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

D5.2 - Analysis of the cost reduction potential of the PV technology

WP5 – Acceleration of innovations' implementation

Section 1 – Document Status

Document information

Deliverable name	CHEETAH_D5.2_Analysis of the cost reduction potential of the PV technology
Lead beneficiary	SolarPower Europe (EPIA)
Due delivery date from Annex I	M18
Actual / forecast delivery date	M22
Dissemination level	Public | ~~Restricted~~ | ~~Confidential~~

Document validation

Name	Organisation	Date	Visa
Ioannis Thomas Theologitis – WP5 leader	SolarPower Europe	08/10/2015	OK
Jan Kroon - Coordinator	ECN	15/10/2015	OK

Document history

Version	Date	Modifications	Name
0.1	30/07/2015	First draft	Ioannis Thomas Theologitis
0.2	4/08/2015	Frist review	James Watson
0.3	03/09/2015	Review	Jan Kroon
0.4	28/09/2015	Review	Eduardo Roman
0.5	05/10/2015	Review	Nigel Taylor
0.6	08/10/2015	Final draft	Ioannis Thomas Theologitis
Final	15/10/2015	Coordinator validation	Jan Kroon

Section 2 – Table of content

Section 3 – Acknowledgements

The authors of this report would like to extend their sincerest thanks and appreciation to those who contributed to the realisation 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:

IEA, IEA-PVPS, Trina Solar, SolarPower Europe (EPIA) and Christian Breyer who willingly shared their work and input data for the completion of this analysis.

Furthermore, part of this work and regarding the assessment of the impact of research innovations belongs to KIC-InnoEnergy. Although partners of this project, the authors would like to highlight their efforts to complement to this task and result in something very useful for our project and consequently for our industry. Our efforts and collaboration on that will of course continue.

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 deliverable builds on the learning curve concept in order to assess the potential for further cost reduction in modules in the coming years and in different technology-families. In addition, it provides an analysis on the Levelized Cost of Electricity (LCOE) evolution and its equation-components that become more critical and impactful. Last but not least the deliverable attempts to provide a methodology on how to properly evaluate the impact of future innovations on the cost of the technology and the capacity to empower the market. Existing references, knowledge and experience of project partners complemented by further in-house analysis form the content of this report.

The purpose of this deliverable to provide a deep analysis and understanding on the outlook of the cost of the technology addressing both manufacturing aspects (learning curve) but also system considerations (LCOE) based on scenarios and hypothesis of the learning curve. Taking that into consideration the additional goal is to see how specific research innovations – such as those in CHEETAH impact this future cost outlook in order to support understanding, prioritization and strategic investments for the short, medium and long-term in the solar PV sector. This is one of the main considerations and objectives of the Cheetah project.

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 to compare the cost of each kWh produced, whatever the generation technology used to produce it.

The current cost of PV electricity can go down to as little as 5,85 US cents/kWh (the ACWA Power tender in Dubai[1]) or even below such numbers when the PV system remains incentivized. 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. The latter can also be supported by Figure 1 below. [2]

[1] Source : pv-magazine at http://www.pv-magazine.com/news/details/beitrag/is-dewa-preparing-an-800-mw-dubai-tender_100018989/#axzz3i2wzgw00 .

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

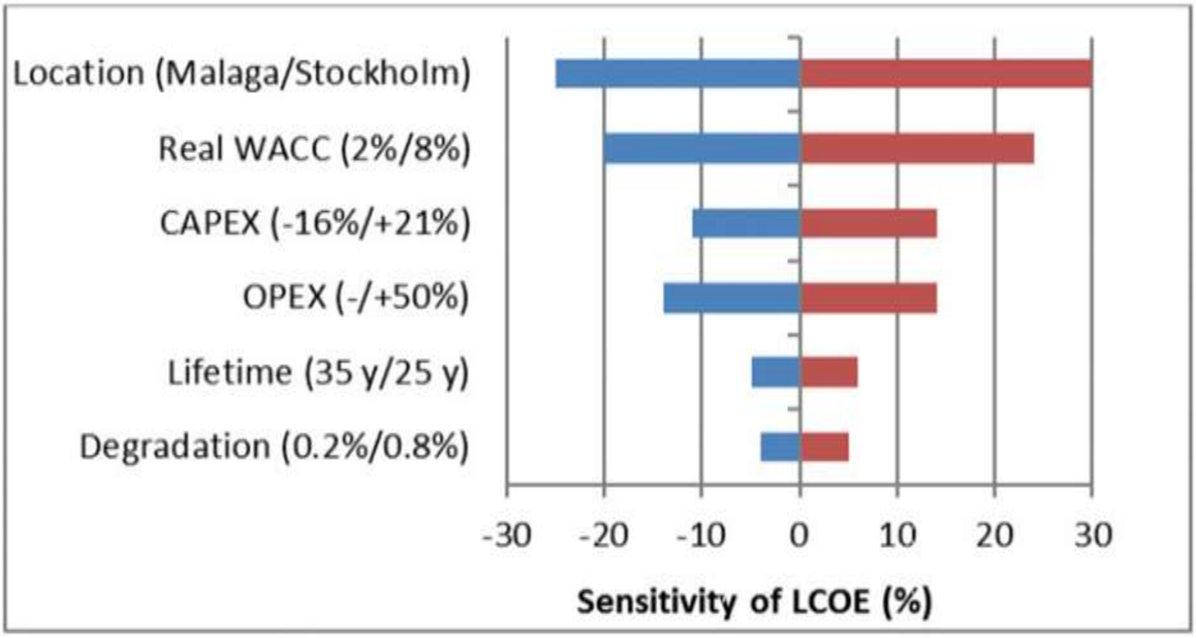

Figure 1 – Sensitivity of PV LCOE in 2030 on location, real WACC, CAPEX, OPEX, system lifetime and degradation compared with a 1 MW ground-mounted system in Toulouse with 5% real WACC, base CAPEX and OPEX, 30 years lifetime and 0,5% annual degradation. All input figures found at the respective source.

This study describes the PV module learning curve to better understand the PV system cost potential for decrease. The theory and concept behind this tool are also presented. Then an evaluation of the different existing PV learning curves compiled in the last years is done. The results are applied to the calculation of the LCOE in several key market segments, with key PV technologies ending up in useful conclusions.

The learning curve concept assumes that technology improvements (through R&D&I) and economies of scale are driving the price of components down at a rate that is linked to the cumulative volumes. The improvements in Balance of System (BoS), margins and cost of capital are also at the core of the LCOE decline analysis. Since some of these elements are difficult to assess in a technology-oriented study, some assumptions will be considered in order to focus the results on the influence of the decrease of price of PV systems and their consequent influence on the cost of PV electricity.

The innovations proposed by the research community in general and the CHEETAH consortium in particular will impact the evolution of the prices in the future. CHEETAH work impacts the LCEO calculation in two ways: 1) costs and efficiency through the CAPEX, and 2) efficiency again through annual energy yield (kWh/kWp effect). The last part of this study will therefore present the methodology used – product of KIC InnoEnergy – to assess the potential of innovations in terms of their cost impact. The final assessment will be included in a future report (D5.3) which is planned to be published at the end of 2015.

Section 5 – Analysis of the cost reduction potential of solar PV

1. The Learning Curve concept

1.1. Theory and Reality – The Learning Curve(s)

The learning or experience curve[3] [4] concept is an empirical law that describes the reduction of product cost in industries. The prevalent mathematical model is the so-called log-linear function shown in the equation-set below which implies a reduction of product cost by a nearby stable percentage as the cumulative production output doubles. This empirical law has been observed in many industries as well as for a various range of technologies.

In a double logarithmic scale plot the power function shows a linear behavior. The slope of this function is then given by the exponent of learning (b) being the crucial parameter in this empirical law. The stable cost reduction is described by the learning rate (LR). For use in calculations, the progress ratio (PR) is introduced, which is defined as unity minus the learning rate.

$$c_t = c_0 \cdot \left(\frac{P_t}{P_0}\right)^{-b} \qquad \text{(Eq. 1.1)}$$

$$PR = 2^{-b} \qquad \text{(Eq. 1.2)}$$

$$LR = 1 - PR \qquad \text{(Eq. 1.3)}$$

1st set of equations: *Empirical law of learning curves according to the log-linear model.*

Abbreviations stand for:

- Historically cumulative output level: $\mathbf{P_t}$
- Initial output level: $\mathbf{P_0}$
- Cost at historically cumulated output level of P_t: $\mathbf{c_t}$
- Cost at initial output level P_0: $\mathbf{c_0}$
- Progress ratio: **PR**
- Learning rate: **LR**

[3] Source : Kersten and all : PV LEARNING CURVES: PAST AND FUTURE DRIVERS OF COST REDUCTION, 26th EU-PVSEC, Hamburg, Germany, 2011

[4] Source : Nemet F. : BEYOND THE LEARNING CURVE : FACTOIRS INFLUECING COST REDUCTIONS IN PHOTOVOLTAICS, ELSEVIER, Energy Policy 34, August 2005

Equation 1.1 implies that learning rates related to different factors of learning cannot be simply added to a total learning rate as the superposition principle does not apply. A learning rate consisting of two contributions is described by **equation 2.1**. The breakdown of a learning rate into two contributions is calculated by **equation 2.2**:

$$LR = LR_1 + LR_2 - LR_1 \cdot LR_2 \qquad \text{(Eq. 2.1)}$$

$$LR_2 = 1 - \frac{1 - LR}{1 - LR_1} \qquad \text{(Eq. 2.2)}$$

2nd set of equations: *Formula for the breakdown of a learning rate into two different factors of learning*.

Abbreviations stand for:

- Total learning rate: **LR**
- Learning rates of the learning factors 1 and 2: **LR1** and **LR2**.

In order to assess the learning effect on the long term, a working hypothesis is proposed and considered. The assumptions and limitations of the following analysis are based on this. The main aspects of the hypothesis are:

- **The considered evoluting capacity could be** the production of PV modules (the shipments is in general a very good approximation) or the installed capacity. Both options have been considered in different existing learning curves. For instance the ITRPV learning curve[5] calculation considers the shipments while the International Energy Agency (IEA) one uses the installed capacities. However this parameter is not the most important since PV installations occur in general within the year of the production of the modules. *The major discrepancies between shipments and installations* should then be the inventories (if we assume that decommissioning or replacement of modules in existing PV systems remains negligible compared to the market level). One can also assume that inventories are just « delayed installations » that are counted at the end of fiscal years. However, this should be tested in order to verify the effects on the learning curve results.

- **The question to use *prices or costs* for the learning curve** of the PV modules is even more important. Prices refer to the amount of money that is paid in fine by the PV developer while the costs refer to the industrial fundamentals. One could then argue that the costs should always be considered. However the price information is publicly available and, due to market laws, has a tendency to aggregate all realities. On the other side, costs are less representative of the evolution of the technology since they represent a sum of elements that are not homogeneous. In addition, it is generally acceptable that cost information cannot be totally reliable. Only listed companies are providing information, that could be verified, and this information is not empty from marketing and strategy considerations. For all these reasons,

[5] The International Technology Roadmap for Photovoltaics (ITRPV) Learning Curve has been published for the last time in 2015 by SEMI Europe. See http://www.itrpv.net/

prices are considered to be the most representative element for this analysis. However, for reasons of thoroughness sensitivity to costs will be examined.

The question of prices and costs should be clearly linked to the question of the capacities. Shipments could be considered as closely related to costs while installations could be considered closely related to prices. In that reality, the analysis becomes more complex since cost data are more complex to assess and the difference between shipments (production) and installation data originates from a delay between production and installation as described above. In that respect we will consider as the main source of data, **the combination of shipment data and PV module prices**.

The Learning Curves will be assessed in USD currency to ease the calculations and reflect the global nature of the PV modules manufacturing and trading. Later on in the report and when it comes to LCOE calculations the euro currency will be used.

1.1.1. A good tool for decision making?

The Learning Curve concept has shown in many industrial sectors its ability to forecast the price evolutions of technology-driven industries. Despite short-term trends, such as the polysilicon shortage in the PV sector in the previous decade, that can derail the curves and make them harder to understand, long-term trends seem to follow patterns that are rather predictable. With 40 years of experience (for crystalline silicon PV modules), the PV learning curve(s) have helped to better understand where the price of module could go and therefore support different strategic roadmaps for the technology. As we will see below, despite differences in understanding or in the input assumptions, it still offers, when well explained, a good tool for decision-making.

1.2. Presentation of existing Learning Curves and data sources

Figure 2 presents the different sources and the respective learning curves that are also used to compile the aggregated learning curve that follows later on.

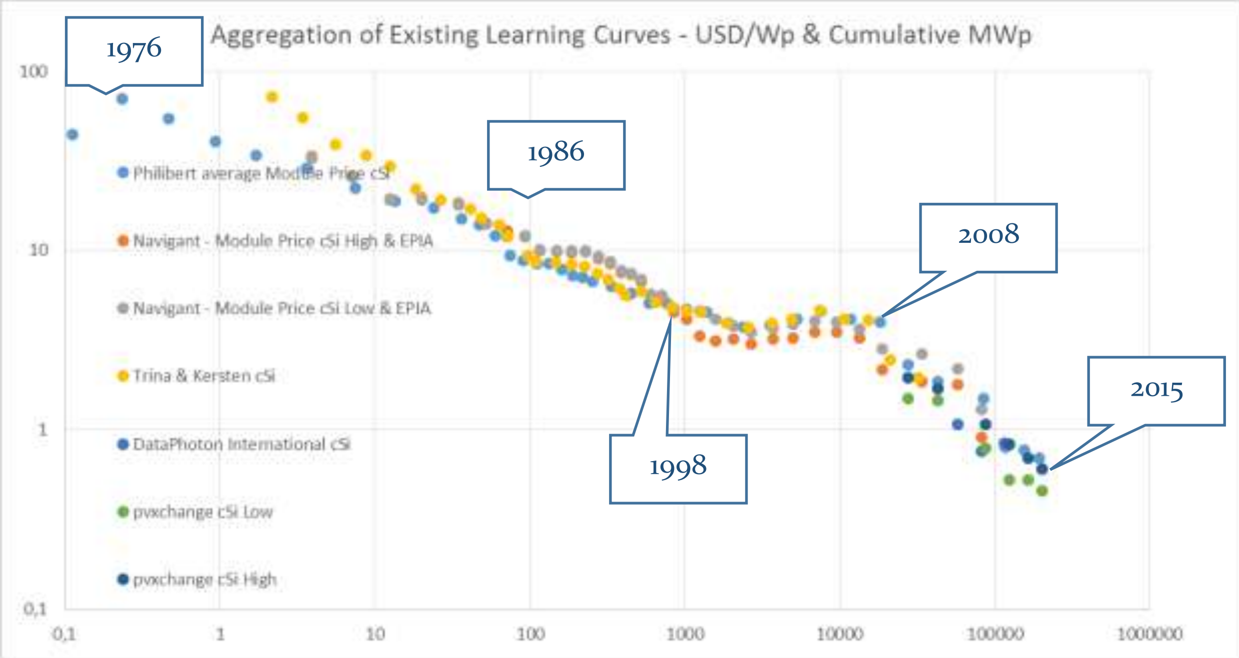

Figure 2 – Existing PV Learning Curves - Philibert (IEA), Mint (Navigant Consulting 2010) & EPIA, Yifeng (Trina Solar), PvXchange, Photon International, Christian Breyer, Kersten & al. – own analysis

1.3. Background data for the analysis

Data for historical capacities, costs and prices are coming from several sources that have been assembled together. One must admit that the quality of historical data is extremely variable and differs from one source to the other. This of course has to do with a number of reasons such as different practices for collecting those data, their treatment etc. Some of those data have undergone a number of updates until today.

From 1992 onwards, the IEA-PVPS data have been logged from official or semi-official sources and are the most reliable available market data for countries followed by the program. In Europe, SolarPoWer Europe (formerly known as EPIA) historical data are the most complete and reliable ones. However, this collection of data from different sources has also inconsistencies.

For the following analysis mainly data provided by IEA, IEA-PVPS, Trina Solar, Kersten, Navigant Consulting, SolarPower Europe (EPIA), First Solar, PvXchange, PVinsights, Christian Breyer, Becquerel Institute, NREL, Sanden, Swanson and Photon International were used.

Inventories, and in general data glitches between production and installations play a minor role since size of inventories declines proportionnally each year to the cumulative installed capacity.

1.4. Creation and Analysis of Learning Curves for PV modules

1.4.1. PV Market Development Scenarios until 2030

SolarPower Europe published in June 2015 its annual Global Market Outlook6 for PV that assumes that the cumulated installed capacity could grow until 2019 from 178 GW to between 396 and 540 GW, depending on the scenario (Figure 3). These additional GW have to be split according to the technology. After 2019, the low scenario assumes that 50 GW could be installed every year globally while the high scenario assumes a 15% annual growth capped at 250 GW a year until 2030 (Figure 4). These numbers refer to all PV technologies together, however a 10% share can be considered on the long term for non-crystalline silicon technologies.

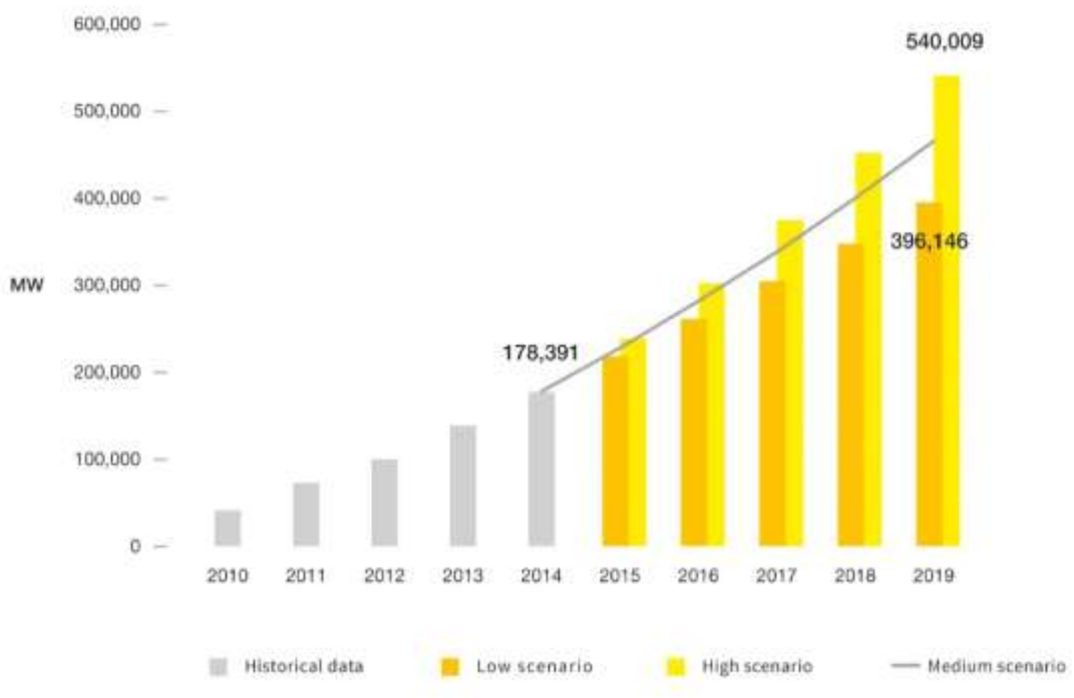

Figure 3 – Global Solar PV cumulative market scenarios until 2019

[6] Source: SolarPower Europe, Global PV Market Outlook 2015-2019, http://www.solarpowereurope.org/insights/global-market-outlook/

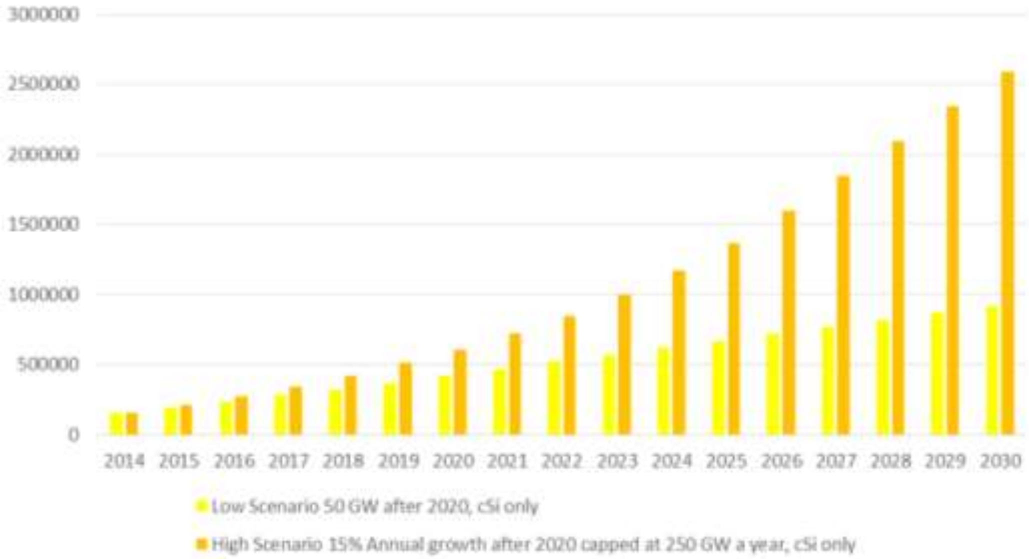

Figure 4 – Cumulative Market Development until 2030 (MW) [7]

The above scenarios can be considered as extremes to provide a range. In 2014 IEA PV roadmap predicted 1721 GW cumulative by 2030 which can be roughly seen as a medium scenario.

1.4.2. Analysis of different Learning Curves – Aggregation of all available data

The assessment of the evolution of PV system prices which is one of the main objectives of this report will be obtained by summing up the PV modules prices and BoS prices including the inverter. In order to assess the potential of the PV module price decrease, the evolution of PV module prices through the concept of the PV modules Learning Curve will be analyzed.

The difficulties to collect reliable data for both Average Selling Prices (ASP) in a defined currency and accurate PV installed capacities had led researchers to produce different learning curves for the same technology. Here it is assumed that these learning curves have been built with reliable data and express different views of researchers on the PV market evolution. In that respect, it is attempted to display all different data together in order to present and then decrease the uncertainty related to data collection in the last 40 years.

Therefore, this first learning curve that is shown in the following Figure 5 has been built with data coming from various sources, all focusing on the price evolution of crystalline silicon modules (mono and poly together) in the last 40 years. In order to eliminate the bias of multiple data sources that are not

[7] Own calculation based on SolarPower Europe's forecasts

totally coherent together, the choice has been made to use all existing data and to compile these data in one single learning curve. *The data shown in the following figure are therefore a compilation of several sources that don't match perfectly, neither in prices nor in cumulative capacities*.

Assessing the Learning Curve (LC) on a 40 years period

The LC computed with the production and the price data shows a Learning rate of 20%. It shows that the price goes down 20% each time the cumulative capacity is doubling. This has been obtained with data coming from several sources as explained in 1.3 paragraph. However, a first quick result of the analysis of the data shows that the regression curve doesn't really match the recent evolution of PV system prices.

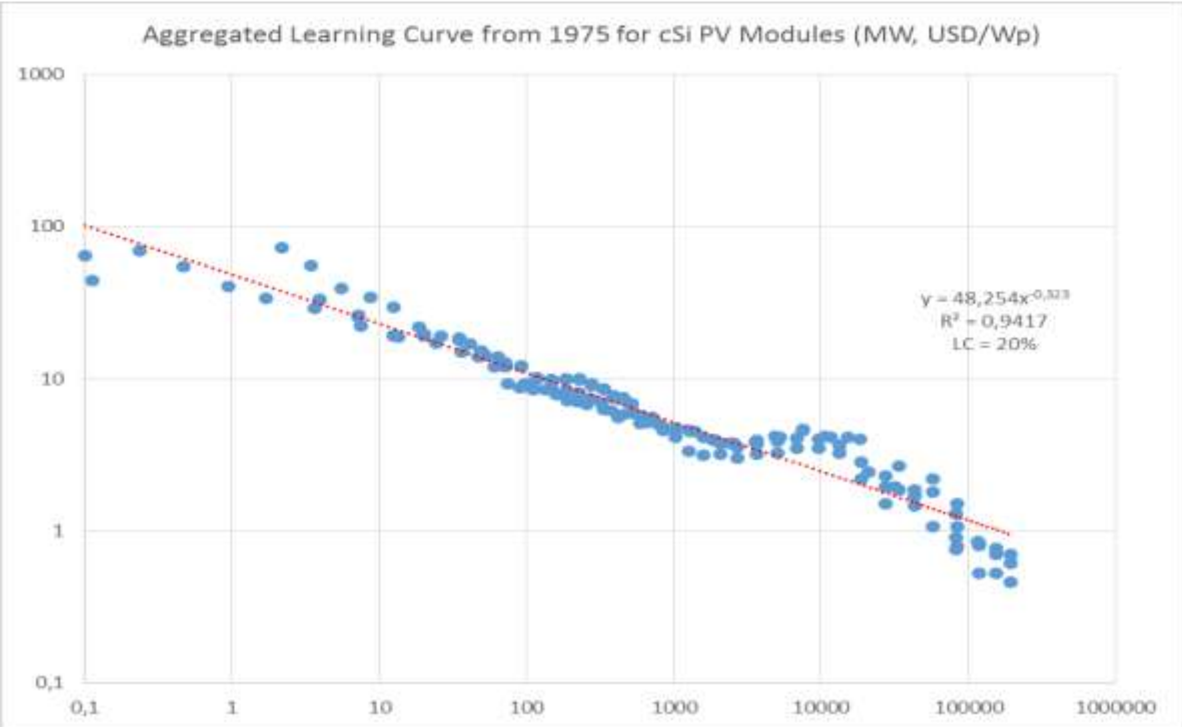

Figure 5 – Aggregated Learning Curve for c-Si modules – 1975 onwards [8]

One major point coming out of this LC and challenged the PV industry was the stabilization of the prices due to polysilicon shortage. One could also overlook this factor and assume that the price derailment out of the curve at that moment was a simple "delay". Nevertheless, since then prices started to drop, pushed by the fast increase of the PV production especially in Asian countries.

[8] Own analysis – aggregation of different existing Learning Curves and additional data from SolarPower Europe

The industry has undergone a lot of changes and experienced an unstable period with periods of consolidation and over this time the price curve *shouldn't be considered as perfectly in line with the learning curve*. However, in 2014 several companies made profits (positive profit margins) again which indicates that prices are back to normal, showing marks of stability.

However, "normal" is debatable due to several anti-dumping cases worldwide that have concluded that some PV manufacturers were either dumping or had benefited from unfair subsidies to develop their industry. While this document is not aiming to address this issue or to confirm whether this is true or not, *it raises the question of which prices and costs can be considered as "normal"*.

A separate focus on 95% of the cumulative production

The following Figure 6 illustrates another way of looking at the evolution of prices for PV modules. Taking into consideration that 95% of the production occurred between 2007 (end of the polysilicon shortage) and today, it makes sense to estimate the learning curves before and after the shortage. It divides then the curve into three segments, including a rather flat one which reflects period of the polysilicon shortage. The learning rates are then the following ones: 20.3% before the shortage, -7.7% during the shortage (which means prices went up) and since then 38.4%. The latest is the most surprising one for anyone who is acquainted with the PV technology, but it reflects the tremendous and fast price decrease that has been experienced in the PV industry over the last years.

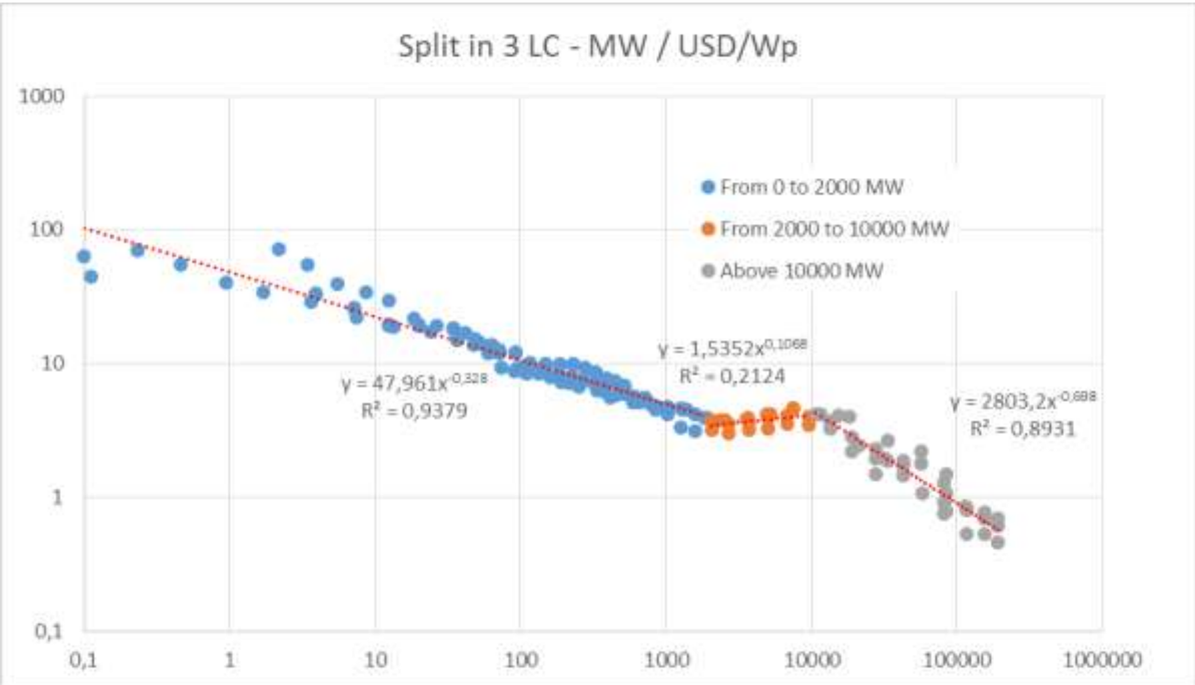

Figure 6 – Split of the aggregated Learning Curve in 3 segments – own analysis

However jumping from 20 to 38% of learning improvement could be considered as revolutionary and therefore an additional analysis can be made. It can be assumed that the polysilicon shortage almost stabilized the prices while the demand grew significantly. *Having that in mind, an interesting challenge*

could be to better understand if this shortage had been simply an incident and what if the next one was the decline of prices following the market stagnation in 2012.

Considering also the support scheme environment during the shortage another could wonder if the flattening of the curve corresponded also to an artificial environment with high financial incentives that kept the price of modules relatively high while the demand was growing faster than the ramping up of the industrial production capacities.

Considering the polysilicon shortage as incident

Following up on the thinking before Figure 7 considers that the prices during the shortage period should be taken out of the series. The conclusion is in that case totally different; *the prices have rejoined the historical learning curve when the cumulative production reached around 40 GW (in 2010) and the evolution since 2011 can be put in perspective with the price evolution before the shortage*.

The learning rate is then closer to the historically accepted one, with 21.2%. And it shows that in the last years, prices had a tendency to be below the learning curve, with the highest prices for classical crystalline silicon cells though being on the curve. This is probably more in line with the understanding of the PV market evolution in the last years. It can also explain that the companies selling at a price close to the curve are the European, Korean and Japanese ones. While the prices significantly below the curve are the prices associated to Chinese, Taiwanese and other South-East Asian companies for crystalline silicon modules with a standard efficiency.

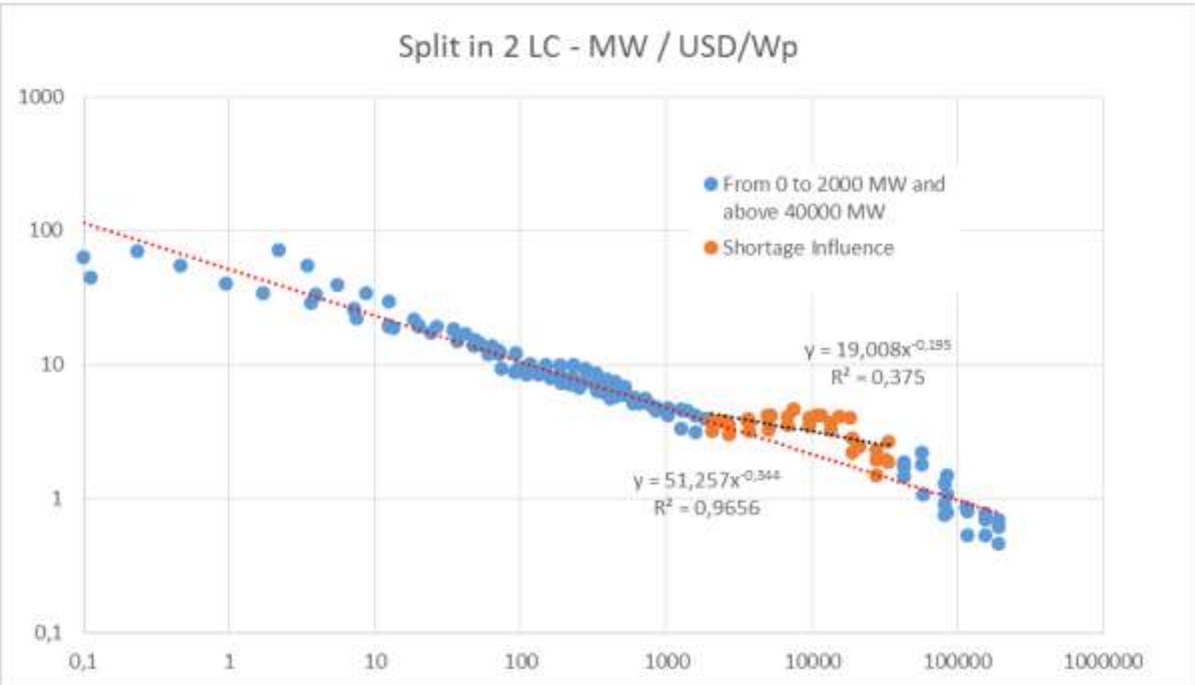

Figure 7 – Split of the aggregated Learning Curve in 2 segments; separating the time of the polysilicon shortage – own analysis

Thin Film Learning Curves

In comparison with crystalline silicon, thin film technologies have experienced a significant market development much later and at a slower pace. The total cumulative capacity for all thin film technologies was around 22 GW at the beginning of 2015[9].

Regarding the type of thin film technologies, the cost and price learning curves have been established for both CdTe and CI(G)S technologies and those are presented in this deliverable.

Given the low market share of a-Si/µ-Si in 2015 these technologies haven't been considered here. This has nothing to do with the confidence of the authors about the future of these technologies, but a simple focus on the two most developed thin film technologies in 2015.

In comparison to crystalline silicon data, ASP can be verified on the market but costs are again a difficult task to collect and verify. However, the data collected for the sake of this report are shown in Figure 8. One should just keep in mind that such data are less reliable and the conclusions with regard to the cost-based LC should be carefully considered.

- *The CIGS price and costs are giving completely parallel interpolation curves, with a very little difference between both curves, which could indicate extremely low margins.*

- *The CdTe price and costs curves indicate how intense the price competition became for CdTe producers as well.*

- The following learning rates have been calculated:
    - For CdTe Costs: 19.7%
    - For CdTe Prices: 39%
    - For CIGS Costs: 8.3%
    - For CIGS Prices: 9%

*The **CdTe** numbers are comparable to c-Si, at least in terms of prices if we remember and accept the 38% learning rate for c-Si in the 95% of the cumulative market segment in Figure 6*. One might assume that the prices are not representative because of the relatively short timeframe considered and the fact that the quasi entire market of CdTe is dominated by one single actor. Moreover the cost learning curve is perfectly parallel with the c-Si price decline, which would tend to indicate that the dominant actor on the market (c-Si) imposes its trends to the other competing technology (CdTe). In that respect, the cost curve of CdTe that looks much more robust should be considered instead of the price curve and we will consider 19.7% as the standard learning rate for CdTe.

The improvement rate for **CIGS** is much smaller than the one associated to c-Si and CdTe. This might indicate a reduced potential for this technology on the medium term or the difficulty to conclude to early useful results since the number of data points are not offering a long-term view.

[9] Source: Own analysis based on SolarPower Europe and publicly available sources

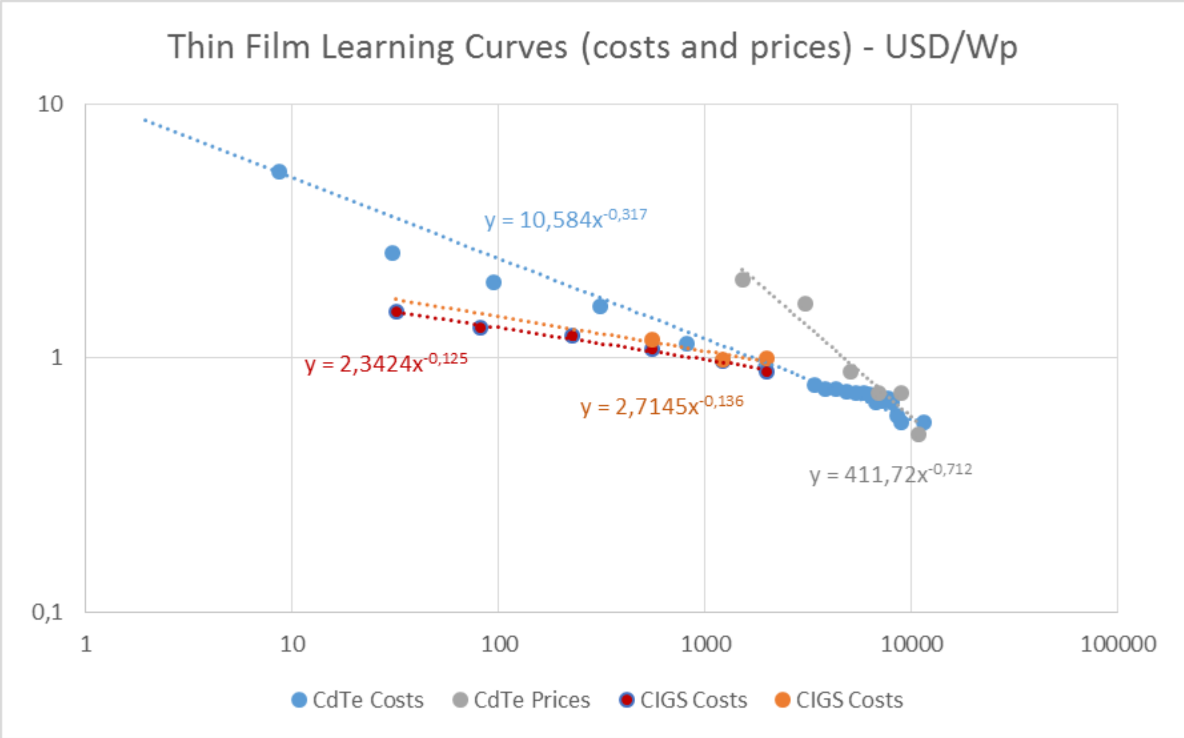

Figure 8 – Thin Film Learning Curves (cost and price) – own analysis

Finally the following figure illustrates the comparison between c-Si and Thin Film technologies in one single figure to allow comparisons.

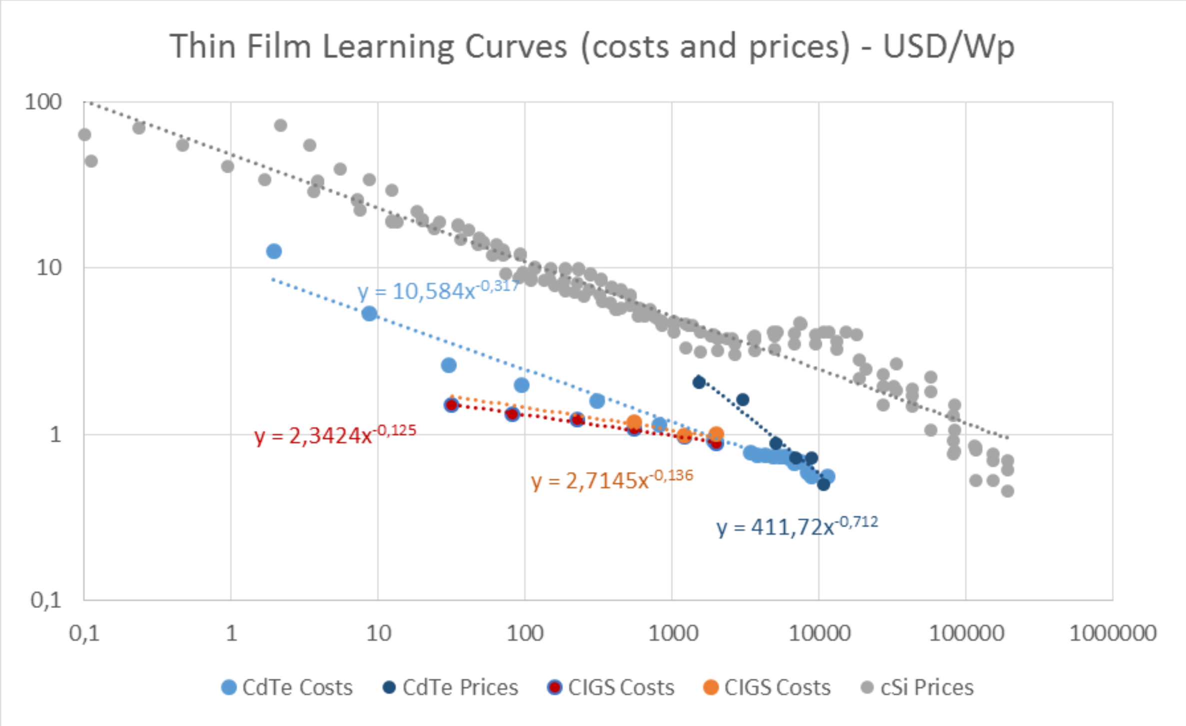

Figure 9 – Aggregated Learning Curve for c-Si and Thin Film curves – own analysis

Recommendations for further research

Due to the sensitivity of such information very few companies are willing to disclose current production cost data. Existing data are subject to interpretation and cannot be guaranteed accurate enough. On the other hand, using cost data instead of price data would only have a meaning if it could be done in a comparable way, weighting data from all continents according to the volume of production.

Installation data can be compared to production data and shouldn't influence significantly the final output. But since installation data (grid connected systems) are not counted in the same way in all places in the world – some use installed systems but not yet connected, some AC power output (MW_{AC}) and not MW_P, very few apparent power (MVA) – one might assume that installation data are not reliable enough for such exercise.

These points could be considered for further research, under the condition of the availability of accurate data.

1.5. Comparison with other Learning Curves

Below a brief comparison is attempted with other known existing learning curves. For those learning curves the background input data were not accessible and therefore were not considered in the aggregated learning curve that was drafted in the analysis before.

1.5.1. The ITRPV Learning Curve

The International Technology Roadmap for Photovoltaic (ITRPV) curve doesn't differ much from the one analyzed in this deliverable. It assumes at the end a 21.5% learning rate that is rather similar to the one calculated here. Shipment and prices differ slightly from the data used in this document, highlighting once more the difficulties to collect reliable cost and price data.

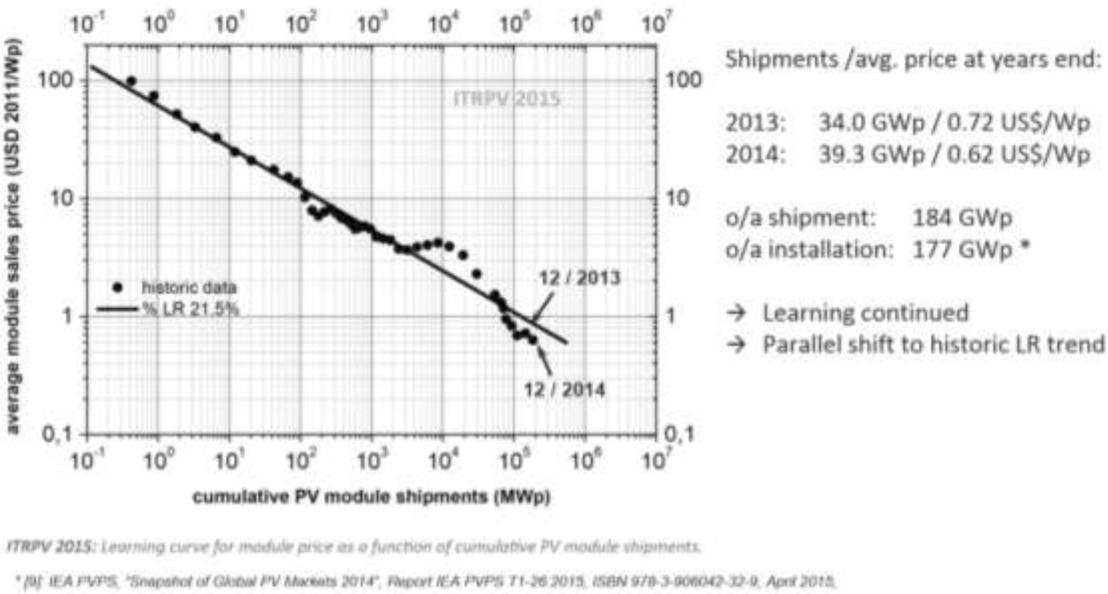

Figure 10 – ITRPV Learning Curve[10]

1.5.2. The Fraunhofer ISE Hypothesis

With a different set of data, the slope of the learning curve can be significantly different as it was seen just before. The Fraunhofer ISE learning curve assumes a different scenario for the future. More concretely it is assumed that the learning curve would be a long term trend that couldn't be questioned and therefore the lowest prices seen so far should decrease at a slower pace in order to rejoin the learning curve at a certain moment (Figure 10).

In this hypothesis, the learning rate of the crystalline silicon technology in the coming years should be decreased to around 10% assuming that rejoining the learning curve at a certain moment would be the goal or price decrease horizon.

[10] Source: ITRPV.net - ITRPV 2015 Release Presentation, downloaded July 9th 2015

This hypothesis can be challenged for several reasons but the most important one is that despite the low prices seen in 2014 and early 2015, many PV manufacturers are making profit again. Fraunhofer ISE seems to assume that the potential for cost reduction thanks to economies of scale has been already used massively and shouldn't contribute much to the cost decline in the coming years.

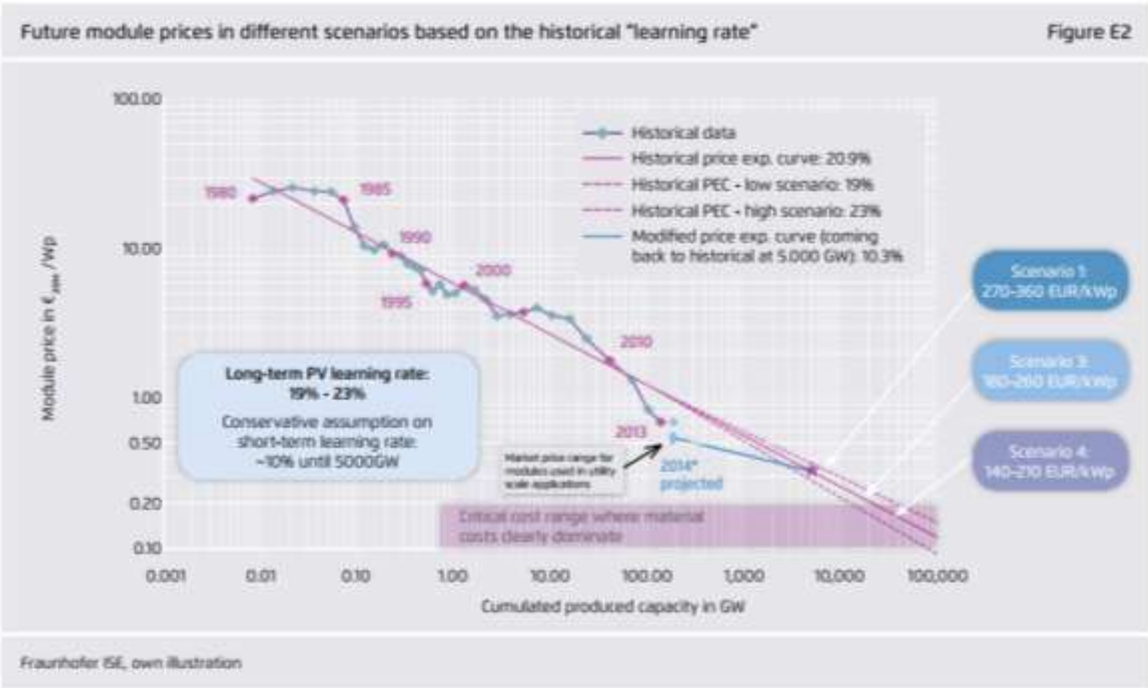

Figure 11 – The Fraunhofer ISE Learning Curve[11]

1.6. PV crystalline silicon cells Learning Curve - Rationale

The price of cells in the PV module represents today around 50 to 60% of the module price. One could assume that the technology gains linked to the cell itself could be isolated from the rest of the cost/price evolution in order to better assess the technology improvement rate for crystalline silicon PV.

Trying to further analyze this and starting from the 20% learning rate in the module learning curve, it is assumed that the other parts of the module remained constant in price over the time. Of course this assumption can be questioned and doesn't represent exactly the reality of the price evolution of PV cells costs – however this can be a way to assess the learning curve of the cell.

The methodology and calculation process used in this deliverable has as follows:

[11] Source: Agora Energiewende, Current of Future Costs of Photovoltaics, Berlin, 2014 - http://www.agora-energiewende.de/fileadmin/downloads/publikationen/Studien/PV_Cost_2050/AgoraEnergiewende_Current_and_Future_Cost_of_PV_Feb2015_web.pdf

- The moment at which the price of the PV module reached around 10 USD/Wp is considered (the year 1986 where discrepancies are less and the sample reduced).
- The two following points are then selected from the aggregated learning curve (the range is rather important, since data are coming from different sources):

Data points for year 1986	Cumulative capacity	Module price
Point 1	72,242 MW	12,08 USD/Wp
Point 1	74,353 MW	9,33 USD/Wp

- If the current cost of the rest of the module components is assumed unchanged (which can be challenged as said before), a couple of points from the PV cell price learning curve can be retrieved, one from when the cumulative capacity was around 73 MW and one from today. *The data for today have been provided by PVInsights.com and can be assumed to represent the current average crystalline module and cell prices on the market.*

More concretely:

- **2015 cell price (PVInsights)**: 0.306 USD/Wp for a cumulative capacity of 178 GW of crystalline silicon modules sold. These 178 GW are calculated from:

  The estimated current (mid-2015) total installed capacity which is 177 GW end of 2014 + 50 GW (market forecast for 2015 based on the medium scenario of SolarPower Europe) = 202 GW minus the cumulative thin film capacity (22 GW, author estimates).

- **2015 difference between modules and cells:** 0,546 USD (modules) – 0,306 (cells) = 0,240 USD/Wp
- **1986 cell prices (Point 1)** = 12,08 USD/Wp (Module price) – 0,240 USD/Wp (2015 rest of module price) = 11,84 USD/Wp – with a cumulative capacity in 1986 = 72 MW
- **1986 cell prices (Point 2)** = 9,33 USD/Wp (Module price) – 0,240 USD/Wp (2015 rest of module price) = 9,09 USD/Wp – with a cumulative capacity = 74 MW

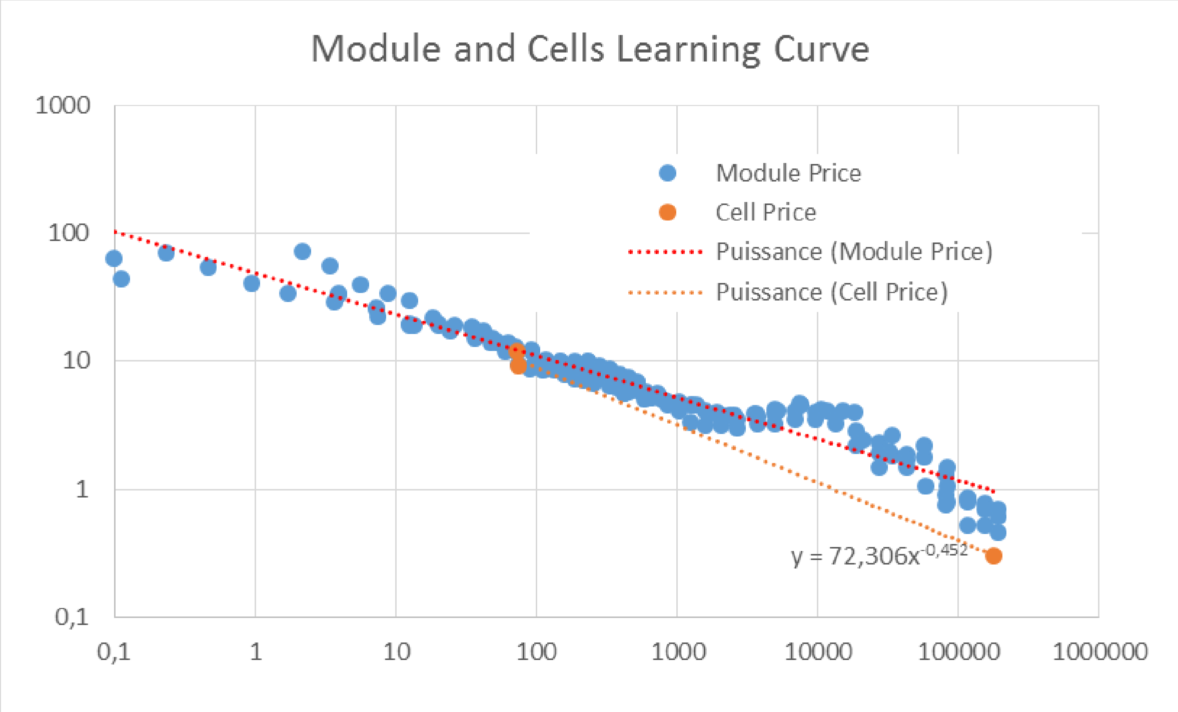

Figure 12 – PV Cells and Modules Learning Curves – Source: own analysis

A rapid assessment gives a steeper learning curve and a learning rate of 26.9%, significantly higher than the improvement rate associated to modules.

This can be intuitively understood since the cost of materials used for the rest of the module (glass, oil-based polymers, aluminum etc.) don't improve at the same speed and in some case is linked to the evolving prices on the market of primary goods.

One element must be noticed though; it is assumed that the cost of all these non-PV components was stable in absolute terms from a module at 10 USD/Wp and a module at 0.5 USD/Wp. This is of course not the case since the cost of some of these components has also decreased over time thanks to massive industrialization.

The conclusion is that, most probably the learning curve of the cell should be assessed separately in order to better understand the potential for price decline. Cell could be considered closer to what we define as final product than the module which is a combination and assembly of more than one "final product". Moreover it can be assumed that the cost of producing and assembling together these materials for producing PV modules will not decline at the same rate of the cost of the cells. For all these reasons, a higher learning curve might be more realistic.

1.7. Conclusions on the Learning Curve method

The crystalline silicon learning curve for PV modules is well documented and the availability of data allows to estimate the learning rate at 20%; a number coherent with the usual understanding from the industry. The hypothesis made for this deliverable is that the industry has entered in 2007 in another realm thanks to its fast development especially in Asian regions. In consequence of that, the learning rate could be much higher for crystalline silicon and establish itself to around 38-39%. We believe that the prices will have to be scrutinized in the coming years to validate that assumption.

In the meantime, assuming a 20% learning rate remains the most conservative and reasonable assumption. This learning rate will also be used for CdTe modules while the CIGS learning rate at 9% will be used with all due caution to avoid conclusions that could be questioned in the coming years with additional data.

2. Application of LC to PV future module prices

In an attempt to use the knowledge built in the previous chapters, the future module prices are assessed by using the previous hypothesis that gives 10, 20 and 38% learning rate for PV modules (c-Si).

The starting point has been taken at 0.546 USD/Wp, according to PVInsights' data, mid 2015. This number can be considered as relatively low compared to prices in Europe in 2015. For instance PvXchange gives a rather different picture for module sales in Europe, with increasing prices from the beginning of 2015 onwards.

In this part of the analysis the modules prices on the European market are considered somehow higher than in the rest of the world. The reader will understand that higher prices are possible and that this document defines a lower boundary to PV prices.

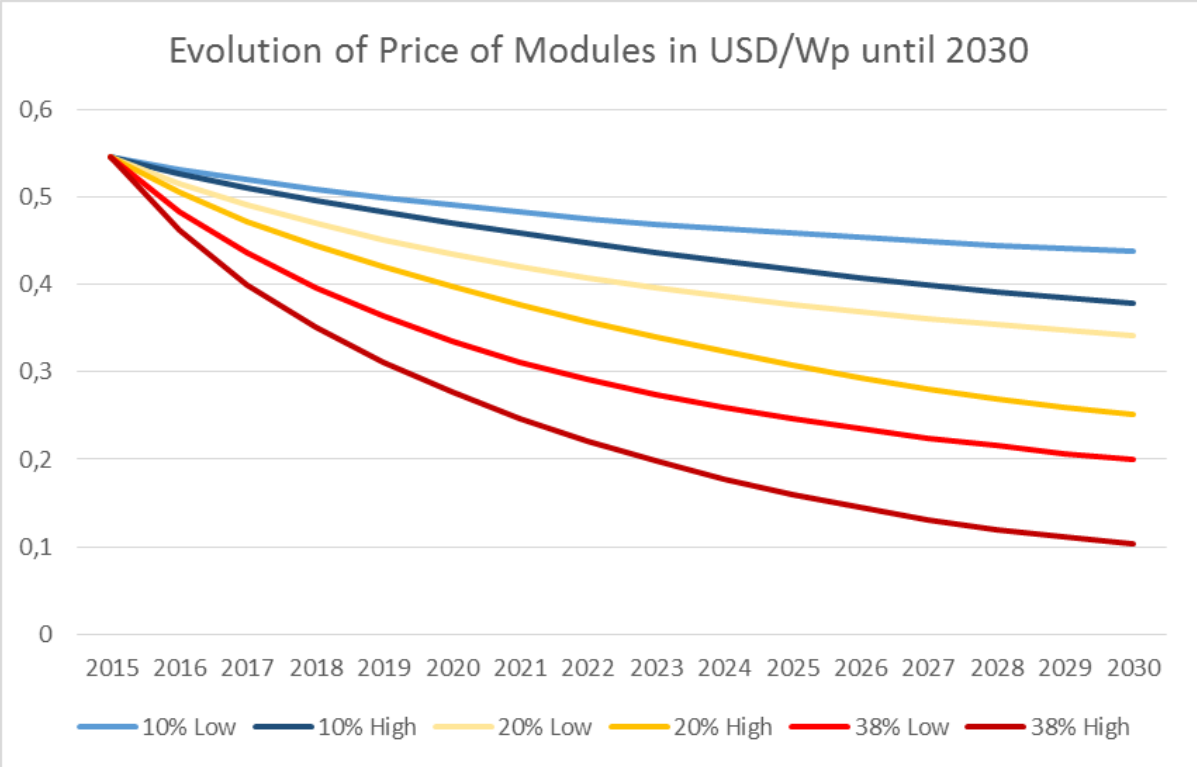

Figure 13 – Theoretical evolution of c-Si module prices until 2030 – Source: own analysis

It can be assumed that the 38% rate in the high market development scenario would bring very early (in 2023) the module price close to 0.2 USD/Wp, a limit that is acknowledged by different experts with today's standards of materials, processes and costs as the critical material cost limit.

Any decrease of the price below that limit can then be perceived as purely speculative for the time being, under the current technologies that are used (i.e. materials, processes etc.). The following table contains the possible PV module prices until 2030. The low and high scenarios have been presented in Figure 4 too.

Table 1 – Evolution of c-Si module prices until 2030, under different learning rates and different market scenarios – in orange are the scenarios based on the Global Market Outlook of SolarPower Europe.

	10%		20%		27%		38%		50 GW after 2020, cSi only	15% Annual growth after 2020 capped at 250 GW a year, cSi only
Module cost	Low	High	Low	High	Low	High	Low	High	MW	MW
2014	USD/Wp								156000	156000
2015	0,546	0,546	0,546	0,546	0,546	0,546	0,546	0,546	193476	210675
2016	0,530	0,524	0,512	0,501	0,499	0,484	0,476	0,454	235763	274934
2017	0,517	0,506	0,486	0,465	0,463	0,436	0,425	0,388	278074	345943
2018	0,505	0,491	0,463	0,436	0,433	0,398	0,384	0,337	322404	423675
2019	0,495	0,477	0,443	0,411	0,407	0,366	0,350	0,297	369417	509360
2020	0,485	0,465	0,426	0,388	0,384	0,338	0,320	0,263	419145	607530
2021	0,477	0,453	0,411	0,368	0,365	0,312	0,296	0,234	469145	720427
2022	0,470	0,442	0,397	0,348	0,349	0,290	0,276	0,209	519145	850257
2023	0,463	0,431	0,386	0,331	0,335	0,269	0,259	0,187	569145	999563
2024	0,458	0,421	0,375	0,314	0,322	0,251	0,245	0,167	619145	1171264
2025	0,452	0,411	0,366	0,299	0,311	0,233	0,232	0,150	669145	1368720
2026	0,447	0,401	0,358	0,285	0,301	0,218	0,221	0,135	719145	1595795
2027	0,443	0,393	0,350	0,272	0,292	0,204	0,211	0,122	769145	1843802
2028	0,438	0,385	0,343	0,261	0,284	0,192	0,202	0,112	819145	2093802
2029	0,435	0,379	0,337	0,251	0,276	0,183	0,194	0,104	869145	2343802
2030	0,431	0,373	0,331	0,243	0,269	0,175	0,186	0,097	919145	2593802

For CIGS and CdTe, the following prices could be reached according to the prices learning curves considered before (in USD). Starting prices are considered at the same level as c-Si in order to avoid current market distortions.

Table 2 - Evolution of c-Si module prices until 2030, under different learning rates and different market scenarios

	CdTe		CIGS	
	20%		9%	
	Low	High	Low	High
2015	0,546	0,546	0,546	0,546
2016	0,514	0,500	0,532	0,526
2017	0,488	0,463	0,520	0,509
2018	0,466	0,433	0,510	0,494
2019	0,446	0,408	0,501	0,482
2020	0,429	0,385	0,492	0,470
2021	0,414	0,365	0,485	0,459
2022	0,401	0,346	0,478	0,449
2023	0,390	0,328	0,472	0,439
2024	0,380	0,312	0,467	0,429
2025	0,371	0,297	0,462	0,420
2026	0,362	0,283	0,458	0,411
2027	0,355	0,270	0,454	0,403
2028	0,348	0,259	0,450	0,396
2029	0,341	0,250	0,446	0,390
2030	0,335	0,242	0,443	0,385

The last hypothesis to be tested is the sensitivity of PV cell prices compared to PV modules. It is still assumed a stability of the "rest of the module" price and a decrease of the PV cell prices according to the 27% learning rate considered before. The following table shows how a 27% learning rate applied to the cell price without any change in the costs of the rest of the module would damp the price evolution.

Table 3 – Evolution of cell prices

Cell Learning Rate		Module Cost	
27%			
Low	High	Low	High
0,306	0,306	0,546	0,546
0,280	0,271	0,520	0,511
0,260	0,244	0,500	0,484
0,243	0,223	0,483	0,463
0,228	0,205	0,468	0,445
0,215	0,189	0,455	0,429
0,205	0,175	0,445	0,415
0,195	0,162	0,435	0,402
0,187	0,151	0,427	0,391
0,180	0,140	0,420	0,380
0,174	0,131	0,414	0,371
0,169	0,122	0,409	0,362
0,164	0,114	0,404	0,354
0,159	0,108	0,399	0,348
0,155	0,102	0,395	0,342
0,151	0,098	0,391	0,338

The cell price could then decline to between 0.1 and 0.15 USD/Wp but the module would remain more expensive in this hypothesis than what could be reached applying a 20% learning rate to the module price only.

To conclude this part of the report and considering the possible price evolution of both c-Si and TF technologies, two elements can be highlighted:

- The future of PV module prices should take into account the evolution of TF technologies as well. However, given the rather constant 10% expected share of TF technologies, it can be assumed that the impact will be negligible compared to other factors already seen. It becomes more critical in higher shares.

- In the comparison between c-Si and TF technologies, the following Figure 14 illustrates the cost decrease until 2030 of all three technologies considered under the two market development scenarios. The cumulative production of all TF technologies has been considered to include CIGS and CdTe. The result is rather simple; with similar market prices today and a lower learning rate, CIGS might see its price declining at a slower pace than c-Si and CdTe. Assuming that current prices are similar for the time being, this would put both c-Si and CdTe as dominant market

forces in the future. However a faster growth of CIGS could compensate partially for the lower price decline potential.

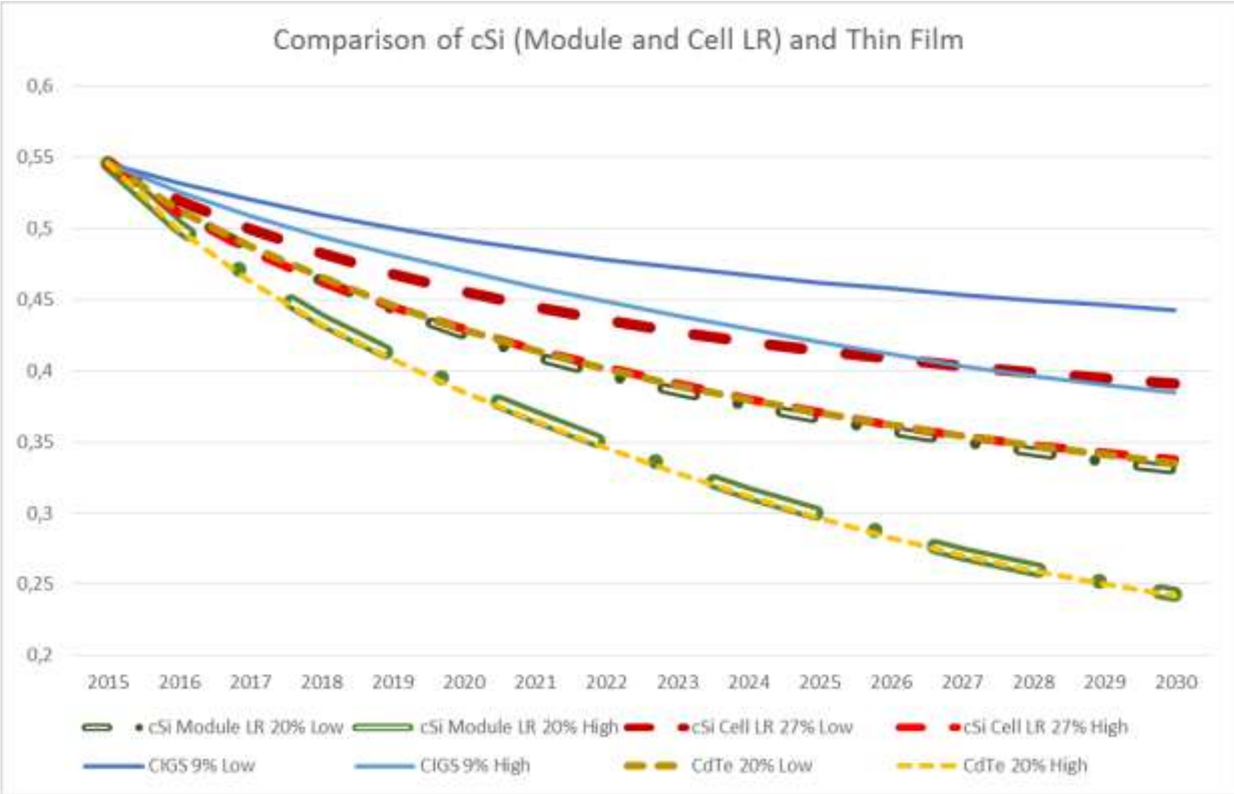

Figure 14 – Summary of all prices of all technologies based on their respective learning rate and under the same market scenarios for 2030 – Source: own analysis

3. Future evolution of BoS prices (incl. inverter)

In addition to the module price evolution, the possible evolution of the BoS has to be addressed as well. The assumptions summarized by Fraunhofer ISE and Agora Energiewende in their 2015 publication on the future of PV LCOE for the future of the inverter prices will be taken into account. [12]

According to this study, the future price of PV inverters is dependent on the system size and the cumulative capacity. It defines two possible values for inverters and a learning rate that can be used to extrapolate future inverter costs according to the scenarios of this report (Figure 15). Assuming 18.9 % learning rate for the inverters, it will give the following results depending on the market scenario (Table 4). Since these sources have used the EUR as the main currency, calculations will be done in EUR.

[12] Agora Energiewende « Current and Future Costs of Photovoltaics ». 2015, - http://www.agora-energiewende.de/fileadmin/downloads/publikationen/Studien/PV_Cost_2050/AgoraEnergiewende_Current_and_Future_Cost_of_PV_Feb2015_web.pdf

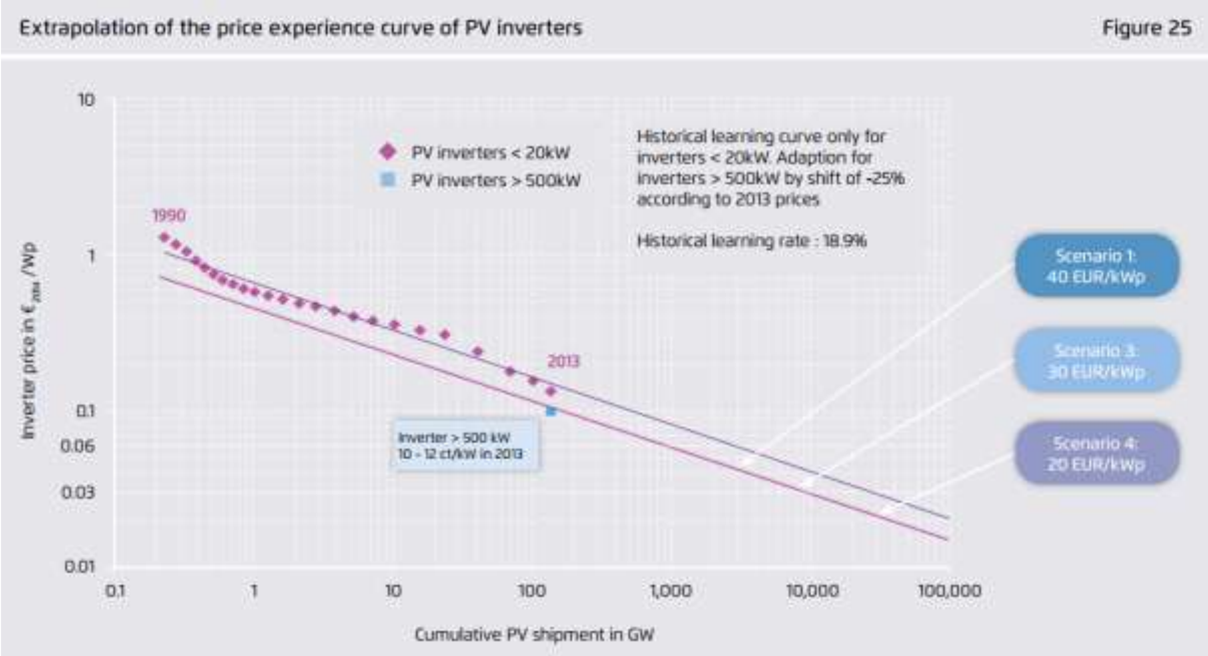

Figure 15 – Learning Curve for inverters – Source: Agora Energiwende

In the same way as before, two market scenarios (Low and High) are used and the inverter price in 2014 with the following average numbers: 0.085 EUR/Wp for utility-scale inverters and 0.2 EUR/Wp for residential scale inverters. Applying the learning rate seen before, it gives the following numbers in 2020 and 2030.

Table 4 – Future price of the inverter in three segments under the two market scenarios

18.9% LR	Residential - Low Market	Residential High Market	Commercial – Low Market	Commercial – High Market	Utility-scale – Low Market	Utility-scale – High Market
2014	0.20 EUR/Wp	0.20 EUR/Wp	0.11 EUR/Wp	0.11 EUR/Wp	0.08 EUR/Wp	0.08 EUR/Wp
2020	0.152 EUR/Wp	0.136 EUR/Wp	0.083 EUR/Wp	0.075 EUR/Wp	0.064 EUR/Wp	0.058 EUR/Wp
2030	0.121 EUR/Wp	0.089 EUR/Wp	0.066 EUR/Wp	0.049 EUR/Wp	0.051 EUR/Wp	0.038 EUR/Wp

Next to the evolution of the module and inverter costs, the evolution of the rest of the BoS have been recently studied in a recent publication of the European PV Technology Platform. The study on the future of the PV LCOE offers some additional data. The following Table 5 will be used for the rest of the BoS only (not the inverter):

Table 5 – Evolution of price of the rest of the BoS by 2030 - Source: EU PV technology Platform – The future LCOE of Photovoltaics, 2015

BoS component	€/kW$_p$ 2014	Area-related share 2014	€/kW$_p$ area-related 2014	€/kW$_p$ area-related reduction by 2030	Other reduction by 2030	€/kW$_p$ other reduction by 2030
Inverter	110	0 %	0	**0**	Learning curve	
Mounting structure	75	100 %	75	**23**	16 %	**12**
Installation work	50	100 %	50	**15**	11 %	**6**
DC cables	50	75 %	38	**11**	9 %	**4**
Grid connection	60	0 %	0	**0**	24 %	**15**
Infrastructure	40	75 %	30	**9**	9 %	**4**
Planning & docum.	35	75 %	26	**8**	7 %	**2**
Transformer	20	0 %	0	**0**	13 %	**3**
Switch gear	5	0 %	0	**0**	11 %	**1**
Total BoS	**445**	**49 %**	**219**	**66**	**10 %**	**45**

Most BoS components, with the exception of the inverters, do not follow the same learning curve as the PV modules. Many components like cables and mounting structures represent conventional technology which does not have similar price reduction potential as silicon and other semiconductor devices. However, a large part of the price of the BoS components depend on the surface area of the system, and hence, the efficiency of the modules. As the efficiency of the PV modules increases, the required area per Wp of installed system capacity and the related BoS price of the system decreases

In reality, most of the components depend both on the power and area of the array. Table 5 above lists the BoS components with the percentage of area-dependence and price in 2014, and area-related and other price reduction by 2030 for a 1 MWp ground-mounted system in Germany (Agora Energiewende/Fraunhofer ISE, 2015). It must be noted that the prices could be even lower for a very efficient project in Germany. However, the prices could be higher in some places due to local conditions related to grid connection, labour costs or higher profit margins. Local BoS price differences are not taken into account.

It can be seen from Table 5 that weighted with the component prices, the share of area-dependence is currently about 50% of the total BoS price. Applying a 0.4 percentage point annual efficiency

improvement (source Fraunhofer ISE) would mean that the BoS price would decrease by 15% by 2030 because of the reduced PV system area alone.

To put it in absolute numbers, it gives a possible "rest of the BoS" reduction from 335 EUR/kWp to 224 EUR/kWp in 2030 for utility-scale plants of around 1 MWp. It can be assumed that a linear evolution of that reduction would give for the rest of the BoS in 2020 around 300 EUR/kWp.

According to the same study, the BoS for residential systems was around 1 EUR/Wp in Germany in 2014 and about 0.66 EUR/Wp in the commercial segment. Once the inverter has been taken out (assuming 0.20 EUR/Wp for a residential PV system and 0.11 EUR/Wp for a 10-100 kWp commercial one), the "rest of the BoS" could be estimated at 0.8 EUR/Wp (residential) and 0.55 EUR/Wp (commercial) in 2014. Extrapolated with the same reduction rate as for the utility-scale system, this would give the following numbers. In order to ease the calculation, *it is assumed that the "rest of the BoS" prices are independent of the market volume – no learning curve.*

Table 6 – Future price of the rest of the BoS for three different segments

Rest of BoS	Residential	Commercial	Utility-Scale
2015	0.8 EUR/Wp	0.55 EUR/Wp	0.335 EUR/Wp
2020	0.716 EUR/Wp	0.492 EUR/Wp	0.3 EUR/Wp
2030	0.535 EUR/Wp	0.368 EUR/Wp	0.224 EUR/Wp

4. Final system prices

System prices are the simple sum of the module prices, inverter prices and « rest of the BoS » prices. It gives the following results according to the three major segments considered. Since the module price evolution has been computed in USD, the mid-2015 exchange rate between the USD and the EUR will be used. *It must be noted that this hypothesis is highly questionable and should be revised on a regular basis in the future. The exchange rate considered will then be:*

1.1 USD = 1 EUR

The following module prices will be considered (Table 7) and the following additional inverters and rest of the BoS prices as well (Table 8).

In order to ease the comparison, the starting price for CdTe and CIGS modules will be considered at the same (low) level as crystalline silicon modules. This hypothesis can be challenged but ensures a sound starting point for the LCOE calculations and shows the evolution differences between technologies.

Table 7 - Scenarios for the Future Price of the PV Modules converted in EUR - Source: own analysis

Module Prices	c-Si – Low Market – 20% LR	c-Si – High Market – 20% LR	CIGS – Low Market	CIGS – High Market	CdTe – Low Market	CdTe – High Market
2015	0.50 EUR/Wp	0.50 EUR/Wp	0.50 EUR/Wp	0.50 EUR/Wp	0.50 EUR/Wp	0.50 EUR/Wp
2020	0.387 EUR/Wp	0.353 EUR/Wp	0.447 EUR/Wp	0.427 EUR/Wp	0.390 EUR/Wp	0.350 EUR/Wp
2030	0.301 EUR/Wp	0.221 EUR/Wp	0.403 EUR/Wp	0.350 EUR/Wp	0.305 EUR/Wp	0.220 EUR/Wp

Table 8 - Scenarios for the Future Price of the BoS including inverters in EUR - Source: own analysis

Inverters and Rest of the BoS Prices	Residential – Low Market	Commercial – Low Market	Utility-Scale – Low Market	Residential – High Market	Commercial – High Market	Utility-Scale – High Market
2015	1 EUR/Wp	0.66 EUR/Wp	0.415 EUR/Wp	1 EUR/Wp	0.66 EUR/Wp	0.415 EUR/Wp
2020	0.868 EUR/Wp	0.575 EUR/Wp	0.364 EUR/Wp	0.852 EUR/Wp	0.567 EUR/Wp	0.358 EUR/Wp
2030	0.646 EUR/Wp	0.434 EUR/Wp	0.275 EUR/Wp	0.624 EUR/Wp	0.417 EUR/Wp	0.262 EUR/Wp

The calculated PV system prices are found then in the below tables. Those are presented per segment as those have been defined for later on purposes i.e. for the calculation of the LCOE and the assessment of impact of innovations. **The segments are**:

- **Segment 1:** Residential with c-Si
- **Segment 2:** Residential with high efficiency technologies
- **Segment 3:** Commercial with c-Si
- **Segment 4:** Commercial with CIGS
- **Segment 5:** Utility-scale with c-Si
- **Segment 6:** Utility-scale with CdTe

For the above, the low and high market scenarios have been used and the respective learning rates for the modules as those are presented in Table 7.

Table 9 – Scenarios for the future price of the PV systems/Residential segment – Source: own analysis

Module Prices	Segment 1 - Residential c-Si – Low Market – 20% LR	Segment 1 - Residential c-Si – High Market – 20% LR	Segment 2 - Residential High Eff. – Low Market	Segment 2 - Residential High Eff. – High Market
2015	1.50 EUR/Wp	1.50 EUR/Wp	Not enough reliable data	
2020	1.255 EUR/Wp	1.205 EUR/Wp		
2030	0.947 EUR/Wp	0.845 EUR/Wp		

Table 10 - Scenarios for the future price of the PV systems/Commercial segment – Source: own analysis

Module Prices	Segment 3 - Commercial c-Si – Low Market – 20% LR	Segment 3 - Commercial c-Si – High Market – 20% LR	Segment 4 - Commercial CIGS – Low Market	Segment 4 - Commercial CIGS – High Market
2015	1.16 EUR/Wp	1.16 EUR/Wp	1.16 EUR/Wp	1.16 EUR/Wp
2020	0.962 EUR/Wp	0.920 EUR/Wp	1.022 EUR/Wp	0.994 EUR/Wp
2030	0.735 EUR/Wp	0.638 EUR/Wp	0.837 EUR/Wp	0.767 EUR/Wp

Table 11 - Scenarios for the future price of the PV systems/utility-scale segment – Source: own analysis

Module Prices	Segment 5 - Utility-scale cSi = Low Market	Segment 5 - Utility=scale cSi = High market	Segment 6 - Utility=scale CdTe = Low market	Segment 6 - Utility=scale CdTe = High market
2015	0.915 EUR/Wp	0.915 EUR/Wp	0.915 EUR/Wp	0.915 EUR/Wp
2020	0.751 EUR/Wp	0.711 EUR/Wp	0.754 EUR/Wp	0.708 EUR/Wp
2030	0.576 EUR/Wp	0.483 EUR/Wp	0.580 EUR/Wp	0.482 EUR/Wp

5. Application to LCOE calculations

5.1. Introduction to LCOE calculation

The Levelized Cost of Electricity (LCOE) is a standard way of calculating the cost of generating electricity from any kind of power plant, taking into account all CAPEX and OPEX costs during the lifetime of the plant. The LCOE model built by Agora Energiewende[13] has been modified to suit the needs of this study in order to make use of the market development scenarios considered above, the different assumptions but keeping the same formatting for the output figures. The basic formula for the calculation used is the below one:

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

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)

For each considered segment from chapter 4, the LCOE has been calculated with the following cross cutting assumptions.

- PV system price according to the segment
- Three different assumptions of nominal weighted average cost of capital (WACC) were considered : 5%, 7.5% and 10%
- Inverter replacement after 10 years at current cost (considering the inverter learning curve seen above) – can be considered as a safe and conservative approach
- Irradiation level have been considered at the European level, from 750 kWh/kWp (north of Finland) to 1900 kWh/kWp (higher irradiation in Spain) in order to provide the whole range of values per each WACC assumption
- OPEX costs declining slowly (-10% in 2020, -20% in 2030).

[13] 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/

- Lifetime starting at 25 years in 2015, increasing at 26 and 27 years respectively in 2020 and 2030. This can be considered as a conservative approach since lifetime can reach and surpass the 30-year boundary by 2030.
- The LCOE ranges have been defined according to the low irradiation combined with the low market uptake for the calculation of the highest LCOE value and to the high irradiation combined with the high market uptake for the calculation of the lowest LCOE.

All the other segment dependent assumptions are included in the respective subchapters. Those assumptions are own assumption and try to reflect an average trend avoiding upper and lower extremes.

5.1.1. Segment 1: Residential PV – standard crystalline silicon

OPEX:

- 10 EUR/kWp per year in 2015
- 9 EUR in 2020
- 8 EUR in 2030

All other parameters according to the previous calculations.

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	6,8	17,3	8,3	21,1	10,0	25,2	5,5	14,5	6,7	17,7	8,0	21,1	3,8	10,9	4,7	13,4	5,6	16,0

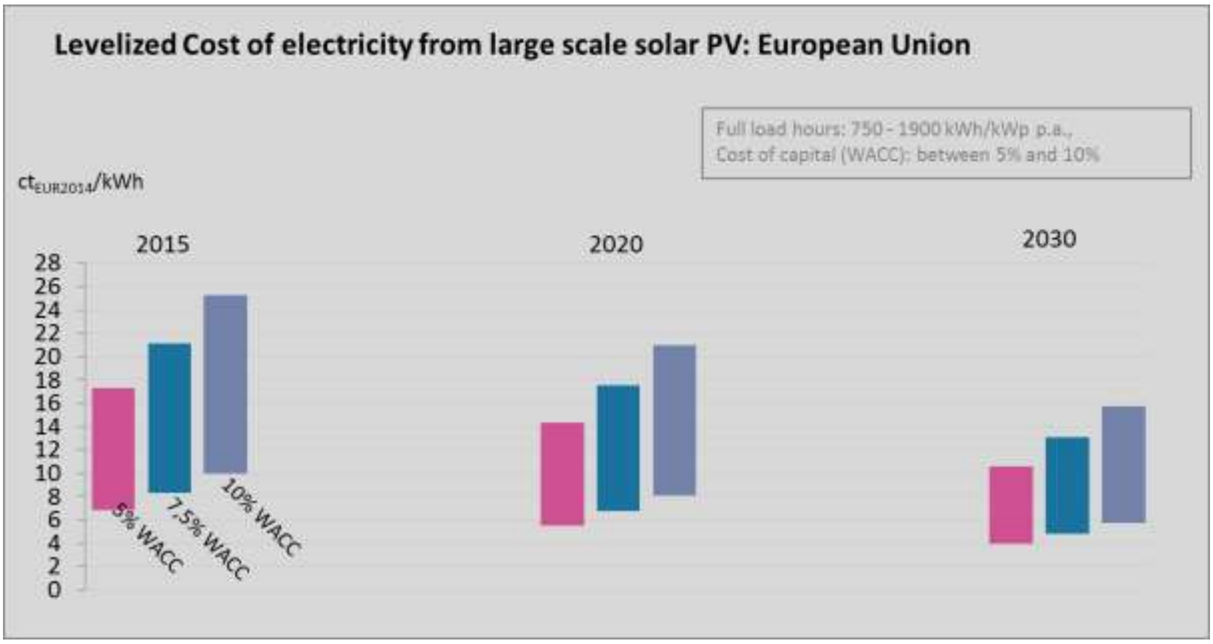

Figure 16 – The Future LCOE of PV Systems considering residential c-Si - Source: own analysis

5.1.2. Segment 2: Residential with high efficiency technologies.

Not considered due to lack of data

5.1.3. Segment 3 : Commercial PV – standard cristalline silicon

OPEX:

- 30 EUR/kWp per year in 2015
- 27 EUR in 2020
- 24 EUR in 2030

All other parameter according to the previous calculations.

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	6,3	15,9	7,5	18,9	8,7	22,1	5,2	13,5	6,1	16,0	7,1	18,6	3,9	10,7	4,5	12,7	5,2	17,8

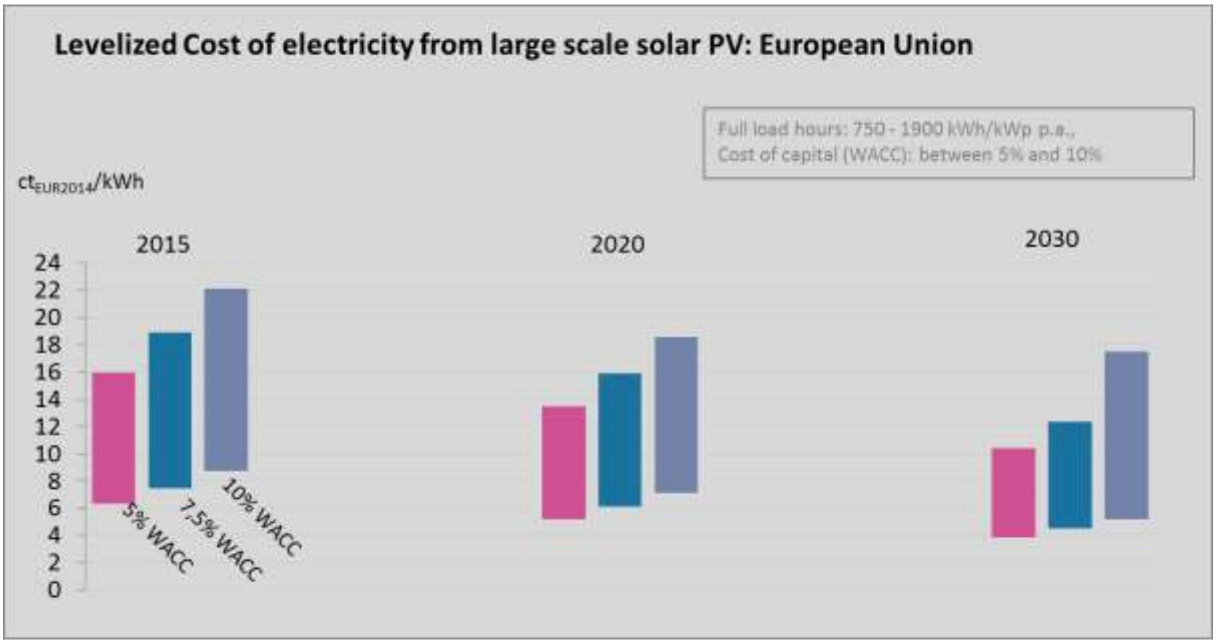

Figure 17 – The Future LCOE of PV Systems considering commercial c-Si - Source: own analysis

5.1.4. Segment 4 : Commercial PV – Thin Film CIGS

OPEX:

- 30 EUR/kWp per year in 2015
- 27 EUR in 2020
- 24 EUR in 2030

Production from CIGS panels has been estimated to be identical to crystalline silicon in standard European irradiation conditions.

All other parameter according to the previous calculations.

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	6,3	15,9	7,5	18,9	8,7	22,1	5,4	14,1	6,4	16,7	7,5	19,5	4,2	11,5	5,0	13,7	5,9	16,1

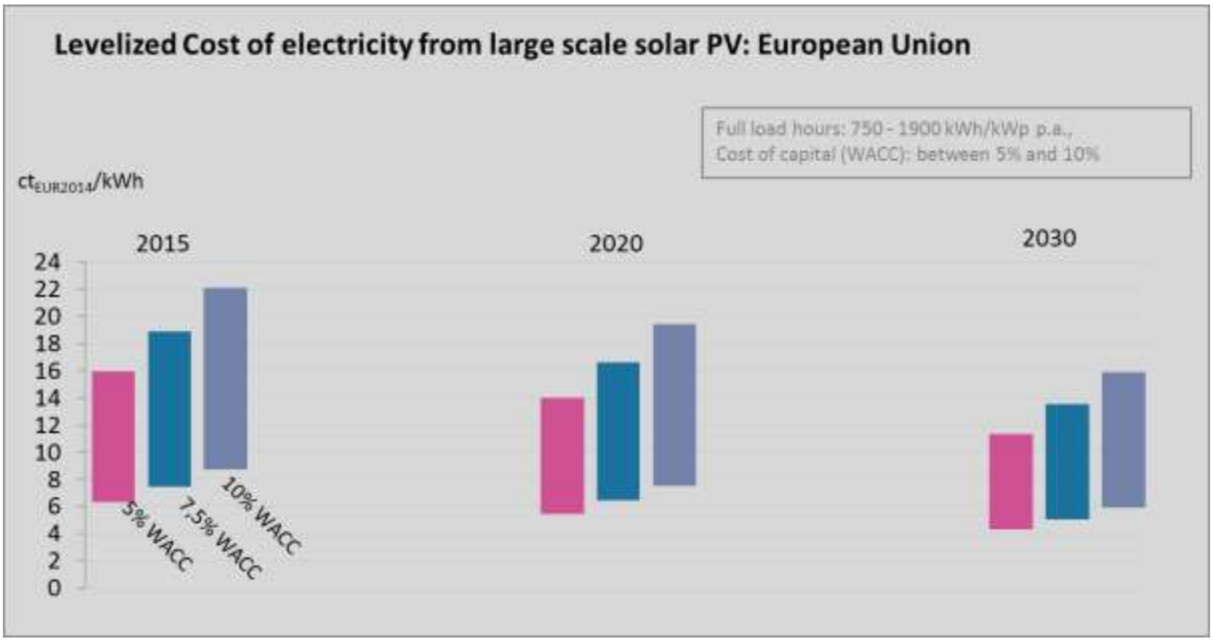

Figure 18 – The Future LCOE of PV Systems considering commercial TF CIGS - Source: own analysis

5.1.5. Segment 5 : Utility-scale PV – standard crystalline silicon

OPEX:

- 30 EUR/kWp per year in 2015
- 27 EUR in 2020
- 24 EUR in 2030

All other parameter according to the previous calculations.

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

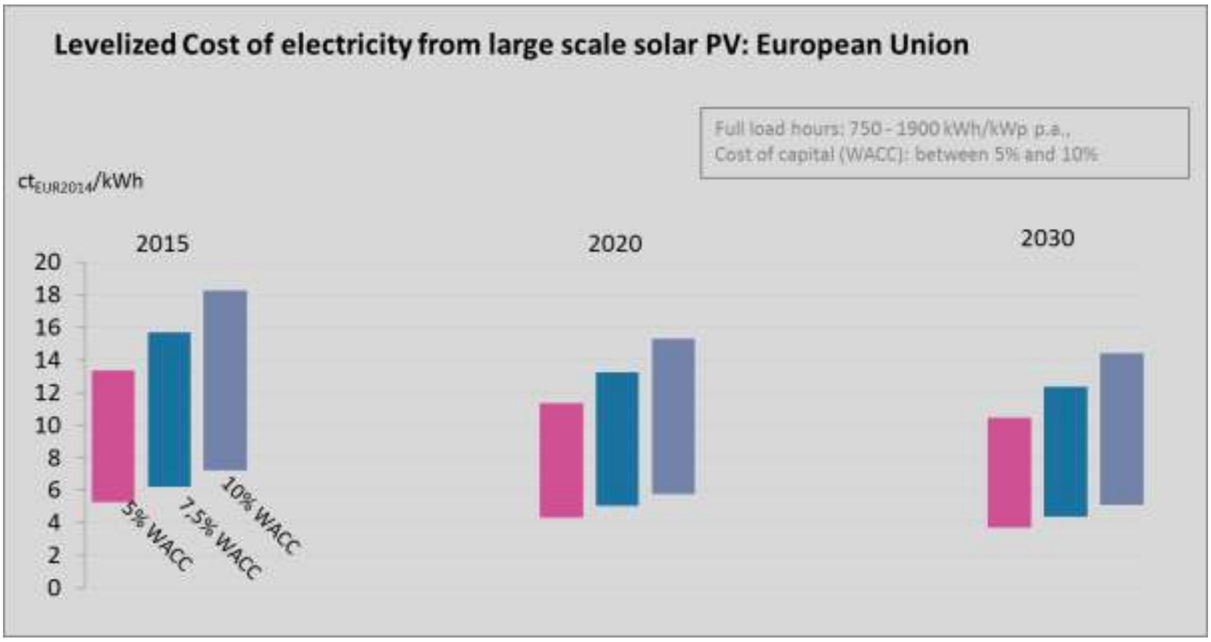

Figure 19 – The Future LCOE of PV Systems considering utility scale c-Si - Source: own analysis

5.1.6. Segment 6 : Utility-scale PV – Thin Film CdTe

OPEX:

- 30 EUR/kWp per year in 2015
- 27 EUR in 2020
- 24 EUR in 2030

Production from CdTe panels has been estimated to be identical to crystalline silicon in standard European irradiation conditions.

All other parameter according to the previous calculations.

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	15,4	3,2	9,0	3,7	10,5	4,2	12,2

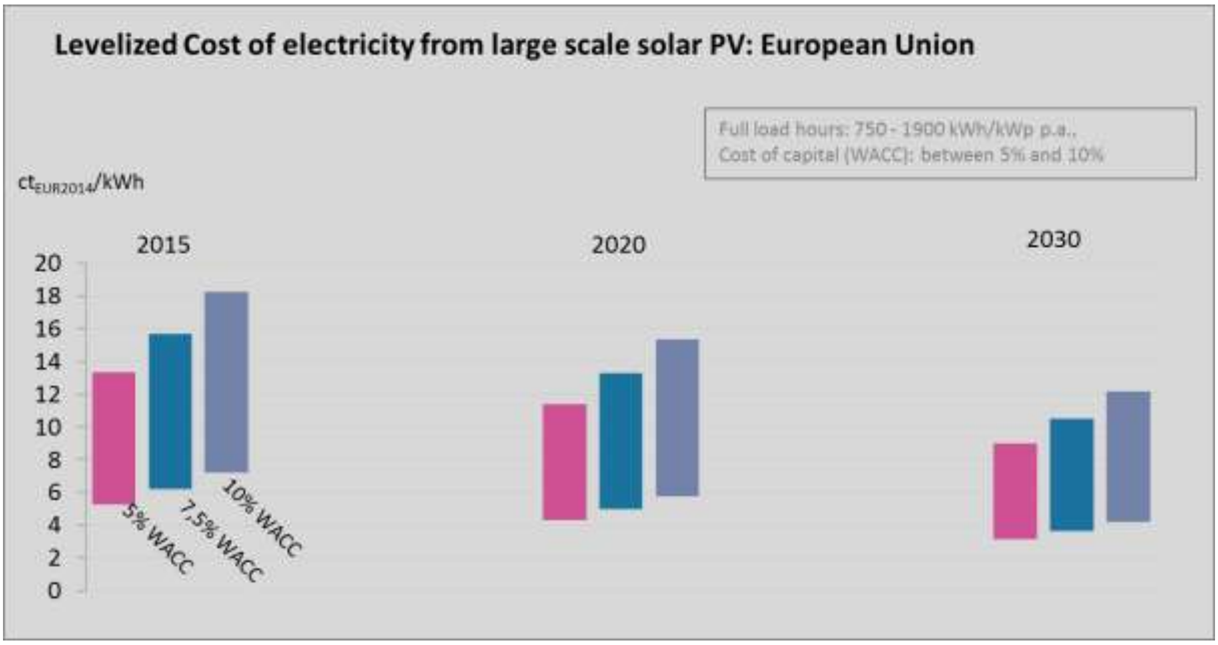

Figure 20 – The Future LCOE of PV Systems considering utility scale TF CdTe - Source: own analysis

6. Conclusions and limitations

This document has analyzed the potential evolution of PV LCOE based on several assumptions that must be well understood.

- The Learning Curve concept is an empirical concept that postulates that the economies of scale and the technological improvement are following a constant pattern, linked to the production volumes. While this has been observed in many industries, the PV learning curve shows how the concept has limitations.
    - The first limitation is based on the fact and the willingness of the human mind to look for friendlier and easier to understand figures. The reason why the Learning Rate used in the PV system price forecast and the LCOE calculation has been chosen at 20%, because it is widely used and commonly accepted as a sensible figure. *However the learning rate calculated with the 95% latest cumulative installations gives a much higher price decrease for crystalline silicon and CdTe. This will have to be carefully scrutinized in the coming years.*

- Summing up uncertainties and errors indeed derails the final findings from the reality (unless those errors are neutralized (compensating errors). *This is the reason why the LCOE calculation has been based on the limited range of possible values.*

- *The assumptions for the price decline of the rest of the BoS (minus the inverter) are less sound than the learning curve-based assumptions for modules and inverters. In several cases, the margins included in the « rest of the BoS » could be used to accelerate the system price decline, especially for residential PV systems*.

- Market prices for PV modules and inverters are fluctuating and it is highly difficult to select one representative value of the PV market, even for one single technology. For that reason, we have chosen to start from the same value for all technologies (except for high efficiency crystalline silicon that is not studied in this document).

Section 6 – Impact on technology innovation on the LCOE

Introduction and Background

Since 2014, KIC InnoEnergy is working on modelling the impact of technology innovation on the LCOE. So far, the results obtained can be described according to the following deliverables:

- 3 reports analysing the impact of technology innovation on the LCOE of offshore, onshore wind and solar-thermal electricity. http://www.kic-innoenergy.com/reports/
- An online application called Delphos (http://www.kic-innoenergy.com/delphos/) that allow to get access to a simplified version of the models used to produce the reports with the following main benefits:
  - Customise calculations according to user experience
  - Adapt the portfolio of innovations to be considered in the modelling
  - Describe new innovations and evaluate their effect on the LCOE

During 2015, KIC InnoEnergy is working on adapting this model to the PV technology with the aim to publish a similar report for this technology as well as to extend the capabilities of its online model to cope with PV technology.

Within Cheetah, the model tool will be used to assess the impact of the innovations developed in the project on the LCOE. At that point in time, and as presented in the current deliverable, the focus is on developing and adapting the methodology. In later on reports the preliminary and final results will be presented, starting with beginning of 2016.

7. Methodology

Note that the following text describes the preliminary methodology that has been established for the application of KIC InnoEnergy cost analysis methods. This methodology might be subject to changes due to adaptation during its application.

In case of changes, this methodology will be updated in the following deliverables.

7.1. Scope of model

The basis of the model is a set of baseline elements of capital expenditure (CAPEX), operational expenditure (OPEX) and annual energy production (AEP) for a range of different representative PV Technologies on given Site Types, impacted by a range of technology innovations. Analysis is carried out

at a number of points in time (years of FID[14])' thus describing various potential pathways that the industry could follow, each with an associated progression of LCOE.

7.2. Preliminary assumptions

A detailed set of project assumptions are established in advance of modelling, covering technical and non-technical global considerations and PV plant-specific parameters.

CAPEX, OPEX, energy and losses breakdown:

This breakdown will be populated with cost and production data for "FID present" so the model can be run properly.

Table 12 – Assumptions and considerations for the modelling and the assessment of innovations

Type	Parameter	Definition	Unit
CAPEX	PV modules	Payment to PV module manufacturer for the supply of the modules to the point of connection to the array cables (can be crystalline-Si or Thin Film technology). Includes: All production costs (cell supply [cell cost excluded], workforce, energy, machinery, etc.) Delivery to warehouse of the installer 5 years warranty Commissioning costs Excludes: Support structures OMS costs RD&D costs	€/W
	Inverters	Includes: Payment to inverter manufacturer for the supply of the equipment to the point of connection to the array cables. Delivery to warehouse of the installer 5 years warranty	€/W

[14] FID = Final Investment Decision= defined here as that point of a project life cycle at which all consents, agreements and contracts that are required in order to commence project construction have been signed (or are at or near execution form) and there is a firm commitment by equity holders and in the case of debt finance, debt funders, to provide or mobilize funding to cover the majority of construction costs.

		Commissioning costs Excludes: OMS costs RD&D costs	
	BoS →structures	Includes: Payment to supplier for the supply of the support structure comprising the foundation and the support structure (fixed or tracker) Delivery to warehouse of the installer 5 years warranty Excludes: OMS costs RD&D costs	
	BoS →collection grid	Includes: Payment to manufacturer of electrical material (cables & other electrical elements, grid code compliance devices) Delivery to warehouse of the installer 5 years warranty Excludes: OMS costs RD&D costs	€/W

	Development, Construction and installation	Includes:
		
		• Development and consenting work paid for by the developer up to the point of Works Completion date (WCD).
		    o Internal and external activities such as environmental and wildlife surveys, resource evaluation (includes metering devices), land negotiation, engineering (pre FEED) and planning studies up to FID.
		    o Further site investigations and surveys after FID
		    o Engineering (FEED) studies
		    o Project management (work undertaken or contracted by the developer up to WCD)
		    o Other administrative and professional services such as accountancy and legal advice
		• Transportation of all equipment from warehouse to site
		• On construction site transportation of all equipment
		• All installation work for support structures, modules, inverters and array cables
		• Commissioning work for all the installation except PV modules and inverters
			€/W

		• Warranty • Commissioning costs Excludes: • Any reservation payments to suppliers • Construction phase insurance • Suppliers own project management • Installation of substation and transmission assets • OMS • R&D costs	
OPEX	Operation and maintenance	Starts once first module is commissioned. Includes: Operational costs relating to the day-to-day control of the PV plant including control room activities and admin/financial services Condition monitoring if applied Planned preventative maintenance, health and safety inspections including module cleaning (once per year) and vegetation care where applicable Corrective maintenance and replacement of broken equipment Security (remote surveillance and patrolling) Inverter extended warranty when apply	€/W/yr
	Other OPEX	Starts once first module is commissioned. Includes: Lease of land or roof Contributions to community funds including all type of tax where applicable. Monitoring of the local environmental impact of the PV farm if applied.	€/W/yr
AEP	Gross AEP	The gross AEP in the first year of the PV plant life at output of the modules and inverters. Excludes electrical array losses and other losses.	MWh/yr/MW
	Performance Ratio	Includes: Temperature losses Inverter losses Electrical array losses to the metering point Potential induced degradation (PID) and Light induced	%

		degradation (LID) Other losses Losses due to lack of availability of PV plant elements. Shadows (building commercial & residential) Low radiation losses Excludes: Transmission losses.	
	Degradation factor	Equipment degradation losses (degradation factor)	%
	Net AEP	The net AEP averaged over the PV plant life at the metering point at entry to the substation.	MWh/yr/MW

Global assumptions:

- Real (end 2014) prices
- Commodity prices fixed at the average for 2014
- Exchange rated fixed at the average for 2014
- Energy prices fixed at the current rate
- Market expectation "mid-view" 15% as Compound Annual Growth Rate (CAGR)

Table 13 – Site types and their description

Nº	Site types	Generic description	Resumed specific description
1	Utility Scale Low radiation site	>5MW ground mounted Low rad / low TºC	10 MW ground mounted Orientation optimal south Example of location: Germany Global radiation: 1200 kWh/m2/y
2	Utility Scale High radiation site	>5MW ground mounted High rad / high TºC	10 MW ground mounted Orientation optimal south Example of location: Spain Global radiation: 1800 kWh/m2/y
3	Building Commercial & residential	<100kW roof mounted	100 kW roof mounted (on factory or warehouse) Orientation south but some shading problems Example of location: Europe average Global radiation: 1350 kWh/m2/y

- Installations' capacity as indicated in the table

- Depreciation time used is 25 years
- An EPC contract approach is used to contracting for construction

Table 14 – CAPEX spend profile

Site type			-2	-1	0
Ground mounted	CAPEX spend			20%	80%
Building mounted	CAPEX spend				100%

Year 1 is defined as year of first full generation.

Generic WACC for simple LCOE calculations:

Ground mounted: 5%

Building mounted: 5%

Technology types:

- Module technologies description:
    - Si: mono or poly-crystalline silicon technology, module efficiency of 17% in 2014
    - High efficiency Si: module efficiency of 21% in 2014
    - Thin Film: module efficiency of 14% in 2014
        - CdTe technology for ground mounted site types
        - CIGS technology for building mounted site type
- Inverters:
    - Ground mounted site types: in the 100kW range
    - Building mounted site type: in the [1-10]kW range
- Support structures:
    - Fixed: aluminum structure with concrete foundations
    - Tracker: one axis tracker
    - Building:
        - Roof top for c-Si
        - BIPV regarding TF
- Array electrical:
    - Ground mounted site types: medium voltage wiring for collection system
    - Building mounted site type: low voltage wiring for collection system

- Construction:
  - EPC contracting ensure transport on a just in time basis and construction
- O&M:
  - Ground mounted plant: local service team within 1 hour driving distance, with 7-day working within office hours and remote management control room with data access via SCADA system.
  - Building mounted plant: low cost O&M strategy, no remote access.

7.3. Technology innovation modelling

The basis of the model is an assessment of the differing impact of technology innovations in each of the PV plant elements on each of the baseline PV plants, as outlined in **Erreur ! Source du renvoi introuvable.**. This section describes the methodology for analysis of each innovation in detail.

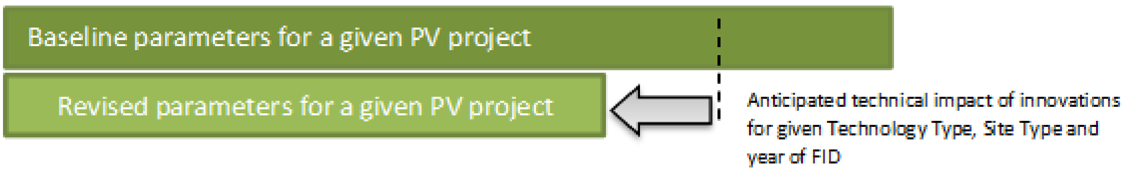

Figure 21 – Process to derive impact of innovations on the LCOE. Note that Technology Type in this study means Turbine Type.

Erreur ! Source du renvoi introuvable. summarises this process of moderation

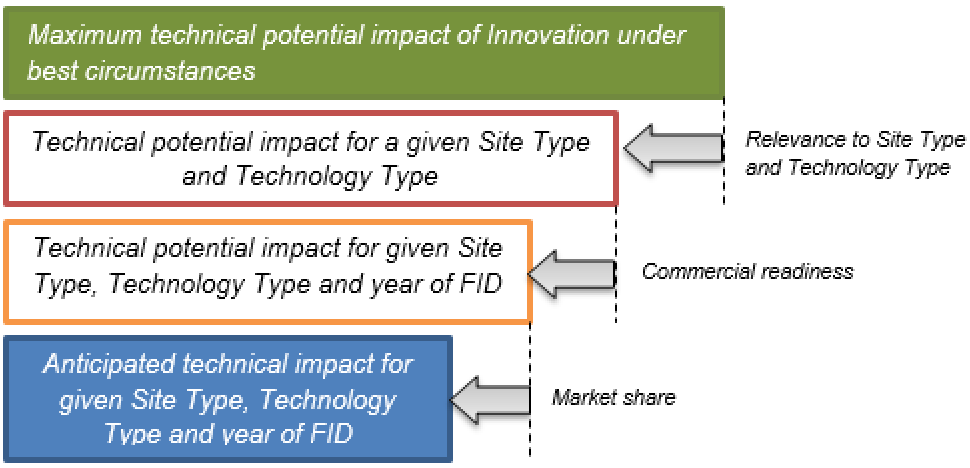

Figure 22 - Four stage process of moderation applied to the maximum potential technical impact of an innovation to derive anticipated impact on the LCOE. Note that Technology Type in this study means PV Technology

In the following points, each of those adjusters is briefly described.

7.3.1. Maximum technical potential impact

Each innovation may impact a range of different costs or operational parameters, as listed in **Erreur ! Source du renvoi introuvable.**. The maximum technical potential impact on each of these is recorded separately for the PV technology and Site Type most suited to the given innovation. Where relevant and where possible, this maximum technical impact considers timescales that may be well beyond the final year of FID.

Frequently, the potential impact of an innovation can be realized in a number of ways, for example through reduced CAPEX or OPEX or increased AEP. The analysis uses the implementation resulting in the largest reduction in the LCOE, which is a combination of CAPEX, OPEX and AEP.

Table 15 – Information recorded for each innovation

Information recorded for each innovation
% impact on cost of: • PV modules • Inverters • BOS Structures • BOS Collection girds • Development, construction and installation • Operation & Maintenance • Other OPEX
% impact on: • Gross AEP, and • Performance ratio.

7.3.2. Relevance to Site Types and Technology Types

This maximum technical potential impact of an innovation compared with the baseline may not be realized on all Site Types with all PV technologies. In some cases, an innovation may not be relevant to a given Site Type and PV technology combination at all. As an example, in PV, the anticipated dominance of silicon based technologies on thin film technologies for some types of sites make the remaining combinations less or not relevant at all. In this way, relevance indicators for a given PV Technology and Site Type may be between zero and 100%, with at least one specific PV technology Type and Site Type combination having 100% relevance.

This relevance is modelled by applying a factor specific to each combination of Site Type and given PV technology independently for each innovation. The factor for a given Site Type and PV technology combination is applied uniformly to each of the technical potential impacts derived above.

7.3.3. Commercial readiness

In most cases, the technical potential of a given innovation will not be fully realised even on a project with FID in 2030. This may be for a number of reasons:

- Long research, development and demonstration period for an innovation

- The technical potential can only be realised through a design's ongoing evolution based on feedback from commercial-scale manufacture and operation, or
- The technical potential impact of one innovation is decreased by the subsequent introduction of another innovation.

This commercial readiness is modelled by defining a factor for each innovation specific to each year of FID, defining how much of the technical potential of the innovation is available to projects with FID in that year. If the figure is 100%, this means that the full technical potential is realised by the given year of FID. For many of the innovations modelled, it is anticipated that further progress will be made after the last year of FID modelled (2030), thus, not reaching 100% by 2030.

The factor relates to how much of technical potential is commercially ready for deployment in a commercial project of the scale defined in the baseline, taking into account not only the offering for sale of the innovation by the supplier but also the appetite for purchase by the customer. Reaching this point is likely to have required full-scale demonstration. This moderation does not relate to the share of the market that the innovation has taken but rather how much of the full benefit of the innovation is available to the market.

7.3.4. Market share

Many innovations are compatible with others, but some are not. For example, innovations relating to silicon technology and thin film are not compatible. Each innovation is assigned to one or more groups (combinations) of complementary innovations and each group is then assigned a market share for each Technology Type and year of FID. This is a market share of a group of innovations for a given Technology Type for projects with FID in a given year. It is not a market share of the innovation in the whole of the market that consists of a range of projects with different Technology and Site Types.

The resulting anticipated impact of a given innovation, as it takes into account the anticipated market share on a given PV Technology in a given year of FID, can be combined with the anticipated impact of all other innovations to give an overall anticipated impact for a given PV Technology and Site Type and year of FID. At this stage, the impact of a given innovation is still captured in terms of its anticipated impact on each capital, operational and energy-related parameter, as listed in **Erreur ! Source du renvoi introuvable.**.

These impacts are then applied to the baseline costs and operational parameters to derive the impact of each innovation on LCOE for each PV Technology and Site Type and year of FID, using a generic weighted average cost of capital (WACC).

The aggregate impact of all innovations on each operational and energy-related parameter in **Erreur ! Source du renvoi introuvable.** is also derived, enabling a technology-only LCOE to be derived for each PV Technology and Site Type and FID year combination.

7.4. Treatment of other effects

To derive a real-world LCOE, this technology-only LCOE is factored to account for the impact of various other effects, defined for each combination of PV Technology and Site Type and year of FID as follows:

- Scenario-specific WACC, taking into account risk beyond that covered by contingency
- Transmission cost, covering transmission capital and operating costs and charges related to the infrastructure from input to the transmission network
- Supply chain dynamics, simplifying the impact of the supply chain levers such as competition and collaboration
- Insurance and contingency costs, both relating to construction and operation insurance and typical spend of construction phase contingency, and
- The risk that some projects are terminated prior to FID, thereby inflating the equivalent cost of work carried out in this phase on a project that is constructed. For example, if only one in three projects reaches FID, then the effective contribution to the cost of energy of work carried out on projects prior to FID is modelled as three times the actual cost for the project that is successful.

A factor for each of these effects will be defined for each specific Technology and Site Type and FID year.

The factors are applied as follows:

- Scenario-specific WACC is used in place of the generic WACC to calculate a revised LCOE, and
- Each factor is applied in turn to this LCOE to derive the real-world WACC.

These factors are kept separate from the impact of technology innovations in order to clearly identify the impact of innovations, but they are needed in order to be able to compare LCOE for different scenarios rationally.

The effects of changes in construction time are not modelled.

8. Required information from the assessment of Cheetah specific innovations

The ongoing work stream at KIC InnoEnergy provides to the project consortium, not only the methodology but also the required baseline scenarios at present FID that will be influenced by the innovations.

It is expected from the Cheetah partners, especially the ones involved in the more technical part related to the innovations that will be studied under this methodology to provide the relevant information to populate the model.

For each concrete innovation, the following list of information is needed:

- **Short title**
- **State of the art** (text)
- **Innovation description** (text)
- **Maximum technical potential impact** (9 values) of the innovation, defined as a % of variation of CAPEX, OPEX, AEP and PR. Note that the % of variation of the CAPEX related to the module might be too complex to track. In this case, KIC InnoEnergy can provide limited access to a premium modelling tool that allow a finest break down of the module costs.
- **Relevance to Site Types and Technology Types** as defined in the baseline scenarios
- **Commercial readiness** in 2020 and 2030
- **Market share** of the innovation / group of innovation

9. Expected outputs

Once duly populated, the model will basically run two types of calculations that give access to the following indicators:

- Simple LCOE calculations to give access to innovation-only impact, expressed and drawn as:
  - A % of changes in CAPEX, OPEX, AEP and PR (relative LCOE value)
  - a % of LCOE change over the period.
- Complex LCOE calculations to give access to an absolute LCOE value taking into account the real world effect derived in the non-technology parameters.

The results give an overview of the single and cumulative anticipated impact of the innovations from present (FID 2015) to future FIDs, in 2020 and 2030, taking into account not only technical parameters but also the penetration of those innovation in the market.

Besides this, the model also allows to look beyond those dates and to identify (if populated) potential longer term activities that could impact the cost of PV on the long run (beyond 2030).