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CHEETAH

Cost-reduction through material optimisation and Higher EnErgy outpuT of solAr pHotovoltaic modules - joining Europe's Research and Development efforts in support of its PV industry

Deliverable

D5.4 – Final report on the R&D impact on cost reduction

WP5 – Acceleration of innovations' implementation

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Section 3 – Acknowledgements

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This final report reflects one of the main work-streams of the Cheetah project, which is related, with the cost assessment of the innovations and the main objectives set by the research partners. Therefore, the active participation of the above-mentioned leading institutes was crucial to the development of credible results.

Section 4 – Executive summary

Description of the deliverable content and purpose

With more than 100 GW installed capacity end of 2016, solar photovoltaic (PV) continues being one of the predominant renewable technologies and one of the most promising technologies for Europe to meet its future energy and climate objectives. However, attached to the market growth, the price erosion seen especially over the last five years has created high pressure throughout the whole PV value chain and an uncertain environment for healthy margins. Either due to overcapacity phenomena in the past or due to radical changes of the regulatory framework, prices have always been a matter of high attention.

In a field of increased competition, the cost of PV electricity needs to be further reduced to enable truly large-scale application of photovoltaics in Europe. The rapid price decline of PV systems by more than a factor two in the last three years has already allowed to achieve grid parity for residential applications in several European countries such as Italy, Spain, Germany and The Netherlands. However, further cost reduction is required and this can be achieved also through reduction of (costs of) materials used in PV systems and components, and through improvements in the overall performance of PV systems.

The Cheetah project acknowledging the necessity for further cost reduction but also enhanced performance, aims at developing technologies that use less and more environmental friendly materials and improving the reliability and lifetime of the final product based on high-throughput processes. More specifically and in support of the objectives of the European Energy Research Alliance and the Joint Programme on Photovoltaic Solar Energy (EERA-PV), the project is working, among others, on high-level technology development in the field of:

- Ultra-thin crystalline silicon (c-Si) solar cells and advanced processing steps,
- Thin film CIGSe microconcentrator solar cells
- Organic PV (OPV) solar cells with improved stability

Whereas the mid-term report only looked at CHEETAH's innovations' cost impact on ultra-thin c-Si solar cells in comparison with the existing "conventional" c-Si technologies that enjoy the largest share of the PV market (>90%)[1], this final report also includes cost estimations and considerations related to thin film CIGSe microconcentrator solar cells and organic PV (OPV) solar cells with improved stability.

Technical innovations attached to cost impact assessments will give a good understanding on the benefits of those research activities and will potentially accelerate the exploitation by the PV industry. Ultimately such results, even if they are subject for further investigations and validations from the industry, will support relevant discussions on research and funding priorities in Europe and the PV sector.

As for ultra-thin c-Si, there is a potential cost reduction of 21 % when comparing benchmark wafer-based crystalline silicon photovoltaic modules (back contact, standard cell thickness, regular wire-cut wafers) to modules using epitaxially grown wafers of 120 µm thickness developed within the Cheetah project. For this wafer thickness only very minor adaptations in cell processing are required, if any at all, leaving the cost structure of that part as it is for standard cells. For thinner than 80-90 µm wafers, wafer costs are decreased further but cell processing costs are expected to increase resulting in a trade-off for the total cost.

Regarding thin film CIGSe microconcentrator solar cells, a profitability analysis was conducted that shows that concentrating CIGSe PV systems are almost always less profitable than non-concentrating CIGSe PV

[1] Source: NPD Solabuzz, published by pv-magazine

systems, when both use tracking with the light conditions in Europe. The used conservative assumption of equal efficiency of concentrated and non-concentrated modules clearly show, that it is the efficiency, which will play an important role. As the research results within CHEETAH showed, there is the possibility of efficiency enhancement given good material quality. Thus, further development of – in particular local grown – material on the micro scale is the key for this technology. Additionally, the profitability analysis for Europe showed, that combined concepts exploiting both direct and diffuse light, are the way to make full profit of efficiency enhancement.

As for OPV cells with improved stability, energy invested was used rather than cost due the absence of a market. Energy cost can be considered a relevant guideline to help identify the options with the most promising overall cost-effectiveness. The conclusion of the energy cost analysis was due to much better stability achieved through ultrabarriers, the chances to reach Energy Return on Energy Invested (EROI) = 1 for ultrabarriers are better than for PET-based encapsulation, even though ultrabarrier based encapsulation is more expensive than PET-based encapsulation.

This final report together with two background analyses, *Analysis of the cost reduction potential of the PV technology (D5.2)* and *Benchmark knowledge of the quality and reliability of PV technology (D5.5.)* complete the cost assessment tasks providing a credible analysis and useful both for the research and the industry community to build on.

Section 5 – Deliverable report

1. Introduction

1.1. Rationale

As the sector continuously matures and the competitiveness of the PV technology evolves, new innovative business models emerge that base their success on the true potential of the PV technology and value the performance of the PV system. Therefore, it is very important to investigate and properly assess the future innovations and technology breakthroughs understanding the impact of R&D on the performance, the cost reduction and consequently the PV business. Taking into consideration the future renewable targets (27% of RES by 2030 which also means 45% of RES power) and the important role of PV, as well as the objectives of the EU's freshly announced Clean Energy Industrial Competitiveness Forum to promote EU global leadership in clean energy technologies, it is necessary to foresee its potential and its limitations and draft of a roadmap (also technological) that will allow PV to develop within a focused, sustainable and healthy environment and become a mainstream source of electricity.

Cheetah stands in favour of these objectives for a thorough assessment – not only technical but also economical – that will enable the European research and subsequently industry community to facelift, upscale manufacturing and support the future EU energy targets. Indirectly this will also support additional macroeconomic challenges that Europe is facing. Solar PV has been proved to be a significant component for creating employment and value for Europe[2].

Thanks to its broad consortium and the consolidation of high level of expertise in the PV sector, the CHEETAH project offered a unique opportunity to pool experience and conduct such analysis the results of which will develop an interface between the PV industry and the project incorporating industry's feedback and address challenges. The cost assessment of Cheetah innovations becomes then rather important for all stakeholders and target groups - researchers, industry but also investors.

1.2. Objectives

Taking into consideration the importance of this work but also the limitations within the project, the main objective for this final report is to give an updated and solid set of information regarding the potential cost reductions thanks to CHEETAH innovations in crystalline silicon (c-Si), thin film and organic PV (OPV). This report will attempt to clarify if the suggested innovations lead to a reduced cost and increased competitiveness in comparison to the existing "standard" c-Si and thin film (CIGSe) technologies and also what the magnitude of this reduction is. (For OPV, no such comparison was possible due to the very limited commercialisation level of OPV technologies and a different approach was taken on an EROI basis.) This will set the confidence levels of the actual cost reduction since there are a number of uncertainties and assumptions for this analysis due to current absence of commercial players and proper benchmarking.

1.2.1. Cheetah innovations under assessment

The present final report looks at:

[2] Source: Ernst & Young, November 2017, "Solar Photovoltaics Jobs & Value Added in Europe", published by SolarPower Europe

1. CHEETAH innovations' cost impact on ultra-thin c-Si solar cells in comparison with the existing "conventional" c-Si technologies:

    - The Epi-wafer based product incorporates all the innovations from the Cheetah project that allow the development of a high-quality c-Si thin foil in a thickness range of 40-180 µm by chemical vapour deposition (CVD) avoiding the wire-sawing process and related kerf losses and drastically shortcutting the value chain of wafer production by avoiding polysilicon formation, ingot formation and wafering. (This final report is based on the actually achieved 100 µm wafer and resulting 80-90 µm cells as opposed to the envisaged 40 µm wafer assessed in the mid-term report, and also relies on updated figures.)
    - This innovation reduce the silicon material use and the kerf loss (in wire sawing) - which is on average around 140 µm - along with a reduction of energy and other consumables required for the crystallization and the wafering process. Consequently, this could lead to a significant cost reduction.
    - As there has been no updated values for wire-cut thin wafers since the mid-term report D5.3, this final report only looks at epi-wafer based products' cost impacts. For the cost impact of wire-cut thin wafers, see the mid-term report D5.3.

2. Cost estimations related to thin film CIGSe microconcentrator solar cells developed in the CHEETAH project:

    - in line with the main aim of Cheetah project, i.e. realizing solar cells with less material but with higher efficiency, the concept of microconcentration on chalcopyrites based solar cells such as CIGSe was used. Two approaches have been realized and tested: (1) The 1D-concentration approach with Array of (7 rows of) 20 interconnected cells. Each section = 10 mm x 3 mm and an Active area of 10 mm x 100 µm² for concentration factor up to 30 suns. (2) The 2D concentration: Array of 67 rows made up of 21 interconnected cells each. Each section = 1x1 mm² and an Active area of ≈ 100 x 100 µm² for an higher concentration factor (100 suns).
    - With this work, it has been proven that functional interconnected CIGSe micro-concentrator modules of 16 % conversion efficiency are feasible. However, the work pointed out some still open issues, mainly related to the necessity of the requirement of a single-Axis or double tracking system and the fact that the quality of lenses can limit total light concentration.

3. Cost considerations regarding organic PV (OPV) solar cells with improved stability, also an innovation of the CHEETAH project:

    - the aim of the CHEETAH project regarding OPV was to accelerate cost reductions in organic PV by addressing the issue of device degradation. In order to achieve the low-cost potential of roll-to-roll coated OPV, it is necessary to encapsulate devices with low-cost flexible barrier layers. The three different encapsulation architectures studied in this report are:
        - Unencapsulated devices,
        - PET-encapsulated devices,
        - Multi-ultrabarrier-encapsulated devices.

1.3. Limitations

This analysis is based on literature review (current relevant publications), own assumptions (knowledge and experience from the research partners) and results extracted by calculation sheets and models built by different project partners. The innovations suggested by Cheetah are still of low Technology Readiness level (TRL) and not ready for large scale commercialization which is indeed the ultimate goal in the medium to long run.

Therefore, there are many factors and components that are still unclear and will be subject to supply chain logistics and other macroeconomic factors such as global economic environment, EU competitiveness etc. In addition, standardization around materials and also processes and equipment for these innovations require updates and improvements that will match with the specifications of those new products. This will substantially impact the cost and quality of those products.

In order to overcome some of the abovementioned global limitations, industry involvement at early stages is important. Industry experts with a clearer idea on market boundaries, technical bottlenecks and supply chain management (SCM) challenges will be able to provide a valuable feedback for our cost assessment work. In a volatile market environment as is the case for PV, discussions should continue beyond the duration of the project to ensure an effective implementation of Cheetah innovations.

2. Methodology

As mentioned before the approach that was used for our first cost assessment results was threefold:

- **Literature review:** A sufficiently thorough literature review was conducted in order to mainly retrieve updated information on costs (wafer costs) and efficiencies of different thickness, cell processing and module production costs. The materials reviewed were scientific papers, studies, online information platforms (e.g. PVinsights) and relevant articles in international media.
- **Cheetah experts' experience:** The information acquired by the literature review was filtered by the relevant consortium experts and enhanced by own in-house knowledge. Besides the core expert group that actively worked on this final report, the whole consortium (34 research partners) validated the results.
- **Modelling results:** In order to fill in the gap of available information upon the literature review and also to increase the quality of our results, specific partners made use of their own models and calculation sheets to extract results.
- **Reference and benchmark technologies:** As a first point of reference to assess the Cheetah innovations, the commercially available technologies were taken into consideration, i.e. commercially available c-Si modules and thin film (non-concentrator) CIGSe modules.
    - Regarding c-Si, from a technological perspective the state of the art back contact technology (not yet commercial) is a more logical choice to compare all developments to. Application of the common practice in module assembly to thin cells (tabbing and stringing) will be unlikely. For that reason back contact technology has been appointed the module technology of choice for the project and a silicon heterojunction (IBC-SHJ) concept as described in the article by [Louwen 2016][5] has been chosen as the benchmark technology. With respect to overall module manufacturing costs this benchmark was estimated at 0.49 USD/Wp in 2017.
    - Regarding thin film CIGSe, the cost analysis compares the profitability of concentrated solar systems to not concentrated systems both using CIGSe solar panels. For the

benchmark non-concentrator CIGSe solar panels data used by [Horowitz et al. 2016] was used.

- As explained above, for OPV, no such comparison was possible due to the very limited commercialisation level of OPV technologies and a different approach was taken on an EROI basis.

2.1. Description of the c-Si epi-wafer cost calculation model and assumptions

For the calculation of the cost of an epi-wafer, it was considered that the process for making such a wafer consists of the following steps:

- Reclaim/clean of the parent wafer where the epitaxial Si foil will be grown
- Anodization
- Low hydrogen annealing (H_2 anneal) and epitaxial deposition
- Lasering
- Detachment

After which the parent wafer is re-inserted into the first process step until the end of its lifetime. In setting up the cost-calculations, existing data for similar process steps were used as reference. Below, more details are given for each process step. As for the impact of the parent wafer itself on the cost structure of the epi-wafer, a detailed description is given below as well.

Base data

In IMEC's model a depreciation of equipment cost over 7 years is assumed. The model is basically independent of the throughput, but for the calculations a throughput of 3000 wafers/h is assumed. The mechanical yield is taken to be high at 99.8% (see comments on the parent wafer below). Different scenarios have been evaluated with wafer dimensions of 125mm and 156mm although results are presented for 156mm size. All equipment and consumption costs are taken to be independent of wafer size, except for the trichlorosilane (TCS) consumption that is used as precursor, the parent wafer cost and the polysilicon-resale (see below).

Parent wafer

For the parent wafer it is assumed that the cost will follow the same trend as anticipated for thin wafers in [Goodrich 2013][3]. This means that, while cost increases with increased poly-silicon consumption, there will also be cost reductions due to kerf loss recycling, diamond wire usage etc. The parent wafer will be used a number of times, depending on the reclaim procedure and the capability to reliably handle thinned-down wafers. In this way, the cost of the (expensive) parent wafer is distributed over several foils. At the end of its lifetime, the parent will be sold at the actual poly-silicon stock price. The breakage rate of the parent wafers should be relatively low due to the mechanical robustness; however any breakage would result in loss of poly-silicon resale and increased parent wafer consumption.

[3] Source: Alan Goodrich, Peter Hacke, Qi Wang, Bhushan Sopori, Robert Margolis, Ted L. James, Michael Woodhouse, *"A wafer-based monocrystalline silicon photovoltaics road map: Utilizing known technology improvement opportunities for further reductions in manufacturing costs", January* 2013, published by NREL

Reclaim/clean

It is assumed that a similar equipment and consumption cost applies as for a texturing wet bench.

Anodization

A similar equipment price as for a commercial plating tool is assumed. For the chemical consumption, a mixture of hydrogen fluoride (HF) and isopropyl alcohol (IPA) is assumed with a maximum bath lifetime which is similar to experimentally observed bath lifetimes.

H_2 anneal and epitaxial deposition

The equipment cost for this step is partly based on feedback from consortium partners. Since wafer loading, temperature transients and H2 anneal are independent of the deposited layer thickness, the equipment cost is assumed to only partly scale with layer thickness. The precursor is TCS, and the usage is taken to be 85% efficient.

Lasering

For this step, conventional tools are used.

Detachment

A relatively simple tool employing a vacuum end effector is envisaged. For this reason, the tool cost and the consumption cost are assumed to be similar to a screen printer, with the exception of paste consumption.

Main assumptions

Main assumptions considered in the cost calculation for the c-Si epi-foil innovation's impact are:

- The first point of reference for our cost comparisons is year 2015 (second half) which is the time that the analysis has been initiated. In order to proceed to a valid comparison and be able to identify the differences in costs between a "standard" product and a product created within Cheetah project, the comparison should be done at a point in time where the conditions will allow to commercialize the Cheetah innovations based on the assumptions unfolded below. At the same point in time the standard product should probably have another cost (cheaper than today, difficult to quantify however). This point in time is what we refer as "ultimate" below and the Cheetah innovations are assessed with respect to this "ultimate" standard as well. It is important to note that since the start of the cost analysis in 2015 the costs for wafers have decreased visibly from 0.9 to 0.8 $/wafer, which is reflected in this updated cost impact analysis, however still a substantially higher level than any future cost projection for epitaxial wafers.
- The analysis considers a "business as usual" case, meaning that to commercialize the cheetah innovations at high production scales it is assumed that all necessary conditions are in place e.g. technical adaptations and new equipment to handle the new thinner products which will keep the cell production yields at high figures. Therefore, the costs for cell processing are assumed constant without specific assumptions (e.g. reductions in metallization etc.).
- Average costs of cell processing and module development from 2015 and average costs of commercial cut wafer from 2017 were used from public available sources. Those are presented in each subchapter below.

- The analysis does not consider gross margins per value chain step – apart from minimum required margins. Therefore cost and price in the report have the same meaning. The cost figures represent the so called Cost of Goods Sold (COGS).
- No taxes are included from the assessment of costs.
- For the silicon (Si) material, the cost assessment assumed an evolution based on experience curves from literature. This supported the assumptions for the future wafer costs.
- Average quality wafers have been considered in the study. For prime quality wafers, possibly essential to maintain efficiency levels for thin cells, costs for cut wafers could be 30% higher.
- Regarding the wafer technology, the analysis assumes a similar cost between the multi- and mono-crystalline wafers due mainly to demand differences (over-demand for multi-and under-demand for mono-wafers)[4]. Same assumption is made for the n-type and p-type wafers.
- The size of the wafer considered was 156x156 mm in pseudo-square shape.
- For processing/cutting the wafers, diamond wire sawing process is considered to be applied.
- The cost reduction of epi-wafer in comparison to the reference cut wafer assumes a production scale of 1 GWp/year.
- For the assessment of the module cost, the back contact (IBC) technology as presented in the paper by Louwen [Louwen 2016] has been chosen as a benchmark with the given shares of costs in the modules presented therein (e.g. share of wafer, cell processing, other materials etc.). It assumes an IBC 60 cell module of 20.5 % efficiency and power output of around 300 Wp.
- Due to the global supply chain of PV and with different sources of information, costs are presented in dollars.

Specific assumptions

Some more specific assumptions are:

- The assumed 20.5% efficiency of the 120 µm epi-foil-based modules is based on the same efficiency as presented in the paper by Louwen. These are presented below in the results section.
- Following on the second point of the global assumptions the yield of cell production is assumed to be 99% and independent of wafer thickness, down to 120 µm.
- The cell-to-module (CTM) conversion ratio is assumed to be > 99%, as has been achieved within the project. This is assumed equal for all wafer thicknesses.
- For all module types, no extra or more expensive cell processing steps are assumed.

[4] Sources: pv-magazine and EnergyTrend, published at pv-tech

2.2. Description of the microconcentrator CIGSe cost calculation model and assumptions

The data available to the CHEETAH consortium show that concentrated CIGSe modules' cost are similar to non-concentrated CIGSe modules' cost. Savings would mostly be the material of the precursor but also less costs for scribes, while the additional costs would include localising the precursor and the optical system needed. Since cost per W_p is similar, in order to investigate the competitiveness of microconcentrator CIGSe solar panels developed by the CHEETAH project, a profitability analysis was conducted by [Dippell 2017] to compare the profitability of concentrated solar systems to not concentrated systems both using CIGSe solar panels based on Germany (Karlsruhe) and in Spain (Cadiz) irradiation and German support scheme.

Main assumptions considered in the cost calculation for the c-Si epi-foil innovation's impact are:

1. There is no inflation, interest or taxes
2. The area is not restricted and does not cost anything
3. Diffuse radiation is isotropic
4. The optimal tilt-angle is approximately the latitude
5. The solar plant runs for the time span it is subsidized

To calculate profitability (return on investment), the following formula was used:

$$return = \left(irradiance \times \eta \times remuneration - \frac{maintenance}{time\ span \times area}\right) \times time\ span \times \frac{area}{investment} - 1$$

Where η denotes the efficiency of the solar system including the efficiency of the solar panel, angle of incidence (AOI) losses, soiling losses and AC-DC conversion losses.

Specific assumptions:

Parameter	Value(s)	Reference
Period of remuneration	20 a	§22 EEG
Remuneration	0,089 €/kWh	[PV Magazine 2017]
Efficiency concentrated	16,0%	
Efficiency not concentrated	14,0%	[Horowitz et al 2016]
Price concentrating solar panel	78,17 €/m²	
Price non-concentrating solar panel	78,17 €/m²	[Horowitz et al 2016]
Global Horizontal Irradiation (GHI)	1117(D) 1810(E) kWh/m²a	[NASA 2017]
Direct Normal Irradiation (DNI)	1073(D) 2303(E) kWh/m²a	[NASA 2017]
System and installation costs including tracking	178,13 €/m²	[Fu et al 2016]
System and installation costs without tracking	164,22 €/m²	[Fu et al 2016]
Operations and maintenance cost tracking	2,25 €/m²a	[Fu et al 2016]
Operations and maintenance cost fixed	1,85 €/m²a	[Fu et al 2016]
Optical losses with tracking	3,80%	[Garcia et al 2016]
Optical losses horizontal panel	11,80%	[Garcia et al 2016]
Optical losses fixed tilt	6,30%	[Garcia et al 2016]
Latitude	49° (Karlsruhe, Germany), 37° (Cadiz, Spain)	
Efficiency DC-AC conversion with tracking	83,33%	[Fu et al 2016]
Efficiency DC-AC conversion without tracking	71,43%	[Fu et al 2016]
1-axis efficiency/2-axis efficiency (η_2)	95,0%	[Lubitz 2011]
fixed/1-axis efficiency (η_1)	0,80 (Karlsruhe, Germany), 0,74 (Cadiz, Spain)	[NASA 2017]

Explanations:

1. Period of Remuneration: The lifetime of a solar panel is between 20 and 30 years, but the guaranteed enumeration period is only 20 years, so this value was taken.
2. Remuneration: For Germany the amount was lowered over the years; we assume the remuneration costs in 2016. The difference to 2017 should not amount to more than 0,1 ct/kWh, but the procedure for the exact remunerations where complicated by the EEG 2017 law and the other values used in the calculations are mostly from 2016. For Spain there is no remuneration at the time of this analysis. We use the German remuneration for Spain, to be able to make an estimate of which type of PV-Systems is economical in Europe independent of country policies, but advise that the gains are highly dependent on the subsidizing by the respective government.
3. Efficiency: The concentration factor c is the geometrical concentration of the optical system multiplied by the percentage of sunlight on the solar panel, which can be concentrated by the optical system.

We assume a concentration factor of 15, which leads to an absolute increase in efficiency of the concentrated solar panel of ca. 2% using the formula

$$\eta_{new} = \eta_{old}\,(1 + \frac{nk_bT}{eV_{oc}}\ln(c))$$

where k_b is the Boltzmann factor, T = 300K is the absolute temperature, V_{oc} = 0,65V denotes the open circuit voltage, n = 1,33 the ideality factor and η_{old} = 14% the efficiency without concentration.

4. Solar panel prices, System costs and maintenance costs: The noted source gives values in \$=W_p and W_p is defined as the power under standard conditions, namely 25°C and 1000 W/m² incident light. In our case this means $W_p/m^2 = \eta \times 1000W/m^2$. Furthermore the €:\$ currency conversion is assumed to be 1:1,2, so that the value in \$/W_p can be converted to €/m² by multiplying by $\frac{\eta}{1,2}$ 1000W/m². For the concentrating solar panel we assume the same cost as for the not concentrating. The savings would mostly be the material of the precursor, while the additional costs would include localizing the precursor and the optical system, but this will be discussed in more detail later.
5. DC-AC conversion efficiency: This efficiency differs for tracking and fixed systems, because the inverter has to be oversized in case of a fixed system.
6. 1-axis efficiency/2-axis efficiency η_2: We assume a value between 94% and 97% which agrees with our calculations. In the source the diffuse radiation is included, but should not have influenced the value by much.
7. 1-axis irradiance/tilted irradiance η_1: We obtain $\eta_0\eta_1\eta_2$ by using satellite data and formula. By dividing by $\eta_0\eta_2$ we obtain η_1, which increases noticeably with the latitude.

2.3. Description of the organic PV energy cost calculation model and assumptions

The CHEETAH consortium found that in the absence of a market, realistic costs of materials and production processes are not available and a relevant cost analysis to represent commercial production could not be made. However, since the cost of energy invested in materials or processes provides a bottom-line indicator of the relative cost of those materials or processes, we argue that the comparison of their relative energy cost is a relevant guideline to help identify the options with the most promising overall cost-effectiveness.

Therefore, an EROI approach was used to estimate which device architecture and encapsulation material has the biggest potential to reach EROI = 1. EROI (Energy Return on Energy Invested) is the ratio of the energy produced over lifetime to the embodied energy.

$$EROI = \frac{Energy\ produced\ over\ lifetime}{Embodied\ energy}$$

Embodied energy is defined as *t*he amount of equivalent primary energy required to manufacture a 1 W_p of OPV module, including all energy to extract and process raw materials, through to production of the finished module (expressed in *MJ/W*$_p$). To calculate the Embodied energy in the OPV devices, Imperial College's model relied on the following steps:

- Define the layer structure of the device (incl. thicknesses), e.g.: Encapsulation (on both sides), top contact, hole transport layer, active layer, electron transport layer, bottom contact, substrate, and include embodied electrical and thermal energy and resulting carbon intensity in all materials;

- Identify the processes involved in fabrication, e.g.: ITO electrode patterning, electron transport coating, active layer deposition, PEDOT:PSS deposition, electrode deposition, lamination; and include embodied electrical and thermal energy and resulting carbon intensity in all processes;
- Define the quantities of materials used in fabrication (semiconductors, metals, solvents)
- Model calculates the total embodied energy and carbon
- Given active lifetime, it also calculates energy return on investment (EROI)

The embodied energy in each layer was calculated from published data for the energy invested in materials supply and in processing.

The Energy produced over lifetime was calculated on the basis of module efficiencies and module lifetimes of the devices studied. Lifetime is defined as the period of time before which degradation to 80% of initial performance is reached.

The three different device architectures with different encapsulation materials studied were:

- Unencapsulated
- PET-encapsulated,
- Mulit-ultrabarrier-encapsulated

To estimate which device architecture has the biggest potential to reach EROI=1, the EROI formula was used to calculate the lifetime at which EROI=1 would be achieved for each of the three studied device architectures. That gives us an idea how long the device needs to last to deliver an EROI>1.

3. Results

3.1. Cost impacts for crystalline silicon PV

The cost assessment results are presented separately for Silicon wafers, cells and modules summarizing the results epi-wafer based products. This section can be considered as an executive summary of deliverable reportD8.13.

3.1.1. Impact on wafers costs

Table 1 below summarizes the costs of wafers both for today and for a relevant point in time where epi-wafers are assumed to be commercially available (ultimate wafer cost). The epi-foil wafers are directly compared with the standard product available now. The comparison is obvious for the current status and for the future – considering a relevant reduction for all thicknesses (also the standard one).

Currently the costs of wafers (spot price) are around 0.8 USD[5] for p-type wafers. As mentioned in the global assumption chapter above, this assumes that both multi and mono Si wafers and n-type and p-type wafers have the same production cost.

Regarding the epitaxial wafer costs, costs have been calculated with the use of IMEC's model. Today this technology is not commercially available and therefore there is no good reference to assume current

[5] Source: PVinsights and EnergyTrend

costs. However, following the assumptions presented in section 2.1, the ultimate cost was calculated for a 156x156mm substrate of 120 µm thickness.

Table 1: Wafer Costs in USD ($) for 2 different substrate thicknesses. The standard substrate is the reference wafer of 180 µm. Current costs assume average values of 2017. "Ultimate" wafer costs are defined as the estimated future prospective minimum costs.

Substrate	Standard 180µm	Epi-foil 120µm
Current wafer cost (COGS in USD/item)	0.81	n/a
Current wafer cost (COGS in USD cents/Watt)*	16.2	n/a
Ultimate wafer cost (COGS in USD/item)	0.66	0.411
Ultimate wafer cost (COGS in USD cents/Watt)*	13.2	8.22

**The translation from USD/item to USD/watt uses the information from IMEC from 2017 and [Louwen 2016] and assumes an IBC 60 cell module of 20.5 % efficiency and power output around 300 Wp, which has been defined as a benchmark. This equals 5 Wp per cell (wafer) with a cost of 0.81 USD (2017) for the case of standard 180µm. Therefore this leads to 0.162 USD/Wp. The same approach has been followed for the rest of the substrates.*

From the results of the above table it is clear that the cost impact of moving to thinner wafers in conjunction with improved wafering processes is significant, no matter the cost of polysilicon. Epi-foils can lead to a wafer cost reduction of 50%, when compared with current benchmark wafer cost (2017) and a cost reduction of 37%, when compared with future ultimate standard 180µm wafer cost.

That creates a very promising environment for commercialisation of those thin wafer based technologies in the coming years.

3.1.2. Impact on module costs

To calculate the cost of the module, the module development costs (or module elements production costs) needs to be added on top of the cell cost. Those elements include normally the cost of stringing/tabbing or other interconnection materials, the cost of the conductive adhesive, the EVA cost, the backsheet cost, the cost of frame, glass and junction box and other costs with different shares depending on the technology, but no real difference in terms of total cost [Louwen 2016].

In order to create a benchmark for these costs, 0.51 USD/Wp has been assumed for a standard 180 µm wafer based module for current costs based on a publication by Louwen [Louwen 2016]. For 120 µm epi-foil substrates lower wafer costs were taken into account as shown above, but keeping all other parameters and module efficiency constant and assuming no decrease in process yields. In table 2 the impact of the reduced wafer costs on module level is shown (compared to the chosen state of the art in 2015). Together with a further minor cost reduction for other module materials (back sheet) the total cost reduction on module level can amount to 21 %. Module assembly (process and materials) costs are dominated by materials which are standard and common for use in solar PV. Therefore the cost reduction potential is assumed low (typically 0.01 USD/Wp as mentioned earlier could be saved by alternative back sheet material) and not much more gain is expected.

benchmark for IBC module			***epitaxial foil 120 µm***	
module eff. (%)	20.5		20.5	
processing yield (%)	99		99	
	costs ($/Wp)			
cut wafer	0.18		0.082	0.411 $/wafer 120 µm (epitaxial)
cell processing costs	0.15		0.150	assuming no additional costs
module materials and processing	0.18		0.170	0.01 $/Wp savings on back sheet (Al)
total	0.51		0.402	
21.1 % cost reduction compared to state of art 2015 for 160 um wafer				

Table 2. Cost reduction potential for PV modules based on thin epitaxial wafers compared to 2015 benchmark

In figure 1 the resulting module cost structures (all based on IBC technology as a benchmark) are given for different wafer types: the costs based on (2015) commercial 180 µm thick cut wafers are compared to the future estimated minimum scenario for the same cut wafer type and to a costs of epitaxial wafers.

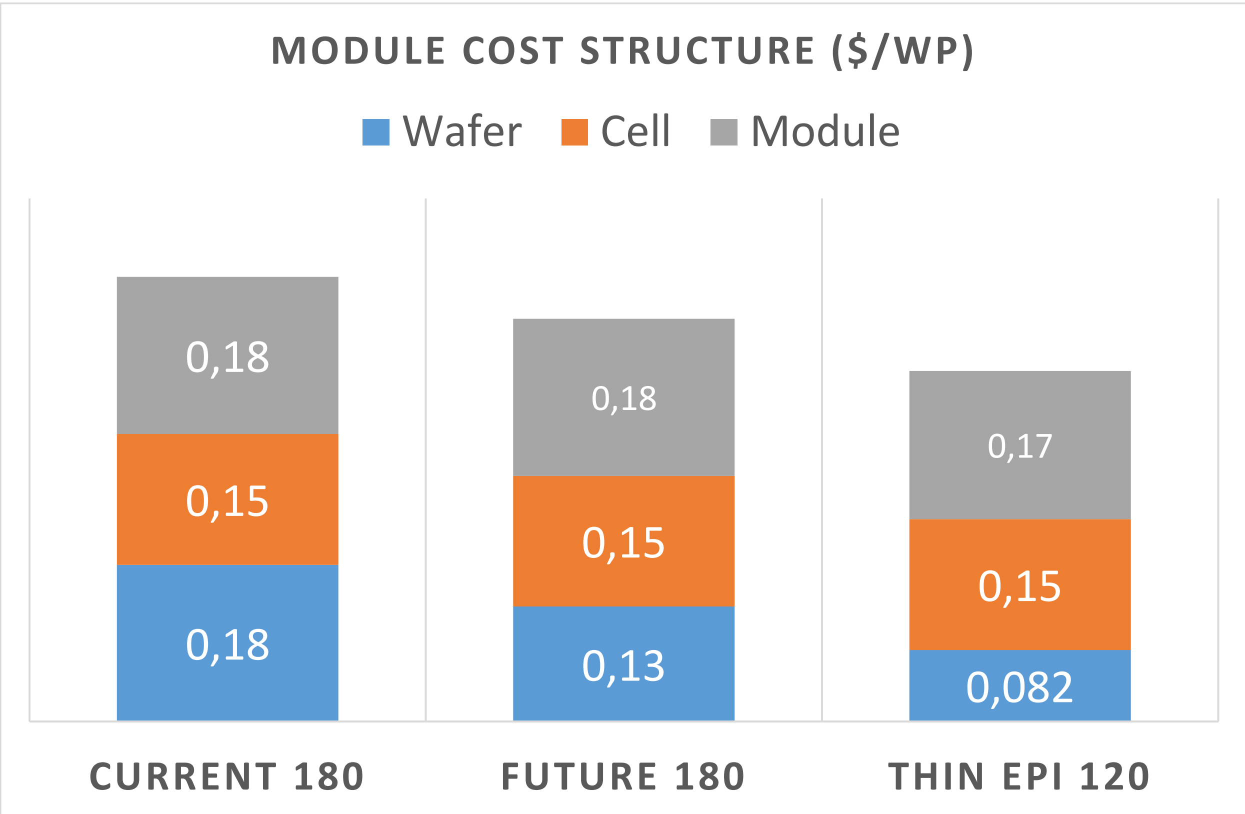

Figure 1. Module cost structures based on wafer spot price for 2017 and future projected costs for modules based on cut 180 µm wafers compared to 120 µm epitaxial wafers

The main factor contributing to the presented cost reduction is the projected price of epitaxial wafers, which is substantially lower than the 2015 spot price of 0.9 $/wafer for standard 160 µm thick cut wafers and also well below the current spot price of 0.81 $/wafer, to put this into perspective of cost figures for 2017. Today this cost for cut wafers is still a main contributor to the total module cost, as illustrated by the cost structures given in Figure 2. At a level of 0.16 $/Wp (derived from the data for silicon plus ingot/wafer presented in Figure 2 for 2017) this comprises 44 % of the total module cost (0.36 $/Wp).

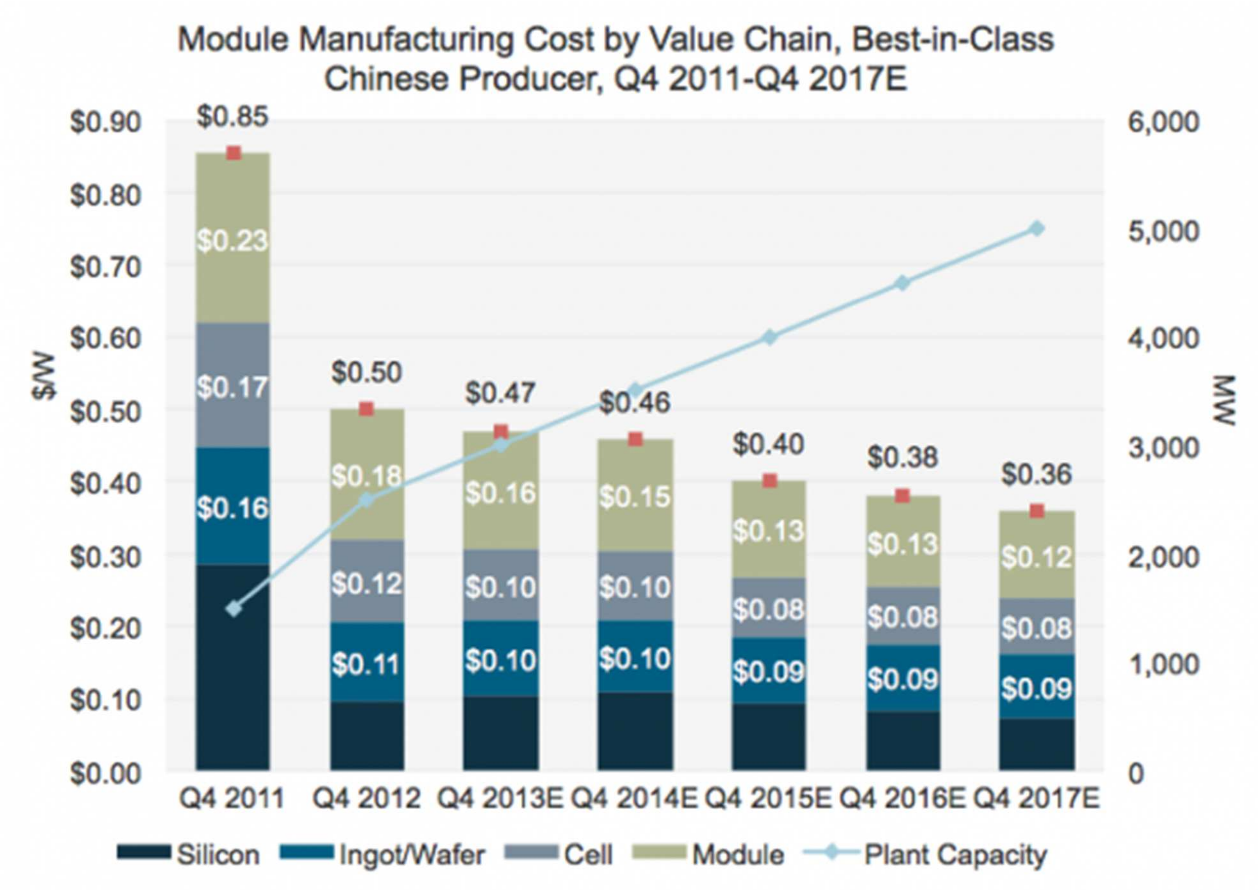

Figure 2. Evolution of cost structure for benchmark module technology [Solar-power-now.com, 2017]

3.2. Cost impacts for thin film microconcentrator CIGSe PV

In Table 5 the calculated returns for the assumptions detailed in section 2.2 are listed. The results are shown for the two locations in Germany and in Spain.

Concentration	**Tracking**	**Return Karlsruhe, Germany**	**Return Cadiz, Spain**
Concentrated	one-axis tracking	-26,75%	77,34%
Not concentrated	one-axis tracking	-9,20%	75,14%
Not concentrated	Tilted fixed	-26,02%	28,02%
Not concentrated	Horizontal fixed	-42,91%	1,97%

Table 5: Returns for different PV systems in Germany and Spain

From the data we came to the following conclusions.

- In Germany, utility-scale solar power plants seem not to be profitable. This can be seen in the results for Karlsruhe, Germany, which is one of the cities in Germany with higher Global Horizontal Irradiance (GHI), but it also holds true for other German cities.
- One-axis tracking seems to be always more profitable than fixed tilted solar panels.
- Concentrating PV systems are almost always less profitable than non-concentrating PV systems when both use tracking with the light conditions in Europe. This can be seen in the results for Cadiz, Spain, which is one of the cities in Europe with the highest fraction of direct sunlight. Even though the concentrating system seems barely more profitable than a non-concentrating system in Table 5, this is assuming a German remuneration. The remuneration in Southern European countries is significantly lower. While Spain and Portugal have no incentives, Greece has cut the feed in tariff to 0,08 €/kWh for non-rooftop systems. The assumption furthermore was a concentration factor of around 15; above that, it has to be investigated, if 2-axis tracking must be employed. Then other types of solar cells would become viable.
- The question is, if it can be more profitable when additionally using the diffuse fraction. We assumed the efficiency of the concentrating solar panel for the direct fraction of sunlight and a lowered efficiency compared to conventional solar modules for the diffuse fraction of sunlight. That is because the efficiency decreases with light intensity. The result was that the solar panel could cost 25 €/m² (Germany) or 30 €/m² (Spain) more than a comparable non-concentrating solar panel and would still achieve the same return. As the manufacturing of such a solar panel is very unlikely to cost 25 €/m², a device which can concentrate the direct portion of sunlight and still use the diffuse portion can be highly profitable.

3.3. Energy cost considerations for organic PV

Table 6 contains data based on the average lifetime values taken from all CHEETAH lifetime measurements. It shows that even in the best possible case (2.8% module efficiency and ultrabarrier encapsulation), the EROI of devices is still less than 1. According to [Görig et al 2016], the EROI of commercial PV modules was between 10 and 25 in 2010 and will be between 20 and 60 in 2020. Organic PV cells developed by the CHEETAH consortium have not yet reached the EROI=1 level.

Architecture	Module efficiency %	Average Embodied Energy (MJ/Wp)	Lifetime (actual) [Years]	EROI (actual)	Lifetime (EROI=1) [Years]	Required lifetime improvement multiplier
Unencapsulated	2.8	1.78	0.000155	0.0015	0.11	683.9
PET/UV-adhesive	2.8	2.8	0.016500	0.1187	0.14	8.4
Multi-ultrabarrier-encapsulated	2.8	23.06	0.409000	0.5129	0.80	1.9

Table 6: Embodied Energy and EROI for different device architectures

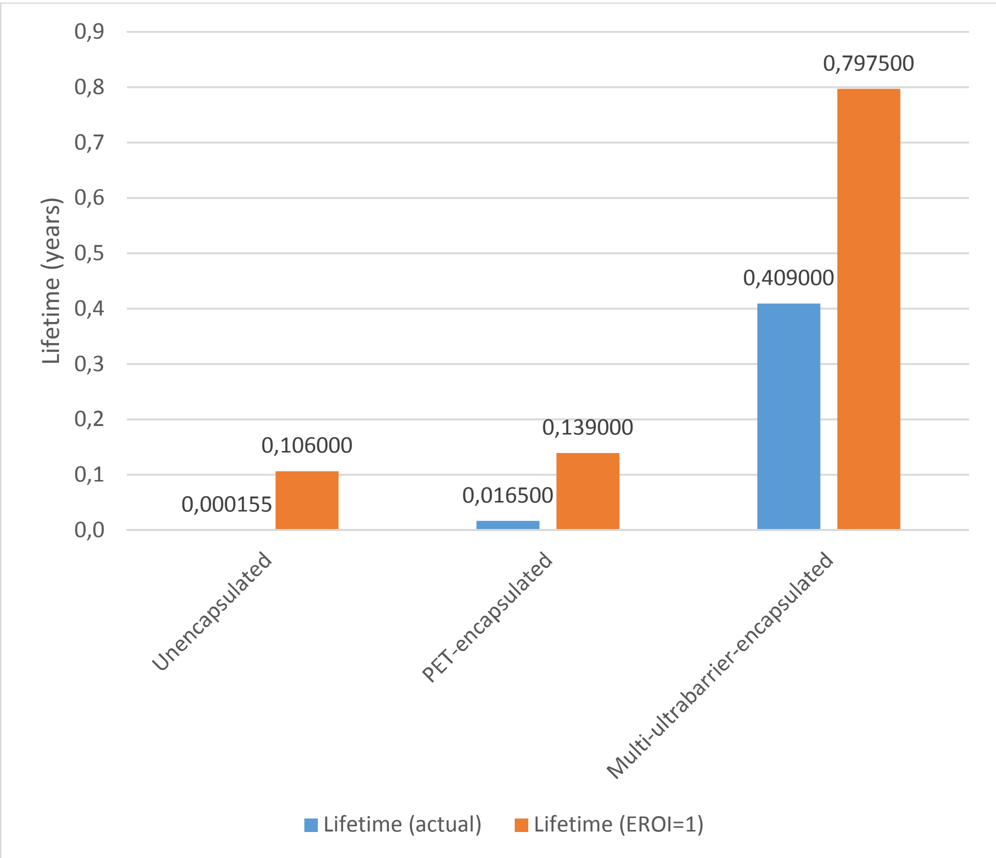

Figure 6: Comparing actual lifetimes with lifetimes needed for EROI=1 of devices with different encapsulation architectures

Table 6 and Figure 6 show the factor by which current lifetimes should be improved in order to achieve an EROI=1. For unencapsulated devices, the lifetime should be improved by a factor of 683.9. PET-encapsulated devices should last 8.4 times longer and multi-ultrabarrier-encapsulated devices would require a lifetime improvement by 90% in order to reach an EROI=1.

The conclusion of the energy cost analysis conducted by Imperial College and DTU is that even though ultrabarrier based encapsulation is more expensive than PET-based encapsulation, due to much better stability achieved through ultrabarriers, the chances to reach Energy Return on Energy Invested (EROI) = 1 for ultrabarriers are better than for PET-based encapsulation.

4. Conclusions and future work

The current report provides a reality check on the cost impact of the research innovations brought by the Cheetah project.

Crystalline silicon

More specifically a step-by-step calculation approach was followed in order to assess the cost impact of the use of 100 μm epitaxial wafers instead of conventional 180 μm thick wire-sawn wafers. Besides all the different technical challenges (e.g. more complex cell processing) and supply chain uncertainties it was shown that the work of Cheetah is very promising and deserves further investigation. Our calculations show that there is ***a 21% cost reduction potential on module level when replacing standard wire-sawn wafers withthin 120 μm epitaxial foils in the chosen SHJ-IBC cell and module technology.*** This fulfils one of the KPIs of the project (KPI 8.2) which aims for 20% cost reduction comparing to state of the art technologies at the beginning of the project (2014). Considering that average prices were used for our benchmark and from late 2015 for cell and module processing and 2017 for wafer costs (i.e. after the beginning of the project), this objective can be considered as achievable. The results showed that comparing ***epi-foil based modules to standard products*** (i.e. 180 μm wafer based) considering their future prospective cost reduction potential (due to cheaper polysilicon and/or improved processes)***, savings of 13% can be achieved***. This reveals the competitiveness of the technology under development based on thin wafers. Regarding the cost reduction potential on ***epi-wafers*** this is found to be very impressive at a level of ***37% when comparing with projected costs for "ultimate" wafers (180 μm)*** and of ***50% when comparing with benchmark cut wafers (180 μm in 2015)***. Both exceed by far the defined KPI of Cheetah project which was set for 30% (KPI 6.5).

The insights and discussions at the European Solar Technology Forum (the CHEETAH project's final public event) on 30 November in Berlin showed that in the current market situation there is not a great drive towards thinner silicon wafers. Silicon is relatively cheap, production yield through the production chain needs to be very high, and efficiency cannot be lost due to poor light management in the cells. Yet the solutions are available already to go towards low cost 100 μm wafers. Wafers at 80-90 μm thicknesses developed in the CHEETAH project, whether they are thinned diamond sawed wafers or thick epi-wafers, still represent a revolutionary jump in technology development for the cell producers. High CAPEX cost and high investments for Epi-wafer lines, technology that has not proven itself yet in volume production and a constantly and aggressively moving wafer cost target makes for a high barrier for the commercial introduction of this technology. Already the cost of Chinese modules is at or near the 30 USCent/W level which was the goal of the CHEETAH project. The benefits of thin wafer technologies are, however, still very interesting. Thin wafers will reduce the environmental footprint of solar cell use by reducing the amount of material, energy and waste which is an argument that will only become more important in the future. These reductions will also enable cost reductions when production is at scale. Thin wafers may enable light weight modules and flexible modules and should therefore lend themselves especially well to BIPV products. These possible niche products may currently be the only way to introduce Epi-wafers to market. These markets may give Epi-wafers a chance to grow in volume so that they become increasingly competitive. Moreover, one may envision parallels with the introduction of other technologies in PV, e.g. PERC cells.

Thin film

Regarding microconcentrator CIGSe solar cells with 16% module efficiency, a profitability analysis was conducted that shows that concentrating CIGSe PV systems are almost always less profitable than non-concentrating CIGSe PV systems, when both use tracking with the light conditions in Europe. KPI 9.5, which foresees a 20% cost reduction via microconcentrator CIGSe cells as compared to standard CIGSe cells, could not be verified with the available data. The assumptions for the profitability analysis were set in a very conservative way. Firstly, the efficiency of the concentrated and non-concentrated modules being equal, which considers the current challenges of fabrication but does not correspond to the final target of efficiency enhancement with concentration. Secondly, the rough estimation that cost reduction due to material saving will be approximately balanced by additional costs resulting from the integration of further components (insulation layer, lenses). Also, here the target is to improve on reducing complexity of additional steps and thus take advantage of the benefit. In the sum and also considering the results from the European Solar Technology Forum, it is obvious that further research is required in order to advance the aspects of material saving and efficiency enhancement as the basic ingredients to make novel concepts successful.

The insights and discussions at the European Solar Technology Forum (the CHEETAH project's final public event) on 30 November in Berlin led to the conclusion that the results are interesting but there is a big gap between the project results and any potential industrial exploitation. The main reason is that today in the PV industry, the efficiency is the most important factor. Cell efficiencies lower than 20% are not interesting enough for industry. Also, the cost reduction is another important aspect and nowadays the cost should be or aim to 20 cents €/W_p. A possible application of the micro concentrator CIGSe concept is in building-integrated PV (BIPV) as "sunny windows", using the diffused light for lighting and the rest for PV.

Organic PV

As for OPV cells with improved stability, energy invested was used rather than cost due the absence of a market. Energy cost can be considered a relevant guideline to help identify the options with the most promising overall cost-effectiveness. Due to much better stability achieved through ultrabarriers, the conclusion of the energy cost analysis was that the chances to reach Energy Return on Energy Invested (EROI) = 1 for ultrabarriers are better than for PET-based encapsulation, even though ultrabarrier based encapsulation is more expensive than PET-based encapsulation.

These OPV results and especially questions related to intrinsic stability and encapsulation are also very relevant for perovskite PV (PKPV). The discussions at the European Solar Technology Forum (the final public event of the CHEETAH project) showed that studies and research on intrinsic stability are considered more important than studies on encapsulation architectures.

KPI10.3 states "Reduced time and embedded energy in the production process". While reduced time in production process was not a target in the project, routes for reduction of embedded energy were identified, which constituted the use and optimization of the existing ultrabarrier packaging rather than substituting these with cheaper alternatives. In particular, strengthening the properties of adhesives used for ultrabarrier packaging was demonstrated, as well as optimization of the electrode protection, which led to demonstration of device stabilities beyond 20 months in operating conditions.

Nevertheless, OPVs and similar technologies are still at the early stage of commercialization and further demonstration of cost/embedded energy reduction and efficiency increase is necessary before implementation of such technologies by industry can be seen.

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