EC Grant Agreement n°609788

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

D5.5 - Impact of quality and reliability on PV competitiveness

WP5 - Acceleration of innovations' implementation

Section 1 – Document Status

Document information

Deliverable name	CHEETAH_D5.5_ Impact of quality and reliability on PV competitiveness
Lead beneficiary	SolarPower Europe (EPIA)
Due delivery date from Annex I	M24
Actual / forecast delivery date	M33
Dissemination level	Public | ~~Restricted~~ | ~~Confidential~~

Document validation

Name	Organisation	Date	Visa
Ioannis Thomas Theologitis - WP5 leader	SolarPower Europe	31/08/2016	OK
Jan Kroon - Coordinator	ECN	12/09/2016	OK

Document history

Version	Date	Modifications	Name
1.0	29-07-2016	First draft	Ioannis Thomas Theologitis
1.0	06-08-2016	Review and comments	Roman Medina, Eduardo
1.0	10-08-2016	Review and comments	Carlos del Cañizo Nadal
1.0	11-08-2016	Review	James Watson
2.0	12-08-2016	Second draft	Ioannis Thomas Theologitis
2.0	25-08-2016	Review and comments	Nigel Taylor
Final	31-08-2016	Final draft	Ioannis Thomas Theologitis

Section 2 – Table of content

Section 3 – Acknowledgements

SolarPower Europe and the authors of this report would like to extend their sincerest thanks and appreciation to those who contributed to the realization of this study by providing data, knowledge and analysis.

The collection of data was a difficult process and among all the different experts and sources that are mentioned throughout this report, the authors acknowledge the specific efforts and contributions of:

the International Energy Agency (IEA) and its Photovoltaic Power Systems Programme (IEA-PVPS), the Horizon 2020 EU funded project "Solar Bankability" (grant agreement No 649997), KIC InnoEnergy with the recent work on the future solar photovoltaic energy costs that was particularly insightful and the European Photovoltaic Technology & Innovation Platform that willingly shared their work and input data for the completion of this analysis.

Last but not least, this work wouldn't have been realized at this level of quality without the contribution of Becquerel Institute both in the collection of data and the analysis but also the drafting of this report.

Section 4 – Executive summary

Description of the deliverable content and purpose

The purpose of this deliverable is to provide an analysis of the cost components (and sub-components) of a standard PV system in order to identify which technology improvements will provide the best returns in terms of quality improvement and LCOE decrease. In that respect, this document goes in depth in the CAPEX and OPEX structure, looking at the sensitivity of each element.

The deliverable complements the cost assessment work of Cheetah, great part of which has already been published in the recent past (D5.2 and D5.3). The report continues exploring the Levelized Cost of Electricity (LCOE) concept that was presented in D5.2 in order to assess the potential of technology improvements to reduce the cost of PV electricity in the coming years. These technology innovations - among which some Cheetah innovation - are considered to improve the lifetime performance of the PV systems (technical and cost), addressing at least partially the quality issues encountered in the field so far.

The report evaluates the impact of potential technology improvements on the LCOE, providing an analysis which is split per component (CAPEX, OPEX and other costs elements). A sensitivity analysis of each of the cost components shows which ones can become more critical and impactful, based on their contribution to the LCOE.

PV competitiveness depends on the ability of PV to provide affordable electricity in comparison with other technologies. In economic terms, the cost of PV electricity is referred to as « LCOE », a method that allows comparison of the cost of each kWh produced, whatever the generation technology used to produce it.

The current cost of PV electricity is rather well known and can go down to as little as 0,0741 EUR/kWh in Germany while extremely low tenders have been seen in South-America or the Middle-East for instance. The 0,0299 USD/kWh (a successful bid in Dubai - UAE) that was announced in 2016 shows how low the LCOE of PV could go under the right conditions, sometimes with indirect incentives or low capital costs. While the LCOE depends on many factors, and especially the solar irradiation and the cost of capital, the question of the cost decrease of the PV system and especially of its components, is still at the core of the discussion on future system prices.

In order to link these results with the technology improvement question, a qualitative analysis of the main failures of PV systems has been studied. A clear connection has been done between the root causes of failure and the need for improvement, with an analysis of the cost components affected.

Regarding the type of the technology improvements that have been considered, the scope of this deliverable includes mainly upstream/manufacturing innovations (to match the work of Cheetah project) and also goes beyond the improvements and research work that is developed within the project. ***However, it provides a clear link and indication of the impact that the main innovations developed in Cheetah can have on the cost of PV electricity in the future – considering the impact they***

have on certain elements and the corresponding share of the total cost. e.g. polysilicon, cell development etc.

This deliverable builds on the results from the abovementioned deliverables of the CHEETAH project, makes use of the recent findings of the 2015 KIC-InnoEnergy study on the future solar photovoltaic energy costs and also considers additional results from other European research projects, such as Solar Bankability.

The main conclusion of this deliverable is the relative weight of technology innovations in the improvement of the PV LCOE. It shows that numerous elements are involved in the LCOE calculation, with various weight in the final LCOE. It shows that technology innovation aiming at increasing the reliability of PV components and therefore improving the output of PV systems must be chosen carefully in order to avoid unexpected side-effects: we could see the case of an innovation that would improve significantly the output but increase the LCOE by affecting the value of one cost element. With all elements begin intertwined, playing on one of them can have impact on several others and finally increase the LCOE when the goal was to reduce it.

Section 5 – Assessing the link between quality improvement and costs

1. Rationale

Quality of PV systems can be defined as the ability to deliver the promised output over a specified period of time. In this respect, any deviation from the expected output during the lifetime of the project will impact the profitability of the investment. Improving quality should therefore be considered as a way to avoid deviations from the expected output. Beyond the "superiority" that sometimes is solely used to define quality, the definition of quality should mainly incorporate "reliability" and "sustainability".

This document will research which are the drivers of quality improvement by analyzing the improvement they have in the output. In that respect, we will use a proxy which is the LCOE or levelized cost of electricity. This LCOE, as described below, will characterize the cost of production of PV electricity, a cost that will increase when the quality decreases. In other words, the LCOE should be minimized at all times.

We will look in particular at the costs of failures and how they impact the LCOE.

The following chapters will follow this structure:

- Which are the costs components?
- How do these costs components influence the LCOE?

- Which are the most common failures and which are the impacted components?
- What is the impact of technology improvements on the LCOE?
- And finally the impact of economies of scale on the LCOE.

2. The LCOE components

2.1. Introduction to the LCOE calculation

The LCOE is a standard way of calculating the cost of generating electricity from any kind of power plant, taking into account all Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) costs during the lifetime of the plant. For the past work (D5.2) - the LCOE model built by Agora Energiewende[1], was modified and used. The basic formula for the calculation is the one below:

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{t,el}}{(1+i)^t}}$$

I_0	Investment expenditures in EUR
A_t	Annual total costs (fuels, O&M costs) in EUR in year t
$M_{t,el}$	Produced quantity of electricity in the respective year in kWh
i	Real discount rate in%
n	Economic operational lifetime in years
t	Year of lifetime (1, 2, ...n)

However, since the above definition of LCOE is much too restrictive to be considered in a detailed cost analysis, the upgraded and more practical formula[2] was used (see below). The equation remains the same but has been detailed with additional components, to allow to describe more in depth the cost impact of each element.

[1] Agora Energiewende, Calculator of Levelized Cost of Electricity for Photovoltaics, version 1.2, 27.02.205, http://www.agora-energiewende.de/en/topics/-agothem-/Produkt/produkt/89/Calculator+of+Levelized+Cost+of+Electricity+for+Photovoltaics/

[2] Source: EU PV Technology Platform, Factsheet on PV LCOE in Europe, 2014-2030. June 2015 - http://www.eupvplatform.org/publications/fact-sheets.html

$$LCOE = \frac{CAPEX + \sum_{t=1}^{n}[OPEX(t)/(1+WACC_{Nom})^t]}{\sum_{t=1}^{n}[Utilisation_0 \cdot (1-Degradation)^t/(1+WACC_{Real})^t]}$$

where

t = time (in years)

n = economic lifetime of the system (in years)

CAPEX = total investment expenditure of the system, made at t=0 (in €/kWp)

OPEX(t) = operation and maintenance expenditure in year t (in €/kWp)

$WACC_{Nom}$ = nominal weighted average cost of capital (per annum)

$WACC_{Real}$ = real weighted average cost of capital (per annum)

$Utilisation_0$ = initial annual utilisation in year 0 without degradation (in kWh/kWp)

Degradation = annual degradation of the nominal power of the system (per annum)

and $WACC_{Real} = (1 + WACC_{Nom}) / (1 + Inflation) - 1$

where Inflation is the annual inflation rate.

2.2. Detail of CAPEX costs

The LCOE considers the CAPEX elements that are spent during the first year of the PV installation. Practically the moment when the CAPEX costs occur is irrelevant in this part of the analysis.

In order to simplify the study, the following numbers are being averaged through all segments and for all technologies. However, one could use the same approach to assess with more details each technology for each segment in a defined location. *In practice most parameters impacting the LCOE are intertwined and it is always a challenging exercise to identify the sole contributions of each of them. Nevertheless, averaging CAPEX elements is an acceptable approximation that delivers accurate and usable results.*

The CAPEX can be split in several elements and in turn those are split between material costs and manufacturing costs (see below).

Table 1 : CAPEX Main Elements

Element	Percentage (%)
Modules	42.7
Inverter	14.9
Rest of BoS	8.9
Other electrical BoS	10.9
Installation	22.5

PV Systems are composed of modules, inverters (that can be integrated into the module itself), and other components that are often referred to as balance of system (BOS). They are components of mechanical elements such as the mounting structure and electrical ones. Finally, the PV system has an installation cost. The BoS can be split between electrical BoS (without the inverter) and the rest of the BoS which refers to mechanical components.

The numbers shown here can clearly differ from one segment to another (e.g. from residential, commercial to utility scale segment) and only represent an average between competitive prices in Europe for utility-scale PV systems (between 0.85 and 1 EUR/Wp) and residential systems (between 1.3 and 1.6 EUR/Wp). These numbers are subject to market conditions and cannot be applied blindly to any country, segment or application. Module prices considered represent the Q2 2016 European prices. In the assumptions considered here, the system price reaches 1,00 EUR/Wp with modules at 0.545 EU/Wp. This situation corresponds at the time of performing this analysis and refers to competitive ground-mounted installations (but not the most competitive ones) and competitive industrial rooftops.

The next level of data breakdown which is given in Table 2 below includes for each of these components the costs of final elements/subcomponents.

Table 2 : Main elements cost break down

Main Element	Percentage (%)	Intermediary element	% System Price	% of main element
Module	42.7	Polysilicon	5.5	12.8
		Wafer	8.7	20.4
		Cells	8.8	20.6
		Module components	17.4	40.7
		Other costs	2.4	5.6
Inverter	14.9	Inverter	14.9	100
Rest of BoS	8.9	Rest of BoS	8.9	100
Other electrical BoS	10.9	Other electrical BoS	10.9	100
Installation	22.5	Installation	22.5	100

At this level of detail, the various elements of the PV value chain for crystalline silicon technologies can already be identified. For thin film technologies, these sub-elements have to be considered together (only module costs are pertinent). In this case the data for components within the module have been computed based on current market prices for each component sold separately (polysilicon, wafers, cells).

The final level of detail consists in splitting each of the elements as described in the table below.

Table 3: Detailed breakdown for each component

Main element	Intermediary element	Element Detail	% System price	% Main Element	% of Intermediary element
Module	Polysilicon	Polysilicon	5.5%	12.8%	100.0%
	Wafer Production	Wafer Production	8.7%	20.4%	100.0%
	Cells	Silver in Cells	0.7%	1.7%	8.1%
		Cell Production	8.1%	18.9%	91.9%
	Module components	Glass	3.0%	7.1%	17.4%
		Back sheet	3.4%	7.9%	19.5%
		Encapsulation	0.8%	1.9%	4.7%
		Frame	3.6%	8.4%	20.7%
		Electrical Components	2.4%	5.5%	13.5%

		Production Costs	4.2%	9.8%	24.2%
	Other costs	Packaging	0.1%	0.2%	3.4%
		Certification	0.2%	0.6%	10.3%
		Warranty	0.8%	1.9%	34.5%
		Shipping	1.2%	2.9%	51.7%
Inverter	Inverter	Inverter	14.9%	100.0%	100.0%
Rest of BoS	Rest of BoS	Mounting Structure	6.9%	77.4%	77.4%
		Infrastructure	2.0%	22.6%	22.6%
Other electrical BoS	Other electrical BoS	DC Cables	4.1%	37.6%	37.6%
		Grid Connection	4.9%	45.1%	45.1%
		Transformer	1.6%	15.0%	15.0%
		Switch Gear	0.3%	2.3%	2.3%
Installation	Installation	Planning & docum.	2.1%	9.2%	9.2%
		Margin module	8.5%	37.9%	37.9%
		Installation work (and margins on other components)	11.9%	52.9%	52.9%

Cheetah project focuses on innovations that also aim at cost reduction at the module level. Therefore, all the sub-components from Table 2 are very relevant to the project's work. Innovative approaches for wafer development with less polysilicon use (ultra-thin wafers and epitaxial foil wafers of 80µm and 40µm respectively), cell and module development have a great potential for further cost reduction, taking into account the shares of Table 2 and 3. The potential has been presented in D5.3 and an updated version of that analysis – including thin film technologies – will be published at the end of 2017.

The numbers in Table 1, 2 and 3 above have been computed based on information provided by several sources such as PV Insights website (consulted April 2016), PV Magazine (Editions of February and March 2016), IEA-PVPS (National Survey Reports 2014), RTS Corporation (direct contact), Louwen 2016[3], Becquerel Institute (direct contact), Bloomberg NEF website (consulted April 2016), the EU PV Technology & Innovation Platform (ETIP PV)[4].

2.3. Detail of OPEX costs

OPEX costs relate to operation and maintenance of the PV system during its lifetime. These costs have been the core topic of different discussions of the last couple of years and have also declined with the professionalization of the PV sector. The breakdown of OPEX costs are more complex to assess since they are covered in general by long-term contracts covering some of the aspects of the operation and maintenance. Furthermore, usually in such contracts there is a cost for a certain fixed services to be

[3] Source: Atse Louwen, Wilfried van Sark, Ruud Schropp, André Faaij, "A cost roadmap for silicon heterojunction solar cells", January 2016, published by Elsevier

[4] PV Costs in Europe 2014-2030, EU PV Technology Platform, published at http://www.etip-pv.eu/publications/other-publications/pv-costs.html

performed and a price for extraordinary or additional services that their frequency varies and therefore the final impact on the LCOE varies.

In order to estimate the different components, this study has compiled the most often quoted elements of OPEX with an average value for each of them. The real numbers could be lower or higher and depend significantly on the market, the site conditions, the O&M contractor etc. In that respect the numbers below are a good approximation of the different costs associated to operation and maintenance which is a growing relative cost in the LCOE[5].

Table 4 : OPEX cost breakdown

Element	Percentage (%)	Breakdown	% of Total OPEX	% of Main element
Operation	25	Management	4.9	19.8
		Security	12.6	50.5
		Monitoring	7.4	29.7
Maintenance	75	Additional maintenance	12.4	16.5
		Preventive maintenance	22.2	29.6
		Module cleaning	7	9.4
		Grass cutting/ fence cleaning	14	18.7
		Inverter guarantee extension	19.4	25.8

2.4. Detail of other LCOE elements

In additional to efficiency, the load factor is needed to transform the received solar irradiation into the yield, the real PV production. In order to reach the final number, losses coming from various components have to be added up, such as the losses at the inverter, the losses due to the temperature, the losses in cables (AC and DC cables), the losses due to shading, the losses due to mismatching (different working conditions at module level), the losses due to a weaker irradiation (than foreseen), the losses due to snow/dust etc. Degradation of the modules has also a great impact on the real yield (and the performance ratio). This element has been considered in the analysis.

The following table illustrates a standard split for common losses. The numbers can vary and only the order of magnitude should be considered.

[5] Source: Becquerel Institute, EU PV Technology Platform, interviews with market actors (conducted from January to April 2016). Numbers have been cross-checked.

Table 5 : Losses breakdown

Loss types	Losses in %
Inverter losses	5,0%
Temperature losses	5,0%
DC cables losses	2,0%
AC cables losses	2,0%
Shadings losses	2,0%
Losses due to weak irradiation	2,0%
Losses due to snow/dust	2,0%

System lifetime refers to the duration of the system. In recent years, the expected system lifetime has been increased for most PV system, above 20 years, with sometimes expectations up to 25 or 30 years. This element has been considered in the analysis. Meanwhile some start to consider that the lifetime could be significantly longer with a repowering of the installation after a certain number of years. This has not been considered but could be considered as an option to lower the LCOE during the lifetime of the entire project. The question of the financing period is essential. In general, LCOE calculations, it is assumed that the financing period is equal to the lifetime of the system which is not the case in real life. The financing period is reduced compared to the lifetime and could even be shorter than 10 years. *This has an impact that hasn't been studied here.*

WACC is the acronym for "weighted average cost of capital" or in other words the cost of financing a PV project, with a mix of equity and debt. The LCOE calculation uses the WACC to discount future cash flows and represents therefore a major contribution to the LCOE. The WACC can also be broken down to several parts such as the risk free rate, the PV spread (the risk associated to PV in general), the country spread (the risk associated to a specific country) and the project spread (the risk associated to the project itself, developer included). *However, due to the upstream nature of Cheetah project, those elements have been considered as out of scope.*

3. Sensitivity of LCOE to its components

3.1. Rationale

The chapter aims at providing the basic tools to identify which cost elements are impacting the LCOE most. This will allow later to make the link between technology innovations and LCOE improvement. Since the LCOE can be reduced by decreasing the impact of failures or degradation on the electricity production and lifetime, it is important to identify which technological improvements can contribute to improve the reliability of PV systems, and the impact on the cost of the components. In that respect, some technology changes can increase the cost of some components, but may impact positively the LCOE through increase of efficiency and reduction of losses. In this specific case, the final impact on the LCOE will be double: positive thanks to the improvement with regard to increased efficiency or reduced losses and negative because of the CAPEX increase.

The following paragraphs present which components impact the LCOE most and to which extent. In the same way the question of losses is analyzed.

3.2. Weighted impact of cost elements in the LCOE

This part of the study envisages the weighted impact of each cost element that was presented above on the final LCOE. A sensitivity analysis has been realized in order to "propose" a ranking of the most interesting elements to be considered for positively impacting (reducing) the LCOE of PV systems. *One however must look at this with a critical eye since the potential of technological improvement can be significantly different from one component to another and therefore conclusions cannot only be drawn according to the current impact on LCOE.*

In order to assess the impact on the LCOE, a 10% variation of each parameter has been applied to evaluate which parameters have the largest impact on the LCOE.

This is of course not the most realistic case since some parameters are expected to change by some percent x and others by some percent y with x being quite different from y. In that respect the following ranking much be considered as indicative and each real technology improvement should be tested according to its real impacts. *Moreover, as said at the beginning of this chapter 3 (3.1) a technology change can impact several parameters together: it could increase the cost of a components significantly but reduce the OPEX, increase the performance ratio or simply the yield. It can also affect indirectly the cost of capital but raising the perceived bankability of the final PV system. All these remarks should be considered carefully before assessing the impact of PV innovations.*

The following hypotheses have been considered to test the sensitivity of the model and have an impact on some components, especially through the CAPEX/OPEX/WACC ratios.

Table 6: LCOE calculation inputs

LCOE	**0,083** EUR/kWh

LCOE COMPONENT					
CAPEX	EURO/kWp	1000			
OPEX	EURO/kWp	30	OPEX grow yoy	Percentage/yea	2%
T	year	25			
WACC nom	Percentage/year	6,0%	WACC nom grow yoy	Percentage/yea	0%
WACC real	Percentage/year				
Utilisation	kWh/m2	1375			
Utilisation	kWh/kWp	1100			
Degradation	Percentage/year	0,5%			
Inflation	Percentage/year	2,0%			

Figure 2 illustrates that, if each parameter is varied independently by 10%, the variation in yield has the highest impact on the LCOE, then the CAPEX, the WACC, the OPEX and lifetime and finally the degradation rate. *It must be noted that the standard degradation rate considered here is 0,5%. The impact would be more significant if the baseline was 1% degradation per year*. But looking more in detail at each component, the ranking appears:

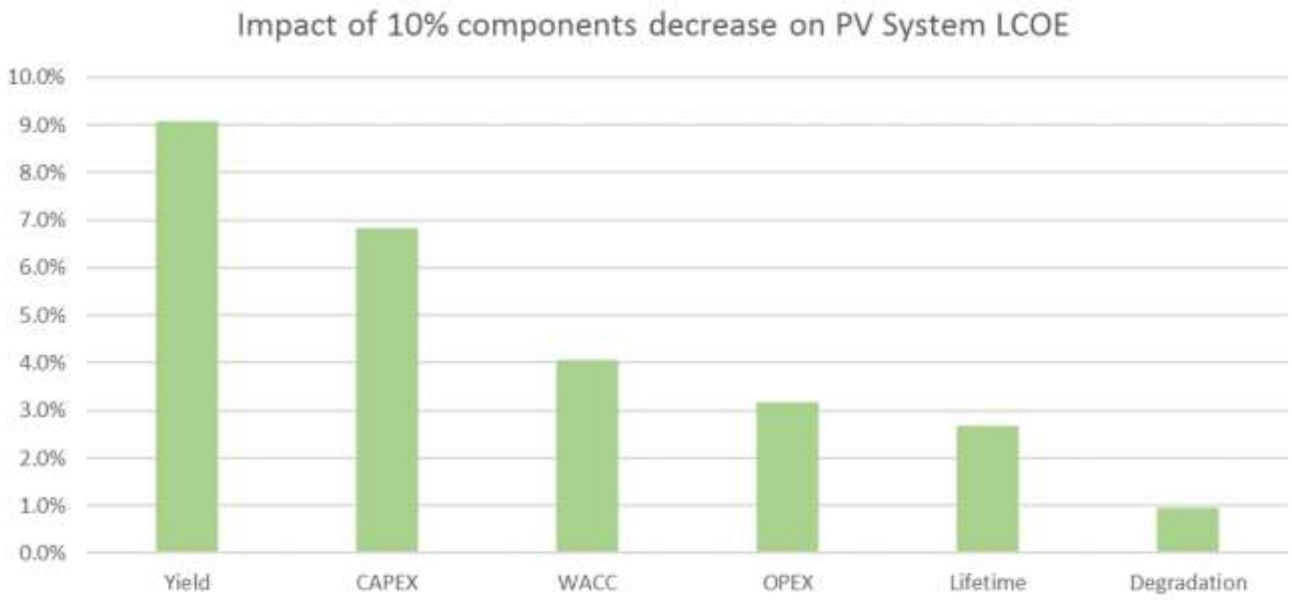

Figure 1: Impact of 10% variation in each LCEO cost component on PV system LCOE

CAPEX elements

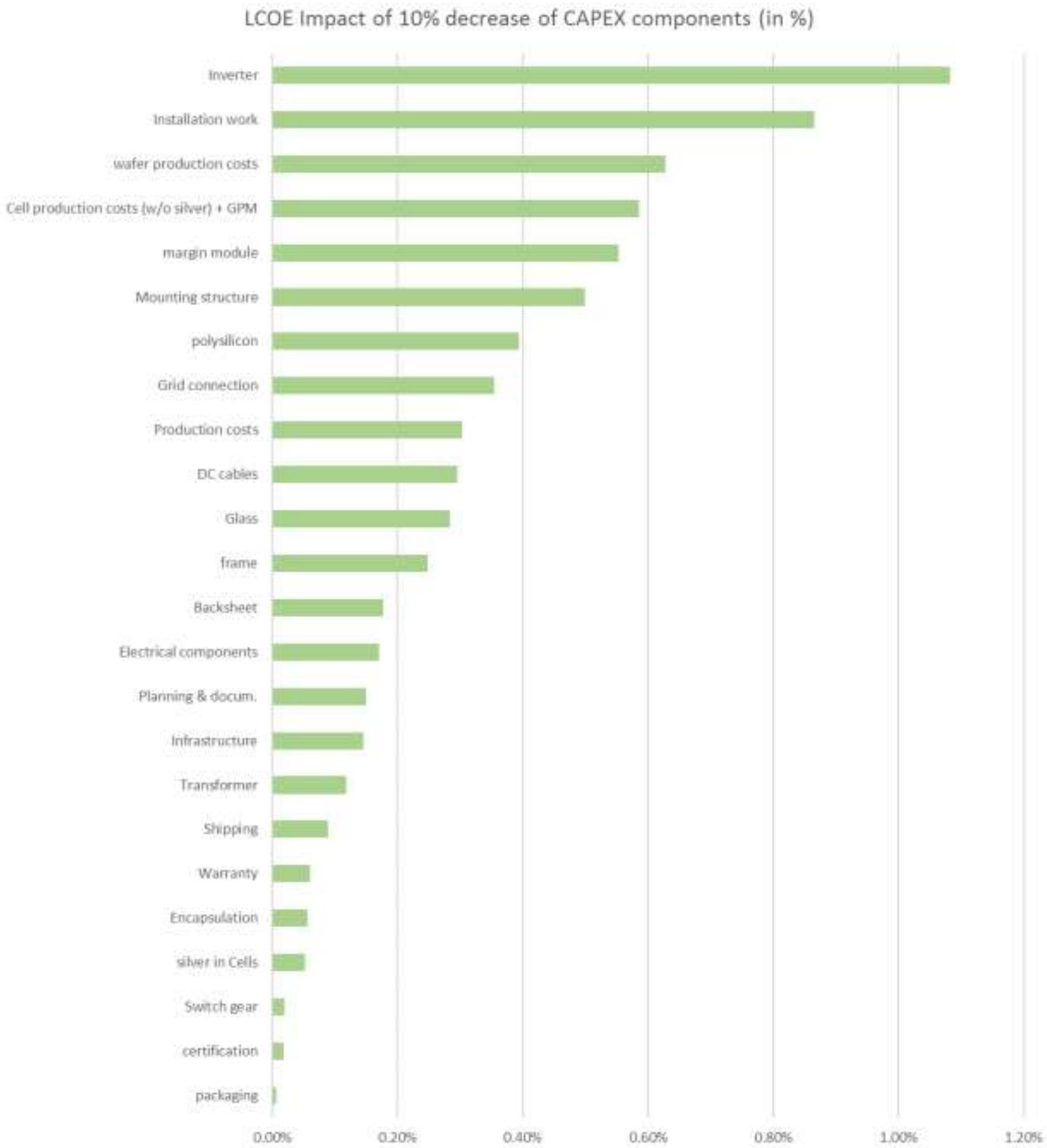

Figure 2: Impact on LCOE of a 10% decrease in each CAPEX components (in %)

From all CAPEX elements, the inverter is the one that can influence most the decrease of the LCOE, followed by installation works. It is rather interesting to note that at the first place we find several elements that are directly influenced by labor costs (e.g. installation work, cell production costs) and other (or the same) elements which are linked to the technology (e.g. wafer production, cell production). The question of the margins is important as well since it appears to be an important component of the LCOE. However, the margins at module level depend on whether or not the module production is vertically integrated or not. In case of vertical integration, the margins are grouped and could indeed represent a major component as we have seen in the figure 3 above. If module production is not vertically integrated, the margins are distributed between all components from polysilicon to modeling and therefore reduced in absolute value, and less visible. This would require a complete chapter in order to assess the advantages and challenges associated to vertically integrated module companies. On the other side, the question of silver in cells or encapsulation comes at the bottom of the list.

Interestingly, a decrease of 10% in the CAPEX of one component alone never brings a LCOE decrease higher than 1%. For almost half of the components considered, the decrease is below 0.2%.

OPEX elements

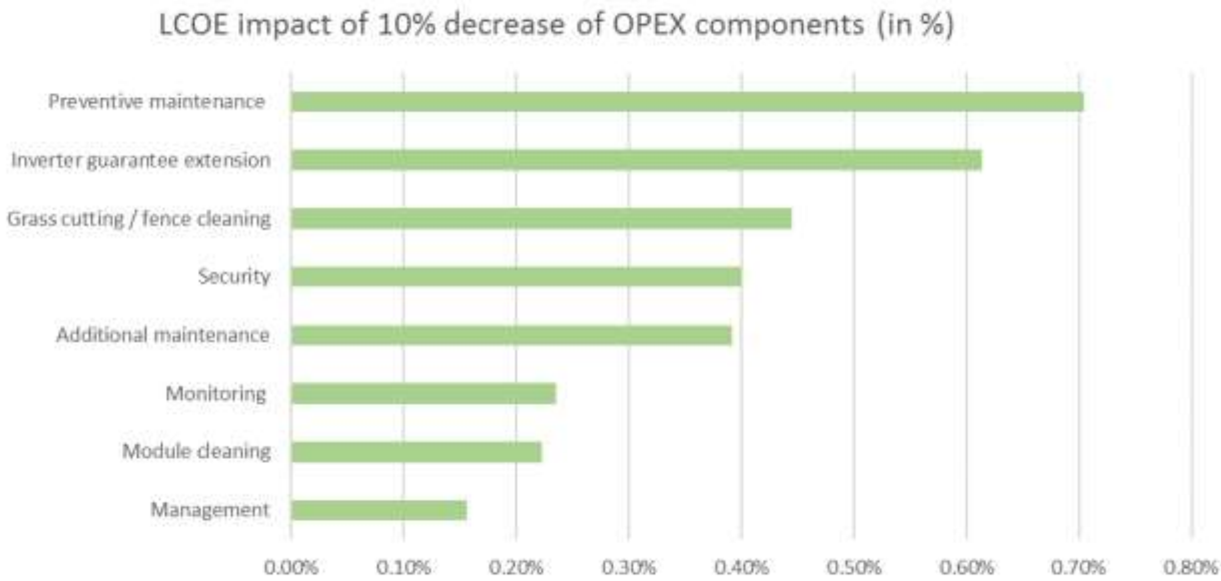

Figure 3: LCOE impact of 10% variation of OPEX components (in %)

Looking at OPEX elements it is interesting to note that preventive maintenance has the highest potential to influence the LCOE, but at a rather low level. This is rather complex since preventive maintenance is supposed to avoid production losses that can be extremely damaging for the PV production. The contribution of these OPEX elements has an order of magnitude close to the CAPEX one and that continues to prove how the contribution of OPEX becomes essential in the LCOE assessment of PV systems. Another element to be considered is the relatively low impact on the LCOE anyway, with a 10% change in the OPEX components leading to less than 1% of LCOE change.

Impact on losses (PR)

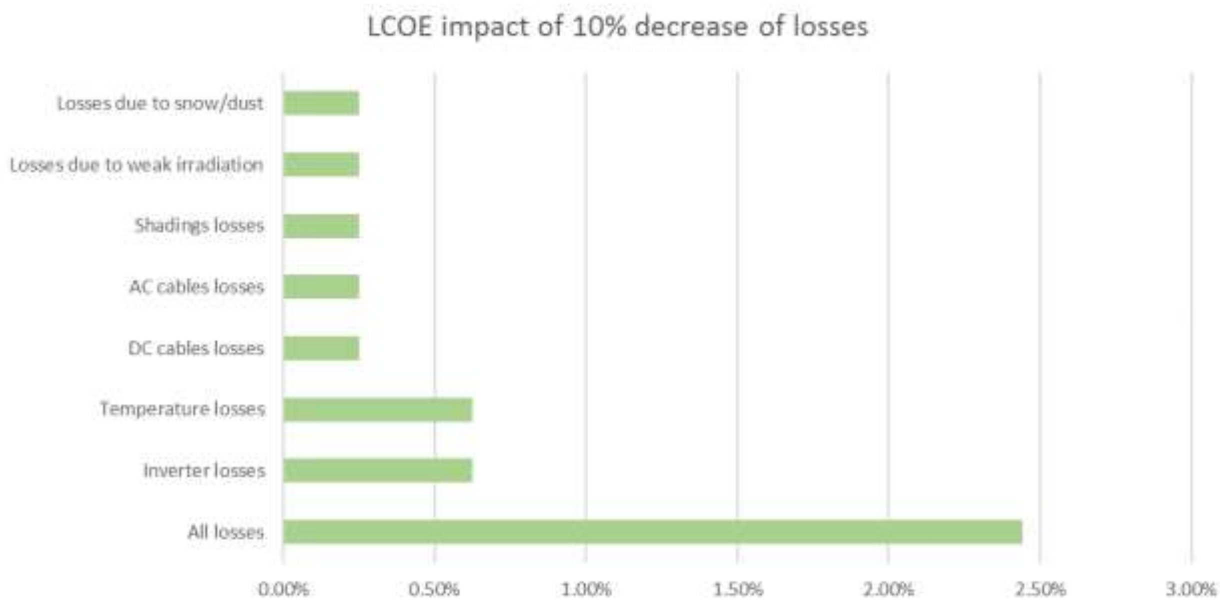

Figure 4: LCOE impact of 10% decrease of losses

Finally, since the LCOE is most sensitive to the system yield, a variation in the losses have a significant impact on the LCOE.

3.3. General Contribution to the LCOE of all major elements

To identify the contribution of each element to the LCOE, the following methodology has been used: as a baseline the contribution of CAPEX and OPEX have been computed using standard parameters and with the WACC set at zero in order to assess the impact of all components separately and the same for the losses and the degradation.

The next steps in the calculation estimates therefore the LCOE contribution of all cost elements first in an ideal situation (no cost of capital at all, no annual degradation, no losses) and estimates after that the impact of these three elements on the final LCOE. This approach allows to make available a model where each contribution to the LCOE can be isolated.

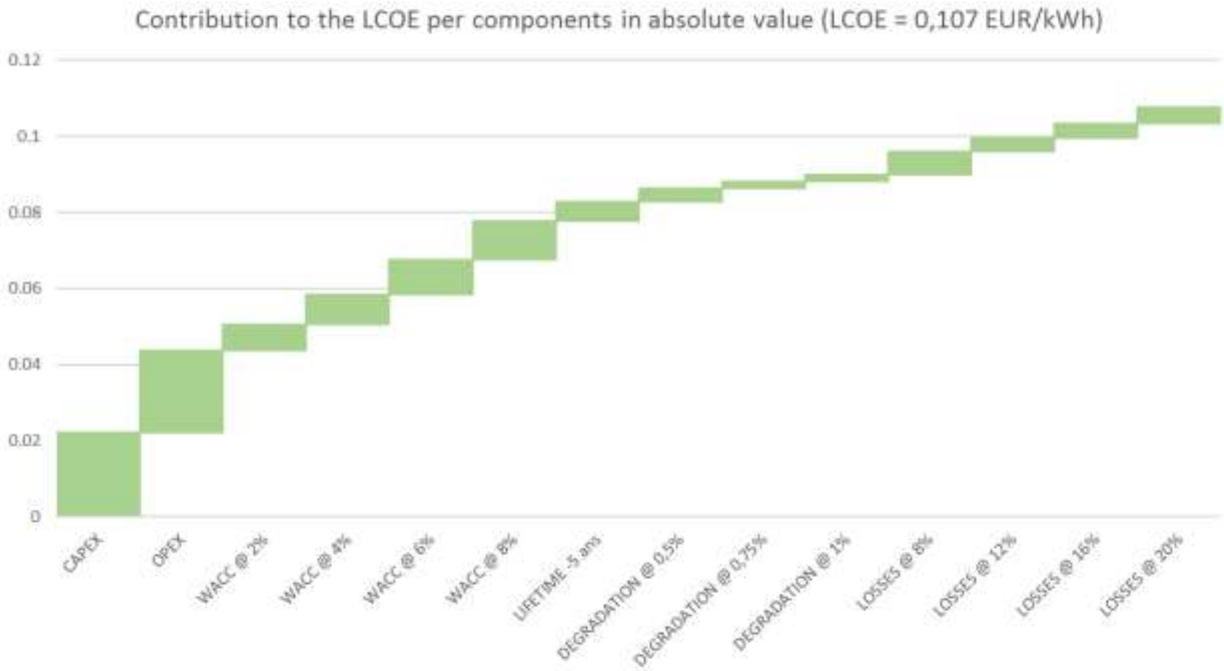

Figure 5: Contribution to the LCOE per components in absolute value (LCOE = 0,107 EUR/kWh)

Figure 6 illustrates how the CAPEX has today a rather limited impact alone on the LCOE. The assumed OPEX (initially 30 EUR/kWp/year, rising to almost 50 EUR/kW /year after 25 years with inflation) represents in this case a major contributor to the LCOE. Although the value is relatively high, investment in OPEX may allow substantial extension of the system beyond the assumed life of 25 years, with a very low LCOE since the CAPEX is written off.

The cost of capital (WACC) has an increasing contribution that becomes even more important per unit when it grows: every addition % of WACC increases more the LCOE than the previous %.

Lifetime shortened has an impact but perhaps not as important as one could imagine, since the last years are contributing less than the first ones. A higher WACC will accentuate this effect, by reducing even more the contribution from the future cash flows. But this hasn't been computed here.

Finally, the accelerated degradation and increased losses contribute significantly to the LCOE. If we consider that OPEX, cost of capital, lifetime, losses and accelerated degradation are all elements that can be linked to the perception of quality, we see how important the part of the LCOE that can be impacted by quality problems can be. In that respect, technology innovations that would increase the CAPEX might have a huge impact on all other aspects, from OPEX to losses with a very limited impact on the LCOE due to CAPEX increase.

Per components

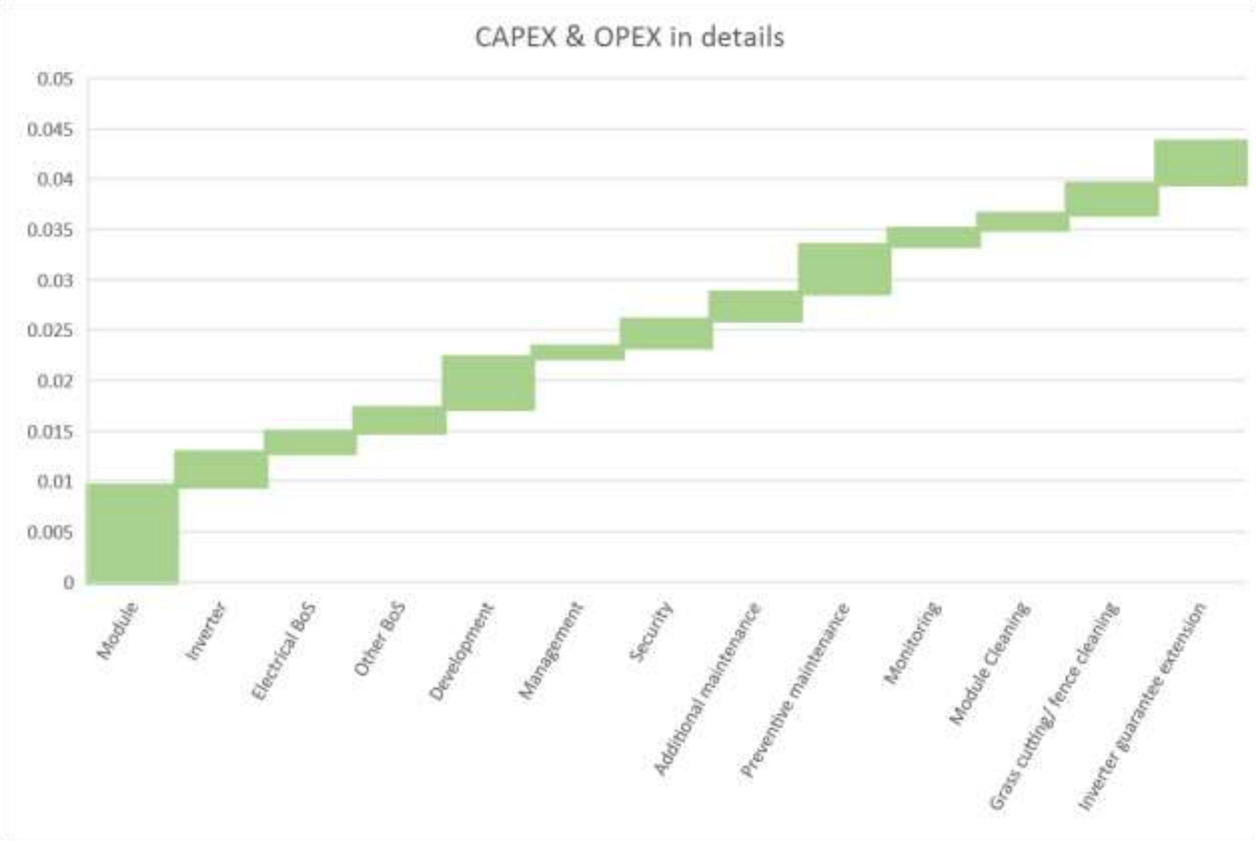

Figure 6: Impact on LCOE of the detailed CAPEX & OPEX elements

CAPEX contributes to almost 50% of the final LCOE. We can also see immediately which are the areas which contribute most to the final LCOE. Some of them where the question of quality might be more important, such as project development (during which the installation process can be bettered) for instance are rather larger in terms of LCOE contribution.

Detailed CAPEX impact

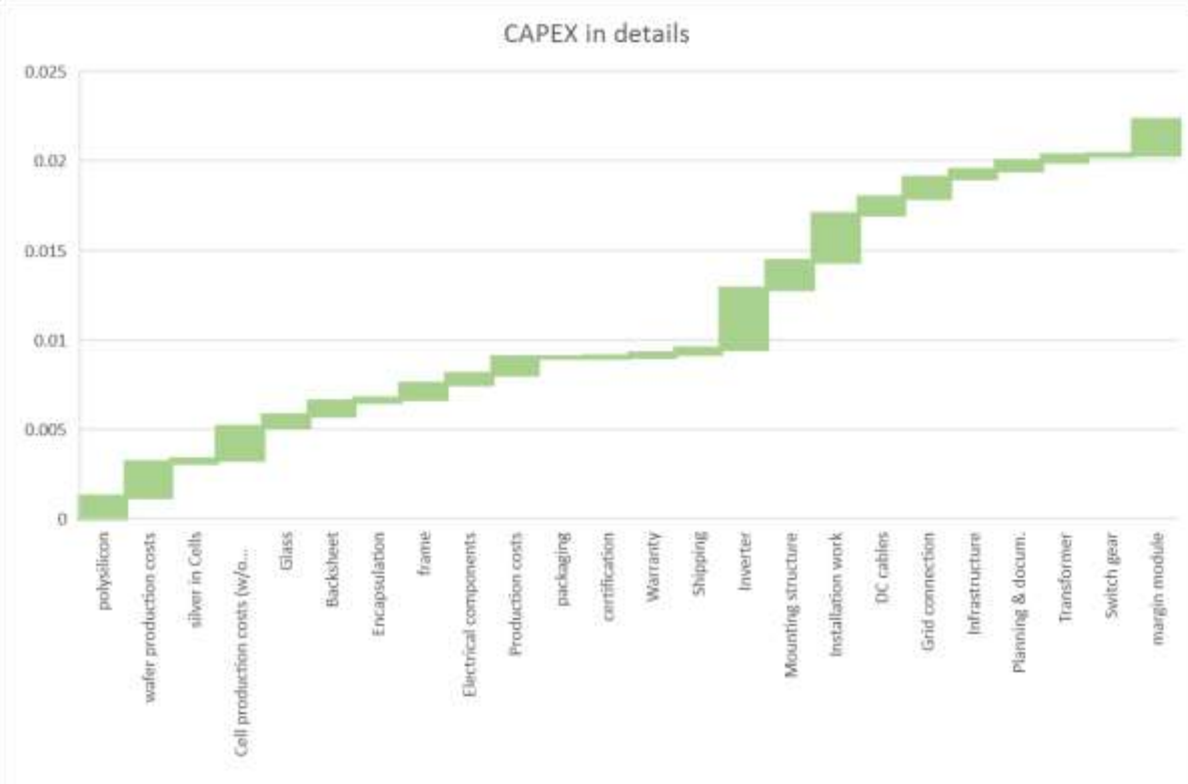

Figure 7: Influence of CAPEX components on the LCOE (in EUR/kWh)

Looking more in depth of the CAPEX impact, we can immediately see which are the elements that will contribute most to the LCOE. In that respect, technology innovations touching the components with the lowest contribution in terms of CAPEX increase, should be favored. We can immediately see here that the impact of some elements on the LCOE is so low that only a major quality improvement might be beneficial.

4. Quantified impacts of PV quality issues on the LCOE

After having seen how different components impact the LCOE, we can examine the other side of the LCOE discussion, which is to identify which are the main causes of degradation and failure, and how they may be solved. In particular this chapter will highlight the LCOE components impacted.

This chapter assesses the impact of quality issues on PV competitiveness through examples from the literature and in particular results from the Solar Bankability project. It shows how losses of performances can be linked to quality issues and how this impacts the PV LCOE.

Amongst many possible sources of performance losses, we decided to select some of them and to link them to possible improvements, in order to estimate the potential impact on LCOE. They represent a wide range of quality issues observed on PV systems and which are relatively known and observed. The data for the analysis below comes from several sources, especially IEA-PVPS (Task 13, review of failure of PV modules), Solar bankability report. Loss estimates are taken from the Solar Bankability report.

4.1. Improper installation or issues during the transportation / installation process

These problems have been analyzed in detail but a detailed discussion is out of the scope of this report. They have been detailed in the Solar Bankability report "Technical Risks in PV projects"[6] as shown in the table below.

Table 7: Improper installation or issues during the transportation/ installation process[7]

Components	Failure 1	Failure 2
Site	Deformation of the land	Roof damage – not adequate sealing methods
PV modules	Mechanically broken/damaged? module	Loose module clamps
Inverters	Wrong installation	Wrong configuration
Mounting structure	Damage of the insolation	Incomplete structure
Cabling	Tighten or loose cables	Exposure to physical damage
Grounding	No existing potential equalization	Wrong combination of material
Monitoring	Wrong installation of sensor	Wrong configuration

Solutions and impacts: Since these points are mostly linked to a lack of know-how, it can be assumed that solving them will require to increase the level of training and quality checks for the installers. The consequence can be a higher cost of installation works compared to unskilled workforce. Meanwhile it can hardly be considered as a technological improvement.

Main LCOE component considered: Transport costs and installation costs.

4.2. Glass breakage

Cause: Glass breakage comes from impact stresses on the glass edge. Frameless modules are more subject to edge breakage than framed modules.

Effect of the problem: Glass breakage affects the electricity output of the cell. The available output current will be that of the lowest output cell – if we do not consider bypass diodes at module level

[6] « Report on technical risks in PV project development and PV plant operation ». Marche 2016. « Solar bankability » project. www.solarbankability.org

[7] « Report on technical risks in PV project development and PV plant operation », op.cit., taken from T.J. Keating, S.A., A. Walker, N.R.E.L., K. Ardani, N.R.E.L., 2015. Best Practices in PV System Operations and Maintenance (No. NREL/SR-6A20-63235). NREL, Golden, Colorado.

(however not always the case since this depends on the module configuration, the number of bypass diodes the reduction of current etc). In that respect it will decrease the yield. Losses can vary from 10 to 50%.

Solutions and impacts: Frameless modules might be more difficult to handle than framed modules. The gain in CAPEX and environmental impact should be put in perspective with the higher requirement for handling and transport, but also during the installation and later the operation and maintenance phase.

Main LCOE component: Frame cost and transportation & installation costs.

4.3. PID (Potential Induced degradation)

Cause: For silicon-wafer-based PV modules: caused by so-called stray currents coming from a voltage difference between the PV module and the ground, the potential-induced degradation degrades the module output: A potential voltage difference can build between the cell and the glass and frame. This allows electrical current to leak and the module loses its peak performance. Some components of the modules and the system are known to contribute to PID. Ungrounded PV systems or systems using transformer less inverters (ungrounded) are subject to PID.

Effect of the problem: Loss of output, yield decrease. Possible (reversible) damage to the cells. Losses can vary from 10 to 70%.

Solutions and impacts: The PID negative effect can be completely prevented if an inverter is used with the possibility of grounding the positive or negative pole. This could result in additional costs since for instance transformerless inverters are less costly. Some manufacturers are also proposing PID-free modules, but at a slightly higher cost. Checks have to be done on the bill of material by the developer, which can also lead to increased development costs.

Main LCOE components: Module costs, inverter costs, development costs.

4.4. Snail trails / tracks

Cause: For silicon- wafer-based PV modules, a snail track is a grey/black discoloration of the silver paste of the front metallization of screen printed solar cells. It is caused by micro-cracks in the PV cells, together with a chemical reaction of the EVA. It is accepted that they are a visible effect of micro-cracks in the cells.

Effect of the problem: Small losses of performances, around 1 to 15 %. However, today manufacturers “fix” the problems in less than 5%.

Solutions and impacts: Micro-cracks can be reduced with a better handling and careful transportation and installation of modules.

Main LCOE components: Transportation, installation costs and cost of modules.

4.5. Defective backsheet

Cause: The first cause is a damage during the transport of the installation of the module. The second main cause is a failure of the backsheet itself during the PV module lifetime due to inadequate materials.

Effect of the problem: Power losses can vary from 1 to 20%.

Solution and impacts: Careful transport and installation can avoid damaging the backsheet of the modules. With regard to the quality of the materials, this can lead to an increase of the module price.

Main LCOE components: Transportation, installations costs and cost of the backsheet.

4.6. Delamination

Cause: Delamination comes from the loss of adhesion between several components within the module. It occurs in general between the PV cells and the encapsulant, but this is not the unique case. It can also happen at the edges, leading to water ingress. In general, it is causing humidity, oxidation, corrosion etc. With the possible ultimate effect of causing fire due to electrical arcing.

Effect of the problem: Loss of power due to optical reflection but also in case of delamination between the cell and the encapsulant, decrease of short circuit current and therefore power losses from 1 to 30%.

Solution and impacts: Better module conception, better choice of materials, and therefore module cost increase.

Main LCOE components: Module costs.

4.7. Hotspots

Cause: Hot-spot heating occurs when a large number of series connected cells cause a large reverse bias across the shaded cell, leading to large dissipation of power in the poor cell. The heating can damage the cell but also the entire module, EVA and backsheet included.

Effect of the problem: It leads to destructive effects, such as cell or glass cracking, melting of solder or degradation of the solar cell, with at the end the failure of the module or at least part of it.

Solution and impacts: Hotspots are due to partial shading of modules, which can be avoided partially with a good evaluation of the shading. Meanwhile this can happen as well due to soiling, which could require a faster cleaning. Finally, the effect can be reduced with the use of bypass diodes in the module, which leads to increased modules costs. Today 2 or 3 bypass diodes are common in the module industry.

Main LCOE components: Cleaning costs in OPEX costs, module costs.

4.8. Soiling /shading

Cause: Dust, snow, rain deposits, bird droppings, pollution. Soiling affects the energy yield of the modules. In addition, it can lead to hotspots (see before).

Effect of the problem: The effect of soiling is mainly a loss of power, from 10 to 30% on the short term. On the long term, it can lead to hotspots and damage significantly the module itself. Shading has similar effects but less intense since the shading moves in time.

Solution and impacts: Faster and better cleaning. Inverters with better MPPT tracking.

Main LCOE components: Yield, Cleaning costs in OPEX costs.

4.9. Failure of bypass diode and junction box

Cause: Undersized bypass diodes can fail due to higher current that the one expected. Junction boxes failures can have numerous causes from corrosion due to poor fixing to the backsheet, bad internal wiring, or poor manufacturing process.

Effect of the problem: This can vary from a simple power loss to module destruction due to hotpot or fire caused by the defective junction box. Estimated power loss per defective bypass diode: 33% and up to 100% - depending on the number of diodes per module.

Solution and impacts: Increase the diode size, better manufacturing of the junction box, better materials and especially the fixing material.

Main LCOE components: Module costs.

4.10. Overheating inverter

Cause: Inverters wrongly sized, or exposed to the direct sunlight, or badly ventilated are exposed to overheating.

Effects of the problem: Overheating will cause power derating in order to avoid damages to the inverter. This happens in general during the best production hours. In addition to power losses, this can lead also to a reduced lifespan for the inverter increasing the OPEX costs.

Solution and impacts: Better sizing of the inverter, protection against excessive heat.

Main LCOE components: Increased development costs (protect the inverter) or oversize the inverter: increased inverter costs.

4.11. Other causes

Many other causes of failure could be assessed, such as overheating junction box, corrosion of cell connectors, all causes of cell cracks, corrosion in the junction box, EVA discoloration, theft of modules, etc. The principle is the same as above: at failures causing additional OPEX costs (due to replacement costs), and reduced output for the PV system have a double impact. The role of the operation and maintenance company will be to limit the time during which the system will produce with a degraded output. Technological improvements have a role to play in limiting technology-related issues, such as PID or delamination. Meanwhile, some failures are purely related to installation features that have little to see with technology improvements and will on the contrary require additional installation, development and/or maintenance costs.

In order to better qualify the losses of performances, the table below (Solar Bankability) provides an estimate for power losses. The numbers are not empirical but an estimate to be tested of the range of possible power losses.

Causes of PV system failures are numerous and well detailed in the literature. The table below gives some examples of key failure types and the power loss that can be associated with. Power losses in this table are not the real ones but an estimation from the authors of the study from which it has been extracted. They indicate an order of magnitude that should be considered as such but shows the extent of possible power losses that such failures might produce.

Table 8: Other causes of failure[8]

Faillures	Power loss [%]	Max power loss [%]
Hotspot	2,00%	20,00%
Delamination	1,00%	30,00%
Glass breakage	10,00%	50,00%
Soiling	10,00%	30,00%
Shading	10,00%	40,00%
Snail track	1,00%	8,00%
Cell cracks	1,00%	15,00%
Defective backsheet	1,00%	20,00%
Overheating junction box	1,00%	33,00%
PID = Potential Induced degradation	10,00%	70,00%
Failure bypass diode and junction box	33,00%	33,00%
Corrosion in the junction box	1,00%	33,00%
EVA discoloration	0,0%	10,0%
Theft of modules	100,00%	100,00%
Broken module	100,00%	100,00%
Damage by snow	100,00%	100,00%
Corrosion of cell connectors	1,00%	15,00%
Unsufficient theft protection	0,00%	100,00%
Improperly installed	5,00%	20,00%
Module damaged due to fire	100,00%	100,00%
Missing modules	100,00%	100,00%

[8] Source: Moser, D., Del Buono, M., Bresciani, W., Veronese, E., Jahn, U., Herz, M., Janknecht, E., Ndrio, E., de Brabandere, K., Richter, M., 2016. Technical Risks in PV Projects, Solar Bankability project

5. Quantified impacts of technology improvements on PV LCOE

5.1. Innovations and LCOE improvement

This chapter assesses the impact of technological improvements on PV competitiveness through examples from the literature and in particular results from the KIC InnoEnergy study. It shows how new technologies can decrease the final LCOE of PV products through specific examples.

The study details several technological improvements, in two parts: what is already expected as market-ready development, and the potential improvements. It splits these improvements according to the PV technology considered.

The following figures estimates how the CAPEX and OPEX will be affected by these technology improvements in the coming years.

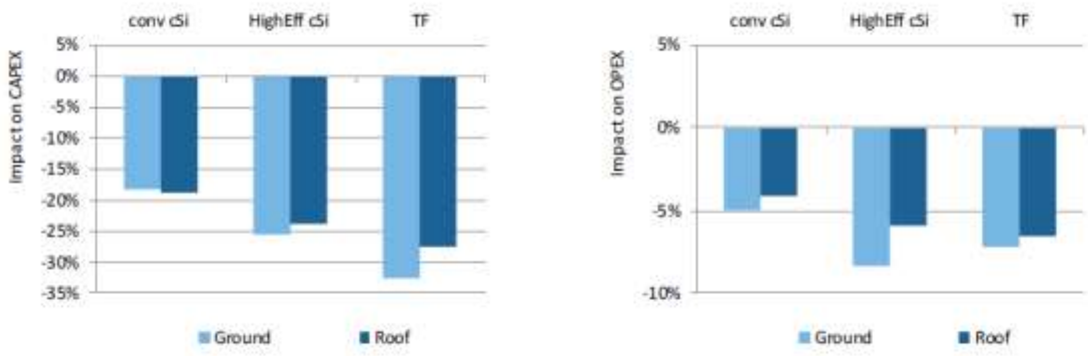

Figure 8: Technology improvements and the effects on CAPEX & OPEX to 2030

It is interesting to note that CAPEX decreases are expected to be more significant for TF technologies. The following improvements have been identified in the KIC InnoEnergy report and others:

- C-Si technologies
    - Silicon feedstock
        - Improvements for silicon feedstock
        - Silicon crystallization
    - Wafers
        - Innovations in wafering
    - Cells
        - Si-based Tandem architectures
        - Back contact
        - Heterojunction
        - Bifacial cells
        - Advanced homo-junction technologies

- Modules
  - Test for defect characterization
  - Improved energy yield modelling
  - Improved connections
  - New cell dimensions and sizes
  - New front cover materials
  - New backsheet materials
  - Frameless or innovative frames
  - New encapsulation materials

- TF technologies
  - Modules
    - Improved deposition techniques
    - Alternative absorbers materials
    - Improved light management
    - Reduce efficiency gap from lab to fab
    - Increase module efficiency
    - New module materials
    - Etc.
- Inverters
  - Improve lifetime
  - Integrated electronics in the modules

Meanwhile, the KIC InnoEnergy study assumes that these technological improvements will be cumulative, which can be debated. For instance, the improvement in homo-junction and heterojunction technologies can't all be cumulated. In addition, some technology improvements could play an important role with or without major changes in the project costs structure. For instance, back contact cells can be developed with homo-junction and heterojunction technologies. The increase in cost due to the technological improvement will have to be mitigated with the increase of efficiency of the module. On the other hand, bifacial cells are the perfect case of the technology improvement that cannot always be summed up with all other improvements. Bifacial cells are not compatible with back contacts. In addition, they require glass-glass modules, but they will deliver a significantly higher output compared to standard mono-facial cells and modules with the same nominal efficiency.

According to the study, the main improvements with regard to CAPEX decrease are listed in Figure 10[9] below, according to the impact on the LCOE calculated in the KIC InnoEnergy study. These numbers have to be considered carefully according to the comments here above.

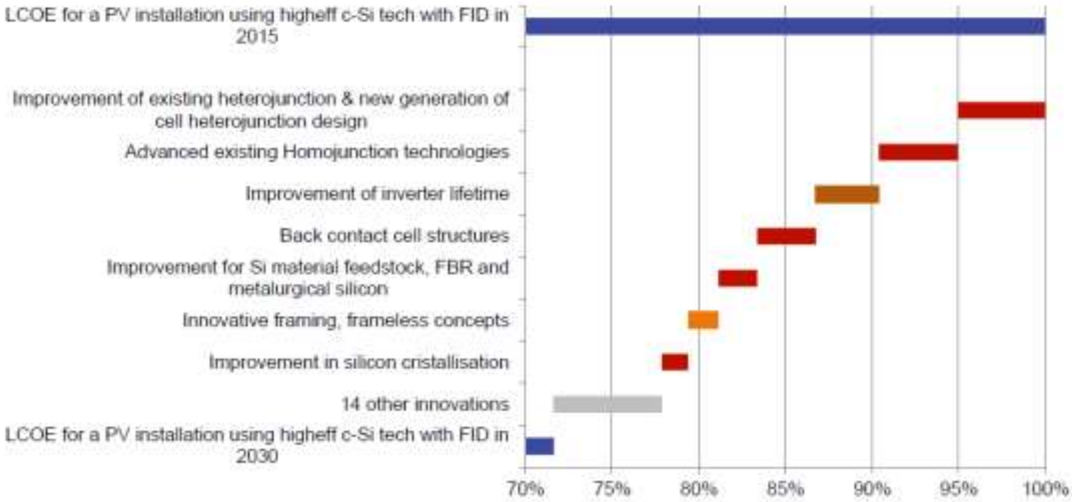

Figure 9: Main improvements regarding CAPEX[10]

5.2. Applying this methodology to quality issues

The KIC InnoEnergy study looks at technology improvements that can decrease the LCOE of PV systems. KIC issues a similar methodology to the one that we have used here, in order to quantify which technologies will improve the LCOE and how much. This methodology should be applied to any kind of technologies solving quality issues as well. As we have seen in the first chapters, not all components have the same contribution to the LCOE and some of them might be chosen as the best way to improve the overall system quality.

[9] Source: KIC InnoEnergy, Future renewable energy cost: solar photovoltaics, 2015

[10] FID means *Final Investment Decision* and is defined by the authors of the study as “the point in a project’s life cycle at which all consent, agreements and contracts required in order to commence construction have been signed (or are at or near the execution stage) and there is a firm commitment by equity holders and, if applicable, of debt finance or debt funders, to provide or mobilise funding to cover the majority of construction costs”.

6. Impact of economies of scale on the LCOE

Next to technological improvements, economies of scale are known to drive production costs down. While this cannot be linked directly to quality enhancements and technology innovation, this shouldn't be forgotten. Reducing the LCOE remains the main objective, through all means, including economies of scale.

This has been verified in the PV industry over the last years, with the most competitive companies, especially Chinese ones, using the advantage of larger production capacities. This point is difficult to quantify precisely because it highly depends on the technology considered and the level of vertical integration. In that respect, vertically integrated actors benefit from not only economies of scale at all levels of their integrated value chain but also the benefit of potentially saving intermediary margins.

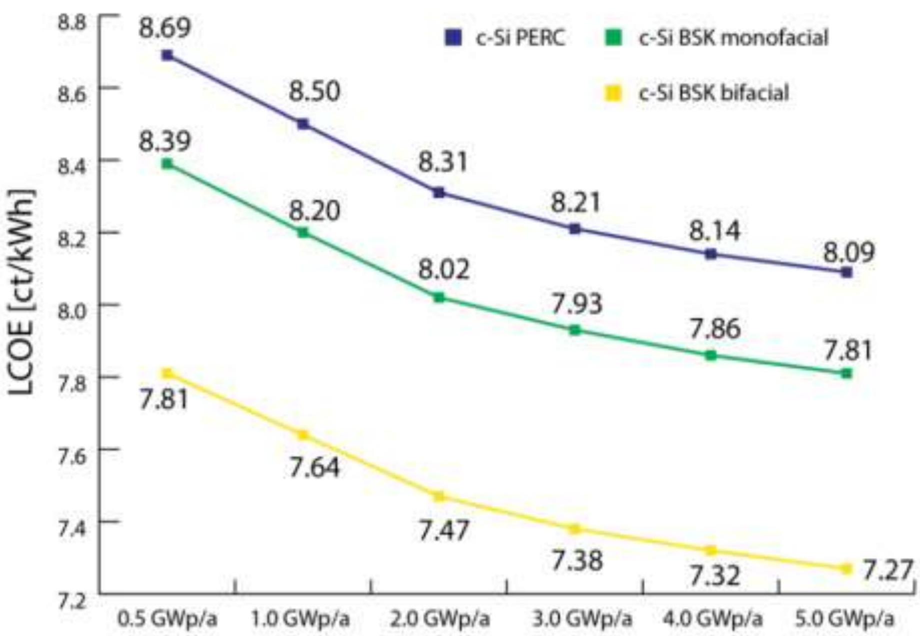

Figure 10: Potential cost decline with economies of scale[11]

The figure above is given as an example of the potential cost decline associated to economies of scale. In addition, in a recent study[12] it is estimated that the difference between 650 MW factories and 3 GW factories is around 0.06 EUR/Wp (0.07 USD/Wp). In general economies of scale can still be seen as a way to bring costs down without technology improvement.

[11] Fraunhofer ISE & IPA, X GW Study 2014 "Studie zur Planung und Aufbau einer X-GW Fabrik zur Produktion zukunftsweisender Photovoltaik Produkte in Deutschland", March 2014 http://www.ipa.fraunhofer.de/fileadmin/www.ipa.fhg.de/Publikationen/Studie_XGW-Fabrik.pdf

[12] IHS study "The Price of Solar Benchmarking PV Module Manufacturing Cost", April, 2016

7. Impact of technology improvements on the future LCOE developments

This chapter assesses the impact of quality issues and technology improvements on future PV competitiveness developments based on the results of the deliverable D5.2. Based on the expected LCOE that could be reached in 2020 in Europe for some market segments, the impact of both positive (technological improvements) and negative (impact of additional losses and PR degradation due to quality issues) is assessed comparatively.

The following figure has been extracted from D5.2 and represents the possible evolution of PV systems LCOE for utility-scale plants in Europe.

Year	2015						2020						2030					
WACC	5%		7,5%		10%		5%		7,5%		10%		5%		7,5%		10%	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
European Union	5,3	13,4	6,2	15,7	7,2	18,2	4,3	11,4	5,0	13,3	5,8	15,3	3,7	10,4	4,4	12,4	5,1	14,4

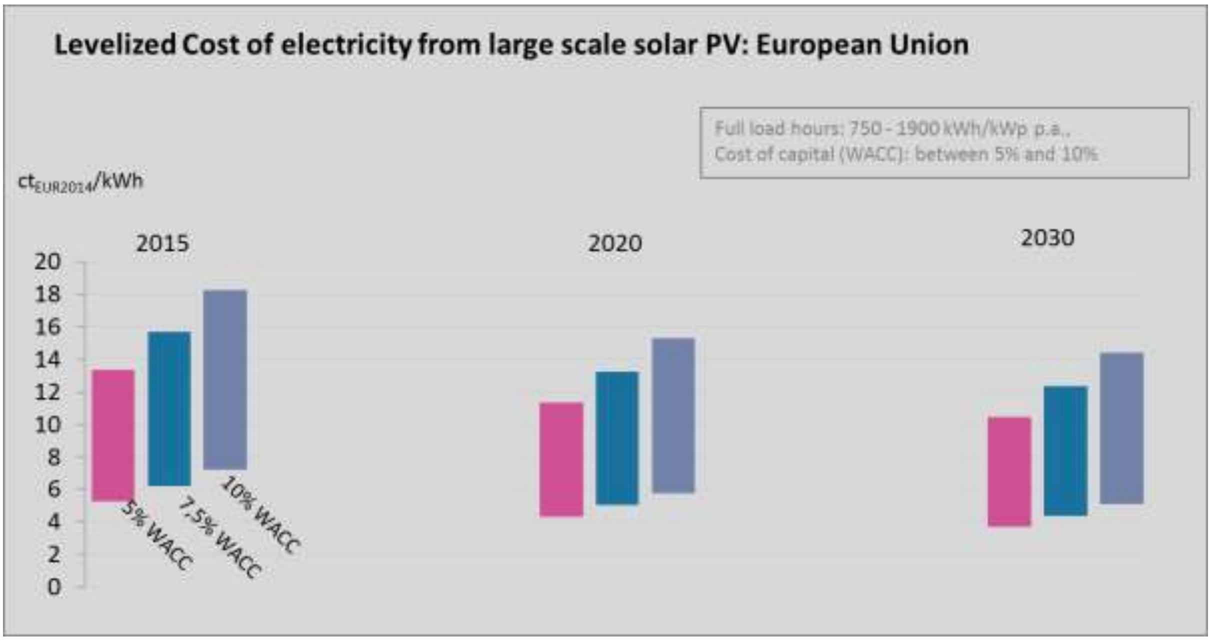

Figure 11: LCOE for utility-scale plants in Europe (from Cheetah D5.2)

According to this calculation, the LCOE decrease with respect to the 2015 level expected in 2020 ranges from 15 to 19%, and from 22 to 30% in 2030. The WACC is not influencing significantly the results unless we consider that the WACC will be reduced gradually until 2030. We can calculate that starting with a 10% WACC in 2015, we reach a 7.5% WACC in 2020 and a 5% WACC in 2030. In that case, the LCOE decrease would be 30% in 2020 and 48% in 2030.

The technology improvements considered before can bring according to KIC InnoEnergy (see previous chapter) the following LCOE decrease for utility-scale plants: up to 28% in 2030. This would validate the expected cost decrease according the PV module and inverter learning curve and even validate the idea that a 20% learning rate is rather conservative. It shows that the potential decrease for PV system costs and LCOE may be slightly higher than the expected decrease of the LCOE using the learning curve assumptions.

8. Where to put effort?

The effort should go in two separate directions:

- reducing the failures in the field through components improvement and enhancement installation procedures,
- continuing to improve all components of the LCOE in order to continue decrease costs (aside of quality enhancement).

The LCOE numbers considered in D5.2 assume that PV systems are behaving in the field as expected, without major failures or degradation issues outside the guaranteed boundaries. The degradation rate of PV production is estimated to stay within acceptable boundaries while the relatively low OPEX costs often seen in the literature are expected to confirm this. However, the reality looks more complex and quality is a major challenge for the PV industry with examples of failures and power losses that are increasing the final LCOE, or in other words, are reducing the profitability of PV plants. In that respect, before increasing the efficiency and reducing further the costs, the question of achieving the promised performances should be considered first.

First effort: development and installation

As seen in the chapter on PV components failure above, a part of PV failures comes from transportation and/or installation issues, causing components failure and at the end, losses of output which cannot always be managed within the O&M contracts. Technology improvements are not playing a major role here, but rather the quality of development, workforce, and the entire set of processes leading to the installation, commissioning and finally operations of the PV power plant. This element could have a negative effect on system prices since it reinforces the quality controls and the need for a qualified workforce.

Second effort: quality of components

With power losses up to 100%, components failure must be solved. In that respect, the underlying question is more to identify how standardization can improve the bankability of products and ensure for the buyer the expected level of performance during the lifetime of the system. This question cannot be disconnected from the quality of the development and installation. For instance, the PID question can be to a certain extent linked to the bill of materials together with best practices for installations. The best components must therefore be assembled respectfully of the right processes and rules.

Third effort: economies of scale

As seen before, economies of scale are extremely important in driving costs down. With a growing PV market, the natural evolution of companies should be to follow the market growth in order to maintain their market share. According to Fraunhofer IPA/ISE study, increasing the size of factories from hundreds of MW to several GW could contribute to decrease the LCOE by around 10%.

Fourth effort: rank the improvements

The contribution of technology improvements to the LCOE has been detailed here above. Technology improvements should be ranked according to several factors but the main one should be the overall contribution to LCOE decrease. Low effects on the CAPEX or OPEX can be compensated largely by effects on the PV output and the other way around. Of course the best developments help to decrease costs (CAPEX, OPEX) while increasing performance.

Fifth effort: cost of capital and bankability

The cost of capital remains on the main factors to decrease the LCOE. The low WACC seen in some recent projects, especially in the Middle East region are raising questions about the risks associated to the projects. In that respect, the first two efforts that are promoting a development of quality PV plants is essential. The ability of PV systems to hold the promises in terms of performances requires low failure rates, lower OPEX costs and at a certain moment a lower cost of capital. This positive spiral can contribute to lowering the LCOE while respecting the risk constraints of investors.

Sixth effort: best practices and standards

International standards are essential to ensuring market transparency, helping cut costs and strengthening investor confidence. When correctly designed, they can also play a critical role in accelerating the uptake of innovative solutions. Over the last 30 years the International Electrotechnical Committee's technical committee on PV has produced a body of over 70 standards and these have underpinned the rapid development of the sector. New initiatives aim to take this process forward. The International Photovoltaic Quality Assurance Task Force (PVQAT) leads global efforts to craft quality and reliability standards for solar energy technologies. The IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications (IECRE) aims to facilitate international trade in equipment and services for use in renewable energy. This envisages a single, global certification system covering all aspects of system design, production and operation. At the financing level, initiatives are in progress to develop templates for project documentation, thereby ower admin costs and increase transparency for contracting authorities, banks and investors.

The efforts from the Cheetah project are included mainly to the cluster of efforts for improving the quality of the components, reducing the CAPEX. The new innovative products and processes proposed in the project aim at increasing the overall performance with the use of less, cheaper and more sustainable materials.

9. Conclusions

This report provides a framework that might be used to select which technology choices might be developed in priority. It doesn't aim at orienting which will be the technology choices that will hit the market in the coming years and will succeed. History has shown that the success of technologies is not only a technical and cost factor but also a marketing one. The power of companies to impose solutions has often beaten the beauty of technology improvements not marketed in the same way.

With regard to PV development, the question is rather complex and one can bet that the financial sector will impose more and more rules that will favor first the technology improvements having a direct impact on the PV performance, reducing failures and guaranteeing a long term output in line with the expectations. This can also explain why old-fashioned technologies might keep a competitive advantage to innovative ones, despite poorest theoretical performances. In that respect, economies of scale may allow products to stay on the market and compete with advanced ones at a similar price, without having the same level of technology.

From a pure technology point of view, the innovations that will contribute to lower several components of the LCOE will have a better chance to impact the market. In that respect, bifacial cells for example could have an advantage: with a limited additional cost (or the same one), they integrate several technology evolutions (frameless glass-glass modules for instance) that will contribute to increase significantly the PV output for utility-scale plants and large flat-rooftops. In the same way, back contacts cells could find their way in the residential rooftops.

The ranking of each technology improvement will have therefore to consider all parameters, CAPEX, OPEX, cost of capital and PV production, but also the perception of the bankability of the final product. All these aspects should be dealt with together in order to decide which technology will really have a chance to impose itself in the coming years, and not only those impacting only one of the components. One should bear in mind that the concept of bankability for a project includes a list of different parameters which are not technical (e.g. legal, political, financial) and have the same or more weight.

Finally, the question of quality remains acute. Its link to technology improvements is not as clear as it appears, with many failures in the field coming from good quality components not well transported, installed or maintained. Moreover, the choice of the components (responsibility of the developer), will have to be improved though best practices. That implies at the end that any technology improvement will have to be accompanied with best practices for the entire value chain, starting with the choice of other components, design of the plant or the installation, and finally operation.