is easily possible, however the cells themselves should not be bent more than 1-2 cm across the wafer size of 156 cm. A repeated bending is only possible were cells are interconnected but should be ideally avoided due to possible detachment of connectors. There is current research on manufacturing cells with very thin Si wafers [43]. These cells would allow a much stronger curvature, potentially repeated bending and even a cost benefit relative to standard cells. However, this is not yet an established technology.

A homogeneous dark appearance can be achieved by employing IBC solar cell technologies [44] or shingled interconnection technologies [42]. Furthermore, blackening of the interconnectors can be performed [45]. All technologies are available in the market; however they require some additional processing (e.g. cell cutting and conductive gluing as interconnection for shingled technology). The c-Si solar cells cannot be made transparent, however parts can be cut out or the distance between cells can be increased to achieve a partial transparency [46].

The impact on climate change, particulate matter, resource usage and eco-toxicity has been investigated in previous publications for crystalline Si solar cells [47–49]. The main aspect regarding eco-toxicity is the usage of hazardous gases and liquids during production. Additionally, small quantities of lead for contact formation within the metallization paste and soldering are used in the module.

Wafer based Si solar cells are the dominating technology in the market and have a market share of around 95% of the 131 GW PV production worldwide [50]. More than 500 research groups in universities, institutes or companies work on and develop this technology.

3.2 Chalcogenide cells

Chalcogenide solar cells are cells that contain chalcogens (e.g. selenides, tellurides) as part of the semiconductor element (e.g. copper indium gallium selenide (CIGS) or cadmium telluride (CdTe) solar cell concepts). These solar cell concepts are usually thin-film based but they can be also manufactured as wafers [51]. Current available module efficiencies are in the range of 16-17% [52] and lab record efficiency is around 22-23% [18]. Figure 4 shows an example of a CIGS flexible module.

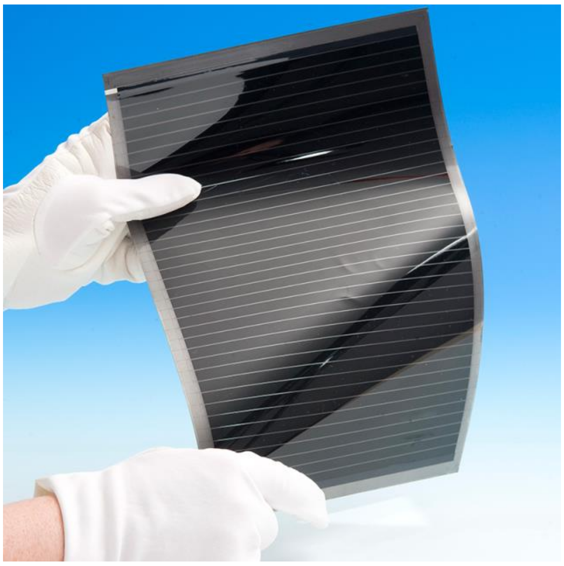

Figure 4: Flexible CIGS solar cell on a titanium foil.

The costs of chalcogenide solar modules are in the same range as c-Si modules. As an example, a façade element including supporting profile and mounting system, costs around 100 €/m² [53].

Regarding long term stability, chalcogenide solar cells are somewhat more susceptible to humidity. Therefore slightly more efforts are required than for c-Si technology [54]. Nevertheless, a guaranteed power output over 25 years is offered in the market.

The performance under lower irradiation and elevated temperature can be different for different chalcogenide cell types [38, 41]. The temperature effect is slightly reduced compared to c-Si while the reduction in efficiency for lower irradiation is smaller for CdTe but slightly higher for CIGS.

A common module size is around 60 x 120 cm² or 120 x 200 cm² [53]. Smaller and larger module sizes are easily possible but require additional processing steps such as glass cutting. Patchwork modules with very large sizes adapted to façade technologies are established in the market. The current or voltage can be easily adjusted by variation of cell size and width within a module. This variation requires just a different layout of the cells and their metallization but does not require additional processing steps.

The flat panel shape can be varied as well and only little effort is required to adjust to special shapes (circles, stars, and others). Manufacturing of curved modules is also possible by coating on the 3D curvature directly. By using a flexible substrate, it is also possible to manufacture fully flexible, lightweight and bendable solar modules.

The appearance of chalcogenide solar cells is very homogeneous intrinsically; conduction bands are usually very thin and only barely visible. Semitransparent modules are available in the market; the efficiency lowers proportionally with increasing transparency.

Chalcogenide solar cells may contain small quantities of elements such as Indium and Gallium. They may even contain small amounts of Cadmium and Selenium which are considered toxic materials. Additionally, further toxic materials are used during production. However, all these elements are only used in very small quantities.

The market size of this cell technology is around 4-5% of the global PV market (around 7.3 GW in 2019) [50]. There are around 50 labs in the world performing active research on chalcogenide solar cells.

3.3 Organic solar cells

Figure 5: Flexible organic solar cell module.

Organic solar cells are made of carbon based materials and electronics, which is under strong development and many materials or material combinations, are being currently explored. The currently available module efficiency is around 6-8% [55] while a lab record efficiency of 17.4% [56] has been recently demonstrated.

The cost of organic solar modules is potentially lower than c-Si technology, however due to the currently much smaller market, the cost per W is in a similar range or even higher as for c-Si cells, while the cost per m² is lower [55].

The long term stability of organic solar cells is comparably low and significant additional efforts have to be performed to prevent degradation [57, 58]. Additionally to the degradation by humidity, the cells also degrade under prolonged UV illumination, which has to be avoided by e.g. UV-filtering. A lifetime of more than 10 years is achievable.

The effect of lower irradiation and elevated temperatures is not as strongly observed as for c-Si solar cells [59].

The size and shape of organic solar cells can be freely varied and manufacturing directly onto curved substrates is possible. Voltage and current of a module can be as simply handled as for chalcogenic solar cells. As standard size, current production equipment provides modules with 20 – 30 cm width and a variable length [55]. Prolonged bending of organic solar cells is possible and the cells will not degrade if the bending radius is not extreme.

As a thin-film based technology, the appearance is homogeneous and even certain transparency of the cells is possible with minimal losses in efficiency [60].

Potentially carcinogenic solvents are used for manufacturing organic solar cells, however, these could be avoided by using alternative (green) solvents [61]. Since similar solvents are also used for the other cell concepts, the eco-toxicity of organic solar cells is considerably lower in comparison to all other technologies.

The market penetration of organic solar cells is at around 0.2 GW in 2019 [50]. The research community for organic solar cells is formed by around 100 research groups worldwide focusing on this technology.

3.4 III-V and III-V tandem cells

III-V cells are developed as single-junction devices with a simpler structure and lower cost but also as multi-junction devices which offer a higher efficiency (see Fig. 6). Both are considered in this text. Additionally, the cells are available as cells on substrate [30] and as thin-film technology on metal foil [32]. III-V solar cells offer an available module efficiency of around 30% and a lab cell record efficiencies of up to 38.8% (for non-concentrated irradiation, 5-junction cell) [56].

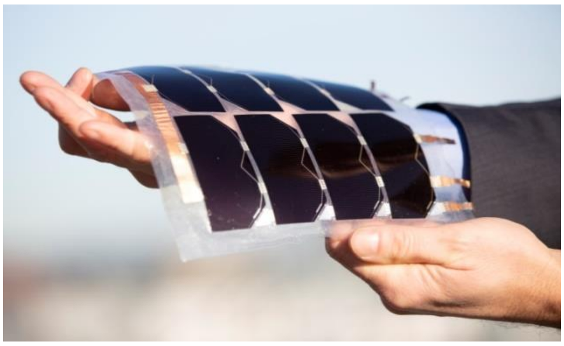

Figure 6: Flexible and light-weight III-V module.

The cost per Wp of a III-V multi-junction cell is currently 1-2 orders of magnitude higher than for crystalline Si. Module costs can even exceed this value due to the required high yield (due to the high cost of breakage) which is achieved by manufacturing modules by hand.

III-V solar cells have been used for decades in space applications where they have demonstrated outstanding reliability [62]. The cells are stable under irradiation and for temperatures of up to 150 °C. Humidity can lead to corrosion in a way that may be similar to today’s Si solar cell devices.

The performance of III-V solar cells under low light conditions and for elevated temperatures is slightly better than for c-Si technology. This is due to a lower dark saturation current and temperature coefficient.

The typical cell size is around 3-4 x ca. 8 cm² and the current and voltage depend on the number of junctions and the specific bandgap energy of the materials. Typical 3-junction devices under AM1.5g have voltages around 2,5 V and currents of around 0,4 A. Voltage output can be varied within a certain range by using different layers and the current can be varied by adjusting the cell size. Cell sizes range between mm^2 for concentrator solar cells up to the maximum size which can be fit onto a 4” or 6” wafer. Cells are produced using photolithography, metallization, lift-off and etching processes on round wafers. Therefore, rectangular cells often have cropped corners to fit onto the circular substrate. There is less standardization and more flexibility for custom designs in terms of cell dimension and shape. Germanium based devices have been manufactured with a thickness in the range of 60-150 µm, with the thinner ones being partly flexible. Thin-film solar cells on metal foil can be even thinner, with a thickness of < 30 µm, and allow shaping into both crystallographic directions without causing cracks [31].

A homogeneous appearance with III-V cells is similarly possible as for c-Si technology. Shingled interconnection has been observed in the market [63]. A level of transparency is in principle possible by using thinner layers; however, it is usually not employed since the efficiency will drop significantly.

During manufacturing some hazardous gases are used and a cell contains small amounts of Arsenide.

The current market volume is around 1.5 MW, mainly for aerospace applications. III-V PV technology is actively developed in around 30 research labs worldwide.

3.5 Perovskite cells

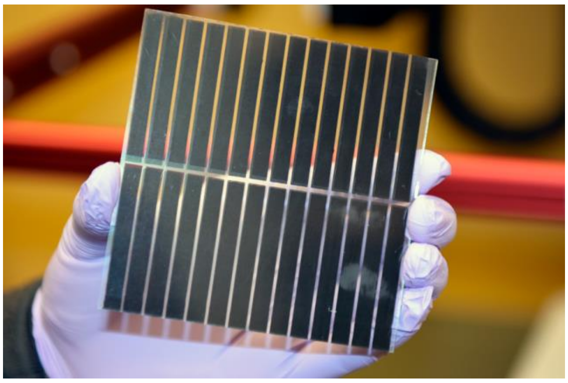

Figure 7: Perovskite solar cells manufactured by the OIST Energy Materials and Surface Sciences Unit [64].

Perovskite solar cells are a rather new technology which has achieved an impressive rise of lab efficiency records. While perovskite modules are currently not available in the market, many companies are already in the testing phase of module products [65]. The module efficiency is currently at around 18% and the record cell efficiency is at 25.2% [56].

The module costs are currently very difficult to estimate but are expected to be lower than for c-Si technology after an initial ramp up phase and considering economy-of-scale effects [66]. Stability issues, however, could lead to a higher LCOE.

Long term stability is similar to organic solar cells; since humidity has a similar deteriorating effect on cell performance. Additional measures have to be performed to prevent humidity from reaching the cells.

The performance under lower irradiation and elevated temperatures is at around 90% for 100 W/m² or 60 °C [67, 68]. Therefore, the cell technology is less affected than other cell technologies.

The size can be varied freely and different 2D shapes are possible to manufacture. As a thin-film based technology, module output parameters can be easily varied just by adjusting metallization and layout during manufacture, similar as for chalcogenic cells. Curvature of perovskite modules has not been investigated in great detail but it is expected to be similar to chalcogenide solar cells and manufacturing in 3D shapes or on flexible substrates is possible. Bending is also possible similarly to organic solar cells.

Perovskite cells show a very good homogeneous appearance. Similar as for chalcogenic cells, perovskites can be manufactured transparent [69]; however the decrease in efficiency scales with increasing transparency.

The current perovskite cell technology contains solubly lead and the risk for a possible release into the environment is higher than for c-Si technology; however manufacturing is less resource consuming.

Since there are only a few companies which are currently ramping up perovskite manufacturing, there is no market penetration. However, there is an increasingly active research community of around 500 research groups worldwide trying to further develop perovskite solar cells.

3.6 Hybrid tandem cells

The term “hybrid tandem cells” in this regard means a stack of different solar cell technologies on top of each other to increase power generation. This is different to III-V or organic solar cells, which use a similar material to achieve a tandem solar cell. Three currently investigated concepts are III-V on silicon [70], perovskite on CIGS [71] and perovskite on silicon solar cells [72]. Only the latter is considered here since there is not yet a visibly clear industrial potential, e.g. a company planning a definite role out for III-V on silicon PV or perovskite on CIGS.

Figure 8: Perovskite-Si tandem solar cell with 28% efficiency manufactured by Oxford PV [29].

The efficiency of modules is not known yet, but it is expected to be somewhat higher than for c-Si. A module efficiency approaching 30% is targeted but needs strong development to be reached. The lab efficiency record of a cell is currently at 29.15% [56].

The cost of such a module can only be estimated as of now and may be higher than for c-Si, but it is expected that the efficiency increase overcompensates the additional costs. Again it depends on the stability whether lower LCOE are possible.

The long term stability is largely affected by that of the perovskite cell and, therefore, similar effects apply as for perovskite cells, with necessary additional efforts for encapsulating the cells.

The effect of low light conditions and elevated temperatures is likely to be driven by the silicon bottom cell. Therefore it might be similar as for c-Si cells.

Since the perovskite-Si tandem cell is a wafer based cell type, the same rules apply regarding size and shape variability as for the c-Si cell technology. The voltage of such a tandem cell is around 1.7 V and the current of a prospective standard size cell of 15.6 x 15.6 cm² is around 4,8 A. Also a homogeneous appearance is only possible by using additional measures such as contact covering and shingled technology. A transparency of the cells is not possible.

The impact on resource use and eco-toxicity is a combination of the impacts of single perovskites and c-Si cell technologies. Therefore, the lead content is similar to the lead content of the perovskite layer and for manufacturing almost the same gasses and liquids are required as for manufacturing the cells separately.

Only very few companies are currently exploring perovskite-Si tandem technology and there are even no field tests completed yet. The research activity specific to perovskite-Si tandem cells is also not as strong as only a few labs have the ability to perform research and development for both technologies. However, many perovskite labs are also working on perovskite tandem technologies in collaboration with c-Si research groups and more than 100 research groups are exploring the topic worldwide.

4 COMPARISON OF CELL TECHNOLOGIES

Table 1 shows a general overview of the different solar cell technologies. While technologies such as c-Si, chalcogenide and III-V are already well established and have demonstrated reliability in the field, newer technologies such as perovskites and perovskite tandems are not yet in the market and long term experience is limited. Therefore, the comparison has to be looked at very carefully since certain criteria such as cost and long term stability are already proven for the established technologies while newer ones still need to show their performance in the field. Here each comparison criteria is briefly discussed and followed by a general comparison considering the 3 criteria groups (LCOE, Design, Future potential).

4.1 Comparison regarding each criterion

Efficiency: III-V solar cells show the highest efficiency in research and also in industry. Perovskite-(Si)-tandem concepts show the potential to provide very high efficiencies as well. Organic solar cells on the other hand have a very strong potential but it is still unknown if a material combination can be found, which provides similar efficiencies as the other current technologies.

Cost: The cost of c-Si and chalcogenic solar cells is the lowest, potentially followed by organic solar cells. This is heavily influenced by economy-of-scale effects (see also Sec. 4.2). The cost of perovskite-tandem will initially be higher than c-Si technology but may drop significantly with large scale production. However, this is still uncertain in the market.

Long term stability: Proven long term stability is provided by c-Si and III-V solar cell concepts even under harshest conditions. Chalcogenic cells follow closely with a proven long term stability. However, this is not the case for perovskite yet, which still need to demonstrate long term stability in the field.

Performance under lower irradiation: The differences between the cell types are minor. Organic and III-V solar cells have an intrinsic material advantage in low light conditions, however chalcogenic solar cells (CIGS) have been observed to perform slightly worse than c-Si.

Performance under elevated temperature: Again the difference between the cell types is marginal. While some c-Si cell technologies are affected by temperature, other materials, especially perovskites, III-V and organic materials show a slightly lower temperature coefficient.

Size variability: The wafer based solar cell types (c-Si, III-V, perovskite tandem) have an intrinsic disadvantage due to a provided standard cell size (which is the smallest for III-V). The thin-film based technologies are in principle able to provide any size easily, but practical reasons (deposition chambers) may still limit the variability for reasonable costs.

Table I: Comparison of the different solar cell types regarding the defined criteria of section 2.2. A plus denotes a comparable positive characteristic for the respective criteria while a minus denotes a comparable lesser fulfillment of the respective criteria. Characters in brackets denote that a very strong development in this category is currently visible and the related 5 year-to-market-potential is estimated.

Criteria	c-Si	Chalco-genide	Organic	III-V/III-V Tandem	Perovskite	Perovskite-Si Tandem
LCOE criteria						
Efficiency	+	o	- (o)	+++	(o)	(+ to ++)
Cost	++	++	+ (++)	--- (o)	(o to ++)	(- to ++)
Long term stability	++	+	o	++	- (o)	- (o)
Performance under lower irradiation	o	-	+	+	o	o
Performance under elevated temperature	o	o	+	+	+	o
Design criteria						
Size variability	o	+	+	+	+	o
Adjustability of electric parameters	o	+	+	++	+	o
Variability in shape	-	+	+	+	+	-
Mechanical flexibility of the technology	-	++	++	+	+	-
Homogeneous appearance	+	++	++	+	++	+
Transparency	o	+	++	o	+	o
Hazardous materials	+	o	++	o	o	o
Future potential						
Market penetration	+++	+	o	o	-	-
Research activity	++	o	+	o	++	+

Adjustability of electric parameters: III-V cells show the greatest advantage for this characteristic since a vast number of substrates are available which can be employed to generate different voltages and the current can be easily varied with the cell size. Besides III-V cells, thin-film based technologies offer a unique advantage in comparison to the wafer based technologies, since interconnection between the cells can be easily adjusted.

Variability in shape: Again, the same principle for wafer based and thin-film based technologies applies. The differences between the technologies are even more pronounced, since the thin-film based technologies can be more easily adjusted. III-V cells have a slight advantage in comparison with c-Si and the proposed perovskite tandem technology due to the smaller standard cell size.

Mechanical flexibility of the technology: The thin-film based technologies are in principle more flexible and can be bent regularly without destroying the solar cell. This is even a standard during roll-to-roll production for organic type solar cells. Additionally, the III-V cell type already has flexible substrates available as well.

Homogeneous appearance: With reasonable additional effort, all technologies can be made such that a homogeneous appearance is possible. Again, thin-film based technologies have an advantage since the homogeneous appearance is already a standard design.

Transparency: To the cost of efficiency, a level of transparency is possible for all types of solar cells either be reducing material thickness or reducing the active area. Organic solar cells offer a unique advantage here, materials can be used which harvest the infrared wavelength range, therefore transparency and efficiency can be high. For thin-film based technologies transparency is achieved by reducing thin-film thickness which is easier than cutting the wafer based cells to achieve the effect of transparency.

Hazardous materials: For all cell types, hazardous materials are only used in small quantities and the potential risk for environment and humans is significantly lower than for almost all other power-generation and power-storing technologies. Lead is contained within c-Si solar cells and perovskite cells. The lead in perovskite is water soluble, providing a potentially higher risk. Selenium and Cadmium are part of the chalcogenic solar cells and Arsenide is part of III-V solar cells. Organic solar cells on the other hand can be used without hazardous materials.

Market penetration: Market penetration is by far the highest for c-Si solar cells and currently non-existing for perovskite and perovskite tandem technologies.

Research activity: The research activity for c-Si is the highest and currently mainly driven by research institutes and companies. Perovskite solar cells also show a high research activity but mostly within academia, which is also visible for organic solar cells.

4.2 General comparison

Crystalline Si solar cells are the dominating technology for PV power plants, which is also visible on their superior performance regarding LCOE criteria (see Table 1). Additionally, c-Si technology benefits from a strong market position and large active research community. The effect of scaling and the technological improvements along the production chain allowed increasing efficiency while also tremendously reducing costs during the past decades. This trend is likely to continue for the next few years. However with the approaching theoretical efficiency limit, questions arise on for how long improvements can be sustained.

Looking at the design criteria, all thin-film based technologies show significant advantages comparing to the wafer based technologies (except III-V technologies). In this area organic solar cells may offer the best overall performance (considering design criteria only) followed closely by perovskites, chalcogenic and III-V solar cells. Therefore, thin-film based technologies could be more suitable if cost or highest efficiency is not the main focus, but specific requirements for cell parameters such as shape, electrical parameters or even aesthetics need to be fulfilled. Nevertheless, c-Si technology is still often used even for those applications since the combination of high efficiency and low costs justifies the additional efforts to match design criteria. If other cell technologies (e.g. chalcogenic) would benefit from the economy-of-scale factors such as c-Si, they may be able to outperform c-Si technologies in many applications. Therefore, a strong application market, where scaling factors could arise, may be able to drive the development of an application focused cell technology. This has already occurred for III-V solar cells, which focus on applications where highest efficiency is the main requirement. With an established niche market of space applications, developments are directed to cost reduction and improving suitability to other applications such as aircrafts.

A big advantage of the non-established technologies is that a standard layout or module design has not yet been defined. Therefore, a single niche application market may develop a standard for this technology, providing the best fit for the specific application.

The future potential beyond the next few years is much more open and difficult to access. Organic and perovskite cell technologies have recently demonstrated surprising developments towards higher efficiencies and are therefore actively developed by the research community. Hybrid tandem cells with a c-Si bottom cell could even replace c-Si technology for PV power plants but there are still further developments necessary to reach this point and the established technologies are also still improving.

5 CONCLUSION

An overview of the different cell technologies is provided to understand the advantages and disadvantages of each cell type for application focused photovoltaics. The comparison is meant to provide a rough guidance, since comparing mature technologies such as c-Si with new technologies such as perovskites or hybrid tandem can never be exhaustive. Potentials of future technologies may be over- or underestimated, similarly to the development potential of established technologies.

The different solar cell types and the comparison criteria have been discussed independently of the respective applications, therefore for every application the weighting of specific criteria may need to be adjusted. Additionally, certain further criteria that are not discussed in this text may also play a role. Examples are the discussed LCA factors such as greenhouse gas emissions during production or the requirement of tempered glass for some applications, which may require additional efforts for some thin-film based technologies. Therefore, each application needs a separate assessment to find the most suitable technology.

Some solar cells concepts have been excluded from the discussion. However, they may play a role in the future and there may also be applications where those concepts may offer unique advantages.

In conclusion this overview of the cell technologies offers a starting point to assess the right solar cell technology for a specific application. It may also help to raise awareness to the criteria to consider for different applications.

REFERENCES

[1] T. E. Kuhn, C. Erban, M. Heinrich, J. Eisenlohr, F. Ensslen, and D. H. Neuhaus, "Review of Technological Design Options for Building Integrated Photovoltaics (BIPV)," *accepted for publication in the Energy and Buildings special issue review articles from the editors*, 2020.

[2] C. Ballif, L. Perret-Aebi, S. Lufkin, and E. Rey, "Integrated thinking for photovoltaics in buildings," *Nat Energy*, vol. 3, no. 6, pp. 438–442, 2018, doi: 10.1038/s41560-018-0176-2.

[3] Geyer D., Stellbogen D., Lechner P., Hummel S., Schnepf J., Huschenhöfer D., "Analysis and investigation of BIPV operating performance based on the PV installations at the ZSW research building," in *Proc. of 36th European Photovoltaic Solar Energy Conference and Exhibition*, 2019, pp. 1439–1443.

[4] P. Heinstein, C. Ballif, and L.-E. Perret-Aebi, "Building integrated photovoltaics (BIPV): Review, potentials, barriers and myths," *Green*, vol. 3, no. 2, pp. 125–156, 2013, doi: 10.1515/green-2013-0020.

[5] M. Heinrich *et al.*, "Potential and Challenges of Vehicle Integrated Photovoltaics for Passenger Cars," in *Proc. of 37th European Photovoltaic Solar Energy Conference and Exhibition*, Online, 2020.

[6] C. Kutter, F. Basler, M. Heinrich, and D. H. Neuhaus, "Integrated lightweight, glass-free PV module technology for box bodies of commercial trucks," in *Proc. of 37th European Photovoltaic Solar Energy Conference and Exhibition*, Online, 2020.

[7] U. Eitner, M. Ebert, T. Zech, C. Schmid, A. Watts, and M. Heinrich, "Solar Potential on Commerical Trucks: Results of an Irradiance Measurement Campaign on 6 Trucks in Europe and USA," in *Proc. of 33rd European Photovoltaic Solar Energy Conference and Exhibition*, Amsterdam, Netherlands, 2017, pp. 2147–2150.

[8] solmove GmbH, *Technology: Power generation and inductive charging with solar roads.* [Online]. Available: https://www.solmove.com/en/technology/ (accessed: August 2020).

[9] Wattway, *New Step for the Wattway Pilot Site in Tourouvre-au-Perche (Normandy, France).* [Online]. Available: https://www.wattwaybycolas.com/en/news/2020/new-step-for-the-wattway-pilot-site-in-tourouvre-au-perche-normandy-france.html (accessed: August 2020).

[10] W. Roth and A. Steinhueser, "Photovoltaische Energieversorgung von Geräten und Kleinsystemen: Begleitbuch zum Seminar des Fraunhofer-ISE," Freiburg, 1997.

[11] W. Roth and J. Schmid, "Photovoltaically supplied devices of low and intermediate power range," in *8. EC photovoltaic solar conference*, Florence, Italy, 1988, pp. 263–269.

[12] P. K. Nayak, S. Mahesh, H. J. Snaith, and D. Cahen, "Photovoltaic solar cell technologies: Analysing the state of the art," *Nat Rev Mater*, vol. 4, no. 4, pp. 269–285, 2019, doi: 10.1038/s41578-019-0097-0.

[13] H. Hanifi, C. Pfau, J. Schneider, and J. Bagdahn, "A Simulation Based Optical and Electrical Approach to Estimate Energy Yield of Various Designs of Curved Modules," in *Proc. of 32nd European Photovoltaic Solar Energy Conference and Exhibition*, Munich, Germany, 2016, pp. 2041–2045.

[14] S. Neven-du Mont *et al.*, "Energy Yield Modelling of 2D and 3D Curved Photovoltaic Modules," in *Proc. of 37th European Photovoltaic Solar Energy Conference and Exhibition*, Online, 2020.

[15] B. Bläsi *et al.*, "Morpho Butterfly Inspired Coloured BIPV Modules," in *Proc. of 33rd European Photovoltaic Solar Energy Conference and Exhibition*, Amsterdam, Netherlands, 2017, pp. 2630–2634.

[16] C. Kutter *et al.*, "Decorated building integrated photovoltaic modules: power loss, color appearance and cost analysis," in *Proceedings of the 35th European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC); Brussels, Belgium*, 2018.

[17] NREL National Renewable Engery Laboratory, "Best Research-Cell Efficiency Chart," 2019.

[18] M. A. Green, E. D. Dunlop, J. Hohl-Ebinger, M. Yoshita, N. Kopidakis, and X. Hao, "Solar cell efficiency tables (version 56)," *Prog Photovolt Res Appl*, vol. 28, no. 7, pp. 629–638, 2020, doi: 10.1002/pip.3303.

[19] M. Powalla, S. Paetel, E. Ahlswede, R. Wuerz, C. D. Wessendorf, and T. Magorian Friedlmeier, "Thin-film solar cells exceeding 22% solar cell efficiency: An overview on CdTe-, Cu(In,Ga)Se 2 -, and perovskite-based materials," *Applied Physics Reviews*, vol. 5, no. 4, p. 41602, 2018, doi: 10.1063/1.5061809.

[20] M. Hermle, F. Feldmann, M. Bivour, J. C. Goldschmidt, and S. W. Glunz, "Passivating contacts and tandem concepts: Approaches for the highest silicon-based solar cell efficiencies," *Appl. Phys. Rev.*, vol. 7, no. 2, p. 21305, 2020, doi: 10.1063/1.5139202.

[21] A. Hinsch, S. Mastroianni, H. Brandt, F. Heinz, M. C. Schubert, and W. Veurman, "Introduction to in-situ produced Perovskite solar cells; a new concept towards lowest module manufacturing costs," in *Proc. of 29th European Photovoltaic Solar Energy Conference and Exhibition*, Amsterdam, Netherlands, 2014, pp. 1493–1497.

[22] A. Hinsch, W. Veurman, H. Brandt, R. Loayza Aguirre, K. Bialecka, and K. Flarup Jensen, "Worldwide first fully up-scaled fabrication of 60 cm x 100 cm dye solar module prototypes," in *Proc. of 26th European Photovoltaic Solar Energy Conference and Exhibition*, Hamburg, Germany, 2011, pp. 187–198.

[23] D. Kaduwal, H.-F. Schleiermacher, J. Schulz-Gericke, T. Kroyer, B. Zimmermann, and U.

Würfel, "ITO-free organic solar cells with roll-to-roll coated organic functional layers from non-halogenated solvents," *Sol. Energy Mater. Sol. Cells*, vol. 124, pp. 92–97, 2014, doi: 10.1016/j.solmat.2014.02.001.
[24] W. Krühler, "Amorphous thin-film solar cells," *Appl. Phys. A*, vol. 53, no. 1, pp. 54–61, 1991, doi: 10.1007/bf00323435.
[25] A. Hinsch, W. Veurman, H. Brandt, R. Loayza Aguirre, K. Bialecka, and K. Flarup Jensen, "Worldwide first fully up-scaled fabrication of 60×100 cm^2 dye solar module prototypes," *Progress in Photovoltaics: Research and Applications*, vol. 20, no. 6, pp. 698–710, 2012, doi: 10.1002/pip.1213.
[26] A. Hinsch, W. Veurman, H. Brandt, K. Flarup Jensen, and S. Mastroianni, "Status of dye solar cell technology as a guideline for further research," *ChemPhysChem*, vol. 15, no. 6, pp. 1076–1087, 2014, doi: 10.1002/cphc.201301083.
[27] P. S. C. Schulze *et al.*, "25.1% High-Efficiency Monolithic Perovskite Silicon Tandem Solar Cell with a High Bandgap Perovskite Absorber," *Sol. RRL*, p. 2000152, 2020, doi: 10.1002/solr.202000152.
[28] A. J. Bett *et al.*, "Two-terminal Perovskite silicon tandem solar cells with a high-Bandgap Perovskite absorber enabling voltages over 1.8 V," *Prog Photovoltaics*, vol. 2, no. 5, p. 1995, 2019, doi: 10.1002/pip.3208.
[29] Oxford PV, *Oxford PV perovskite solar cell achieves 28% efficiency.* [Online]. Available: https://www.oxfordpv.com/news/oxford-pv-perovskite-solar-cell-achieves-28-efficiency (accessed: August 2020).
[30] AZUR SPACE Solar Power GmbH, *Products Special.* [Online]. Available: http://www.azurspace.com/index.php/en/products/products-special (accessed: August 2020).
[31] H.-L. Chen *et al.*, "A 19.9%-efficient ultrathin solar cell based on a 205-nm-thick GaAs absorber and a silver nanostructured back mirror," *Nat. Energy*, vol. 4, no. 9, pp. 761–767, 2019, doi: 10.1038/s41560-019-0434-y.
[32] Microlink Devices, Inc., *Products Photovoltaics.* [Online]. Available: http://mldevices.com/index.php/product-services/photovoltaics (accessed: August 2020).
[33] A. Mondon, N. Klasen, M. Mittag, M. Heinrich, and H. Wirth, "Comparison of Layouts for Shingled Bifacial PV Modules in Terms of Power Output, Cell-to-Module Ratio and Bifaciality," in *Proc. of 35th European Photovoltaic Solar Energy Conference and Exhibition*, Brussels, Belgium, 2018, pp. 1006–1010.
[34] S. K. Chunduri and M. Schmela, "Taiyang News Advanced Module Technologies: 2019 Edition," Munich, 2019.
[35] PVinsights, *Weekly Spot Prices.* [Online]. Available: http://pvinsights.com/ (accessed: August 2020).
[36] Fraunhofer ISE, *Recent Facts about Photovoltaics in Germany*, 2020. Accessed: June 2020. [Online]. Available: https://www.pv-fakten.de/
[37] SOLARWATT GmbH, *30 years warranty period on SOLARWATT glass-glass modules.* [Online]. Available: https://www.solarwatt.de/gruende/service/garantie (accessed: August 2020).
[38] B. Marion, M. G. Deceglie, and T. J. Silverman, "Analysis of measured photovoltaic module performance for Florida, Oregon, and Colorado locations," *Solar Energy*, vol. 110, pp. 736–744, 2014, doi: 10.1016/j.solener.2014.10.017.
[39] T. Mishima, M. Taguchi, H. Sakata, and E. Maruyama, "Development status of high-efficiency HIT solar cells," *Solar Energy Materials and Solar Cells*, vol. 95, no. 1, pp. 18–21, 2011, doi: 10.1016/j.solmat.2010.04.030.
[40] M. Kasemann, K. Rühle, Gad K. M., and Glunz, S. W., "Photovoltaic energy harvesting for smart sensor systems," *Proceedings of SPIE*, 2013.
[41] F. Mavromatakis, F. Vignola, and B. Marion, "Low irradiance losses of photovoltaic modules," *Solar Energy*, vol. 157, pp. 496–506, 2017, doi: 10.1016/j.solener.2017.08.062.
[42] P. Baliozian *et al.*, "PERC-based shingled solar cells and modules at Fraunhofer ISE," *Photovoltaics International*, no. 43, pp. 129–145, 2019.
[43] NexWafe GmbH, *Product.* [Online]. Available: https://www.nexwafe.com/#product (accessed: August 2020).
[44] D. D. Smith *et al.*, "SunPower's Maxeon Gen III solar cell:: High efficiency and energy yield," in *Prof. of 39th IEEE Photovoltaic Specialists Conference Tampa*, Tampa, FL, USA, 2013, pp. 908–913.
[45] C. Kutter *et al.*, "Decorated Building-Integrated Photovoltaic Modules Power Loss, Color Appearance and Cost Analysis," in *Proc. of 35th European Photovoltaic Solar Energy Conference and Exhibition*, Brussels, Belgium, 2018, pp. 1488–1492. Accessed: Jan. 14 2020.
[46] MaterialDistrict, *Transparent Solar Cells by Sunways AG.* [Online]. Available: https://materialdistrict.com/material/transparent-solar-cells/ (accessed: August 2020).
[47] A. Müller, "A comparative life cycle assessment of mono-Si PV module production: Impact of module design and manufacturing location," Bachelor-Thesis, Albert-Ludwigs-Universität Freiburg im Breisgau, Freiburg i. Br., Germany, 2020.
[48] M. M. Lunardi, J. P. Alvarez-Gaitan, N. L. Chang, and R. Corkish, "Life cycle assessment on PERC solar modules," *Sol Energ Mat Sol C*, vol. 187, pp. 154–159, 2018, doi: 10.1016/j.solmat.2018.08.004.
[49] R. Frischknecht *et al.*, "Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems: IEA PVPS Task 12, LCA Report IEA-PVPS 12-04:2015," 2015.
[50] Fraunhofer ISE, "Photovoltaics Report," Jun. 2020.
[51] Midsummer AB, *Midsummer About us.* [Online]. Available: https://midsummersolarroofs.se/en/about-us/ (accessed: August 2020).
[52] NICE Solar Energy GmbH, *CIGS Module.* [Online]. Available: https://nice-solarenergy.com/de/cigs-module.html (accessed: August 2020).
[53] Geyer D., Lechner P., Stellbogen D., Hummel S., "Systemtechnik für PV-Fassaden mit Dünnschichtmodulen," in *Forum Bauwerkintegrierte Photovoltaik*, Bad Staffelstein, Germany, 2019.
[54] A. Hinsch *et al.*, "Dye solar modules for facade applications: Recent results from project ColorSol," *Solar Energy Materials and Solar Cells*,

vol. 93, 6-7, pp. 820–824, 2009, doi: 10.1016/j.solmat.2008.09.049.

[55] Heliatek GmbH, *Product.* [Online]. Available: https://www.heliatek.com/product/ (accessed: August 2020).

[56] National Renewable Energy Laboratory (NREL), *Best research-cell efficiencies.* [Online]. Available: https://www.nrel.gov/pv/ (accessed: August 2020).

[57] S. B. Sapkota, M. Fischer, B. Zimmermann, and U. Würfel, "Analysis of the degradation mechanism of ITO-free organic solar cells under UV radiation," *Sol. Energy Mater. Sol. Cells*, vol. 121, pp. 43–48, 2014, doi: 10.1016/j.solmat.2013.10.021.

[58] S. B. Sapkota, A. Spies, B. Zimmermann, I. Dürr, and U. Würfel, "Promising long-term stability of encapsulated ITO-free bulk-heterojunction organic solar cells under different aging conditions," *Sol. Energy Mater. Sol. Cells*, vol. 130, pp. 144–150, 2014, doi: 10.1016/j.solmat.2014.07.004.

[59] M. Kasemann, K. Rühle, K. M. Gad, and S. W. Glunz, "Photovoltaic energy harvesting for smart sensor systems," *Proc. of SPIE*, vol. 8763, 87631T, 2013, doi: 10.1117/12.2018052.

[60] A. Colsmann, A. Puetz, A. Bauer, J. Hanisch, E. Ahlswede, and U. Lemmer, "Efficient Semi-Transparent Organic Solar Cells with Good Transparency Color Perception and Rendering Properties," *Adv. Energy Mater.*, vol. 1, no. 4, pp. 599–603, 2011, doi: 10.1002/aenm.201000089.

[61] R. A. Sheldon, "Green solvents for sustainable organic synthesis: state of the art," *Green Chem.*, vol. 7, no. 5, p. 267, 2005, doi: 10.1039/b418069k.

[62] A. W. Bett, F. Dimroth, G. Stollwerck, and O. V. Sulima, "III-V compounds for solar cell applications," *Appl. Phys. A*, A69, no. 2, pp. 119–129, 1999, doi: 10.1007/s003399900062.

[63] Businesswire, *Alta Devices Introduces New Solar Product to Enable Flying Cell Phone Towers.* [Online]. Available: https://www.businesswire.com/news/home/20190423005283/en/Alta-Devices-Introduces-New-Solar-Product-Enable (accessed: August 2020).

[64] OIST, *A Perovskite Solar Cell.* [Online]. Available: https://www.oist.jp/news-center/photos/perovskite-solar-cell-0 (accessed: August 2020).

[65] A. Extance, "The reality behind solar power's next star material," *Nature*, vol. 570, no. 7762, pp. 429–432, 2019, doi: 10.1038/d41586-019-01985-y.

[66] A. L. Zafoschnig, S. Nold, and J. C. Goldschmidt, "A tight race for lowest costs of electricity production: techno-economic analysis of silicon, perovskite and tandem solar cells," *submitted to nature energy*, 2020.

[67] W. Tress *et al.*, "Performance of perovskite solar cells under simulated temperature-illumination real-world operating conditions," *Nat Energy*, vol. 4, no. 7, pp. 568–574, 2019, doi: 10.1038/s41560-019-0400-8.

[68] R. B. Dunbar *et al.*, "Device pre-conditioning and steady-state temperature dependence of CH 3 NH 3 PbI 3 perovskite solar cells," *Prog Photovolt Res Appl*, vol. 25, no. 7, pp. 533–544, 2017, doi: 10.1002/pip.2839.

[69] A. J. Bett *et al.*, "Semi-Transparent Perovskite Solar Cells with ITO Directly Sputtered on Spiro-OMeTAD for Tandem Applications," *ACS applied materials & interfaces*, 2019, doi: 10.1021/acsami.9b17241.

[70] R. Cariou *et al.*, "III–V-on-silicon solar cells reaching 33% photoconversion efficiency in two-terminal configuration," *Nat. Energy*, vol. 3, no. 4, pp. 326–333, 2018, doi: 10.1038/s41560-018-0125-0.

[71] Ahlswede E. *et al.*, "A journey form perovskite to tandem solar cells with CIGS bottom cells," in *5th International Conference on Perovskite Solar Cells and Optoelectronics*, Lausanne, Switzerland, 2019.

[72] J. Werner, B. Niesen, and C. Ballif, "Perovskite/Silicon Tandem Solar Cells: Marriage of Convenience or True Love Story? - An Overview," *Adv. Mater. Interfaces*, vol. 5, no. 1, p. 1700731, 2018, doi: 10.1002/admi.201700731.