MODULES AT A PRICE OF 10 $ct/Wp – DREAM OR REALITY?
NEW APPROACH FOR FUTURE COST AND PRICE PREDICTIONS

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ABSTRACT: In this paper a new cost model methodology is introduced which allows to predict future module costs and prices based on technology learning and price experience. As point of reference for the cost model the major cost parameters for producing wafers, cells and modules are analyzed for the year 2018. Similar to Price Experience Curves with characteristic Price Experience Factors (PEF) we have introduced Technology Learning Factors (TLF) which allow for the various technology and cost parameters an extrapolation to cumulated volumes of wafers, cells and modules produced in the future. If the resulting future prices are inserted into today's PEC for modules a good correlation is seen compared to the historical PEC extrapolation without the need of bending or shifting. Assuming realistic, yet ambitious, market growth rates allow the determination of specific times for which a certain total cost and associated price will be reached. As a result it can be shown that module whole sale prices of 10 $ct/Wp are neither a dream in the long run (>2040) nor reality short term (until 2030) when fair cost calculations and margins are considered.
Keywords: Cost Reduction, Economic Analysis, Price Experience, Cost Learning, Technology Learning, Market Development

1 INTRODUCTION

In recent years the prices of crystalline silicon photovoltaic (PV) modules have decreased rapidly. This may lead to the perception that this trend will continue at the same rate and PV module prices could be half of today's prices or even less within only a few years. As today's module prices strongly deviate from the long-term price experience curve (PEC) for PV modules there is a high uncertainty associated with the future price trend.

The approach presented in this work starts with a widely accepted description of the cost structure in 2018 and it takes into account all relevant input parameters for wafer, cell and module add-on cost numbers. Our data set is taken from NREL [1] with additional few inputs by ITRPV [2] and own research [3].

The advantage of Price Experience Curves (PEC) with double logarithmic plots showing price versus the cumulative sold global volume is the fact that time is not a parameter. Instead, from the slope of these typical straight lines the so-called Price Experience Factor (PEF) is obtained which is a measure for the change (in %) for every doubling of the cumulative volume. For different products it has been shown that for technology-oriented products (semiconductors, flat panel displays) Price Experience Factors (PEF) are in the range of 30-40%, while products with mature technology and a high proportion of material cost like solar modules and batteries this PEF is lower in the 15-25% range and even less (~10%) for only material-based products [4-6].

The innovative approach of this paper is based on the introduction of Technology Learning Factors (TLF) for the variety of input parameters. This new calculation model allows for the total cost and price development a look into the future based on cumulative sold production volume. With the assumption of various growth numbers one can attribute a certain cumulative volume at a given price with corresponding years.

2 2018 COST AND PRICE SITUATION

2.1 Reference data set

Starting point is the cost structure of wafers, cells and modules in 2018 as summarized in Fig.1 [1-3]. The cost structure is based on a vertically integrated production company purchasing poly silicon from the international market and producing Cz-crystals, wafers, cells and modules. Our data are neither describing the cost structure for highest efficiency levels (HIT and back-contacted cells) nor the mainstream multi-crystalline cells, but the one for monocrystalline PERC(/L) solar cells which favorably decreases total system cost by decreasing area related cost due to high efficiency and reasonable in-between module prices.

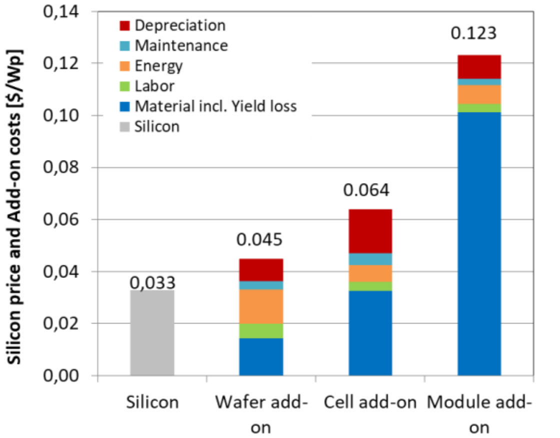

Figure 1: Add-on cost for c-Si wafers, cells and modules for the base year 2018.

Companies need a reasonable margin on top of the production cost in order to pay not only the administrative departments (finance, legal, human affairs and management body) but also the sales department and R&D activities to sell globally the products and accomplish the needed cost decreases to stay competitive. We take in our study a margin of 15% (including a small but necessary operating margin) which transforms the production cost into an ex-works sales price. To obtain the wholesale price we have to add transportation cost and trade margin (5%, see Fig.2). The average whole-sale price in 2018 from pvXchange [7] for modules produced with main stream mc-Si cells (~) and high efficiency mono cells is ~0.29 \$/Wp and ~0.38 \$/Wp, respectively (exchange rate 1.15 \$/€). As our cost model is based on mono PERC/L, our calculated whole sale price is in the middle of their price range.

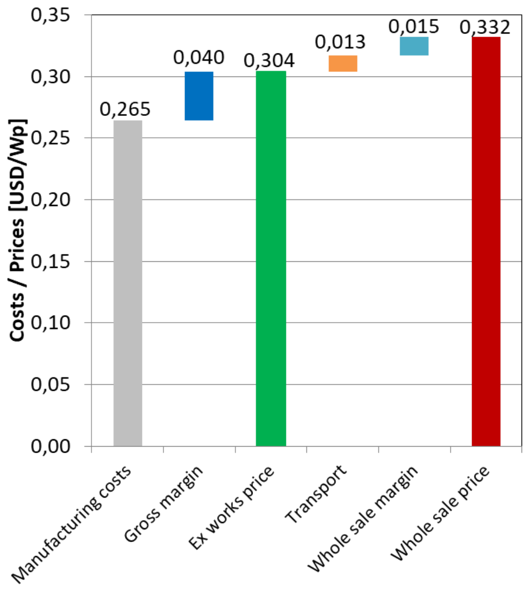

Figure 2: Starting data set for production cost, ex-work and whole sale prices for 2018 [1-3].

2.2 Regional and industry policy-driven cost and price changes

The data in Fig.2 do not reflect cost changes for production in different regions worldwide. In a recent study by NREL [1] the influence on cost elements for the various add-on steps for different production countries (Germany, US, South Korea, Taiwan, urban China, Philippines, Malaysia and lowest cost China) was analyzed. The different regions have changing cost parameters due to (a) depreciation (invest support by state and/or regional governments, (b) different financing parameters, (c) operation & waste management (local/regional differences), (d) electricity & supply (regionally different), (e) different labor cost and (f) differences in material cost. For the first half year 2018 their corresponding ex-works price (without operating margin) for modules varied quite substantially in the range 0.29 (lowest cost China) and 0.46\$/W (Germany). Our base case (0.30\$/W) corresponds with their lower price regions.

2.3 Methodology for defining PEFs, TLFs and CLFs for the cost parameters

For the individual material-based cost parameters (see Fig.1) there are prices paid by the wafer-, cell- and module producer which follow typical Price Experience Curves (PEC) with price/unit versus cumulated sold volume. The unit may be weight in kg (e.g. silicon, paste, chemicals), area in m² (e.g. front glass, back-sheet, encapsulation material), length in m (e.g. frame, back rail, cables), pieces in number (e.g. junction box, diodes, connectors) and the respective cumulated volume is counted as given for the units.

The correct way to proceed would be the construction of the individual PEC's for the considered cost parameters from principally available market data. While this could be the task of a number of bachelor and master theses, we will follow a simplifying more generic way. Using a number of well-known PECs we will define 3 different categories of products characterized by an average Price Experience Factor (PEF, sometimes also called Learning Rate). We will then group each of the various cost parameters into one of the 3 categories and use thereafter the corresponding generalized PEF.

There are well-known PEF's for products for a variety of products. Examples together with their corresponding Price Experience Factors (PEF) [4-6] are summarized in Table 1, where the various products are grouped into three categories.

Table 1: Examples for 3 technology categories (I – III) with different products exhibiting different PEFs.

Category		Example	PEF [%]
(I)	New and/or technology dominated technologies.	Semiconductor storage chips (\$/bit)	40
		Flat Panel Display (\$/m²)	35
(II)	Mature and/or less technology dominated technologies	PV Modules (\$/Wp)	20
		Battery cells (\$/kWh)	15-25
(III)	Material based products	coated glass, frames/rails, cables	~10

Experience shows that the cost for the produced unit (e.g. wafer, cell or module) is significantly changed by technology development, which we assume to follow a similar pattern like PEC/PEF, namely a change in % for every doubling of the produced volume, which we define as Technology Learning Factor (TLF). Examples are:

- The silicon cost per wafer unit depends linearly on the thickness of the used wafer (plus the associated kerf loss). Technology development along the value chain from wafering through handling in the cell process until stringing and laminating allows the use of continuously thinner wafers.
- The cell metallization cost is influenced significantly by the amount of silver per cell. Continuous technology development has impressively demonstrated the decrease of silver per cell unit.
- An important cost driver is the depreciation of the used equipment. The continuous development by machine builders has shown that the throughput per machine (e.g. given in numbers of cells per hour) could be massively increased while only moderately increasing the price per machine. This increase had also the consequence that the personnel cost decreased as the number of personnel per machine stayed about constant.

The producer for wafers, cells and modules is the one who determines the Cost Learning Factor (CLF) given in %-change of the cost/W when the cumulative sold volume is doubled. The quality of the poly-silicon and wafer, the cell architecture determining the efficiency and the chosen module structure are the handles which change the combined PEFs and TLFs for the individual cost parameters into the CLFs. In Fig.3 a scheme is shown how to arrive at module prices starting from the various cost parameters with associated PEFs, including their associated TLFs from which the CLFs can be calculated. This determines the total cost for the value added steps wafer, cell and module add-on. The addition of the various margins result in the ex-works and whole-sale price for modules.

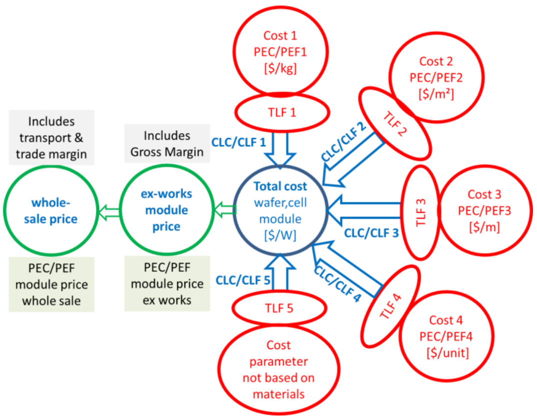

Figure 3: Cost constituents for the total cost number together with the ex-factory and whole sale price.

Table 2 shows in more detail which PEFs have been used in our calculation. For cost parameters, driven mainly by new technology, we have the highest PEF for "equipment invest" driven by the machine building industry. Cost parameters which almost exclusively depend on material cost are grouped into category III while all others are grouped into category II.

Table 2: Price Experience Factors (PEFs) used for the various cost parameters.

Category	**PEF [%]**	**Cost parameter**
(I)	30	Equipment invest for units of wafers, cells and modules [Mio$/1000 units]
(II)	20 20 20 15	Facility invest for wafer, cell and modules [$/GWp]; junction box [$/module] Other consumables for wafer, cell and modules [$/kg]; Virgin poly Si [$/kg]
(III)	10	Sawing wire, glue and saw blades [$/kg]; Ag and Al paste price [$/kg]; Frame, glass, encapsulant and backskin [$/module] Connectors

Table 3 summarizes the most influential TLFs used in our calculation. In particular for the throughput in cell production there was a pronounced increase driven by the machine building industry which we expect to happen also in the future. For the majority of parameters we assume a TLF of 20% while for wafer thickness and kerf loss we see it more limited to 10%. The TLFs for "Other" have been determined from the past development as given by ITRPV [2] and own experience.

Table 3: List of Technology Learning Factors (TLFs) for respective cost parameters

TLF [%]	**Cost parameter**
30	Throughput increase for cell production
20	Crystallization and wafering yield increase [%]; energy consumption decrease [kWh/wafer] also for cell and module]; labor intensity for wafer, cell and module [headcount/line]; decrease of Ag and Al mass per cell [mg/cell] yield loss [%]; cell breakage [%]
10	Wafer thickness and kerf loss decrease [µm]
Other: 8 4 0.8	Throughput increase for wafer and module production Cell efficiency increase Cell to module power ratio increase

3 RESULTS AND DISCUSSION

3.1 Development of parameters driven by Technology Learning

Using the TLFs from Table 3 a selectin of start parameters derived from NREL [1] is shown in Table 4 as function of the cumulated production volume.

Table 4: Development of selected technological parameters as function of cumulative production.

Parameter		**Cumulated production**		
		0.5 TWp (2018)	10 TWp	20 TWp
Wafer edge length	mm	156,75	167	169,51
Diagonal	mm	210	224	227
Wafer thickness	µm	180	115	103
Cell efficiency	%	21,5	25,4	26,4
c2m power ratio	%	98,50	101,9	102,7
Crystallisation Yield	%	90	96,1	96,9
Kerf Loss	µm	85	54	49
Wafering Yield	%	97,5	99,0	99,2
Throughput increase	%	100	139	150
Energy consumption	kWh/wafer	0,86	0,38	0,31
Labor intensity	HC/line	290	112	90
Ag mass	mg/cell	98	43	35
Al mass	mg/cell	1000	439	362
Throughput increase	%	100	305	397
Energy consumption	kWh/cell	0,34	0,15	0,12
Labor intensity	HC/line	65	25	20
Yield Loss	%	1,00	0,39	0,31
Throughput increase	%	100	139	150
Energy consumption	kWh/module	22,5	9,8	8,06
Labor intensity	HC/line	95	37	29
Yield Loss	%	1,00	0,39	0,31

Note that the improvement between 0.5 and 10 TWp is based on >4 doubling periods while the further development to 20 TWp has only 2. As the change is determined by the TLF for each doubling period there is a much higher relative change between the data for 0.5 and 10 TWp compared to 10 and 20TWp.

3.2 Determination of resulting CLFs

Using the above described PEFs and TLFs from Tables 2 and 3 the Cost Learning Factors (CLFs) for the cost parameters used in this study are fitted to the calculated cost vs. time dependencies and summarized in Table 5.

Table 5: Fitted Cost Learning Factors (CLF) from PEFs and TLFs. Average CLFs for wafer, cell and module add-on cost are given in brackets. Overall CLF for total module cost is 22%.

Cost parameter [$/Wp]	**CLF [%]**
Wafer add-on cost	*(23)*
Net polysilicon	28
Sawing wire, glue and saw blades	14
Remaining materials	23
Electricity and Direct labor	31
Depreciation equipment	35
Depreciation facility	25
Cell add-on cost	*(28)*
Other consumables and Electricity	23
Direct labor	31
Equipment and facilities maintenance and paste	31
Depreciation equipment	35
Depreciation facility	25
Yield loss	40
Module add-on cost	*(18)*
Materials	16
Consumables and Electricity	24
Direct labor, Equipment and facilities maintenance	31
Depreciation equipment	35
Depreciation facility	25
Cell breakage	41

The CLFs shown in Table 5 can be approximated by using the following formula:
CLF [%] = 100 – [(1-PEF/100)x(1-TLF/100)x100]

3.3 Cost and price development versus cumulative production volume

Based on a cumulative volume of installed modules at the end of 2018 with ~0,5 TWp the add-on cost for wafer, cell and module is calculated as function of the future cumulated production volume using the CLFs from Table 5. The ex-works and whole-sale price of 10 $ct/Wp is reached at a cumulative volume of ~ 15 and 22 TWp, respectively, as seen in Fig. 4. The same set of parameters used for the increasing production volumes was also taken to calculate backwards to ~200 GWp (see Fig.4). The comparison of the calculated module prices (~0.6 $/Wp) show good correlation with the cost and price numbers of 2014, when this cumulative volume of 200 GWp was reached. Prices in 2014 are reported by pvXchange in the range of ~0.5 €/Wp which is with the exchange rate of 1.2$/€ in that year ~0.6 $ct/Wp.

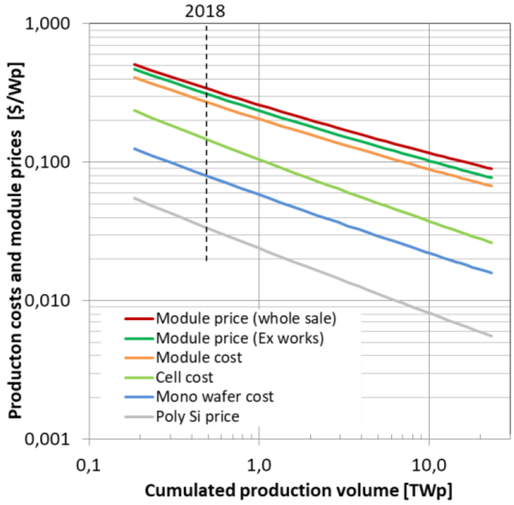

Figure. 4: Calculated costs for poly Si, wafer, cells and modules as well as ex-works and whole sale module prices as function of cumulated production volume.

A sensitivity analysis was performed to check our model's robustness when changing TLFs and PEFs. As seen in Fig.5 when we change all TLFs and PEFs by +20 and -20% at the same time, the whole sale price (for 15% GM) at 10 TWp is only changed -19% and +23%, respectively. In reality it is very unlikely that for our data set all TLFs and PEFs will have to change in the same direction. More realistically some numbers may be higher and some others lower.

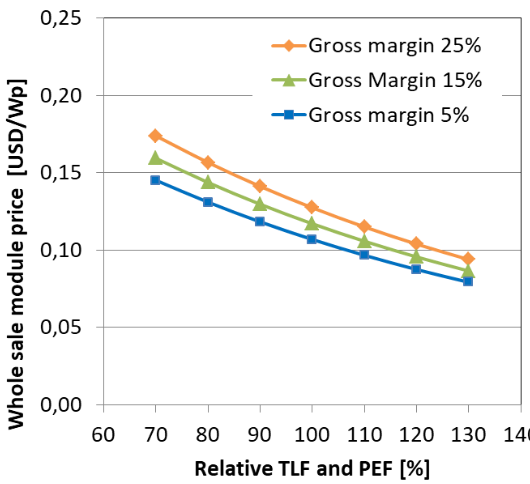

Figure 5: Calculated whole sale module prices at 10 TWp cumulated production volume in dependence of a relative change of all TLF and PEF values simultaneously for three Gross Margins

3.4 Market growth scenarios

For our market growth scenarios in this study we assumed a logistic growth of the annual production volume instead of the commonly used global PV installation. The growth curve used as medium scenario in our study is shown in Fig. 6. The growth curve taken here asymptotically approaches 25 TWp in 2080 and shows an annual production of ~1.5 TWp after ~2060. Note that the cumulative production volume is much bigger than the cumulated installed market as in the latter case the assumed module lifetime of 25 years is taken into account. Two additional growth scenarios were analyzed: a "low one" with only 8 TWp cumulative installations (0.5 TWp/a annual production at saturation) and a "high one" with 75 TWp cumulative installations and a 4.5 TWp/a annual production. For the three growth scenarios we take the (whole-sale) price versus cumulative produced volume from Fig. 4 and combine it with the cumulated production versus time from Fig. 6 and plot the module price versus time as seen in Fig. 7.

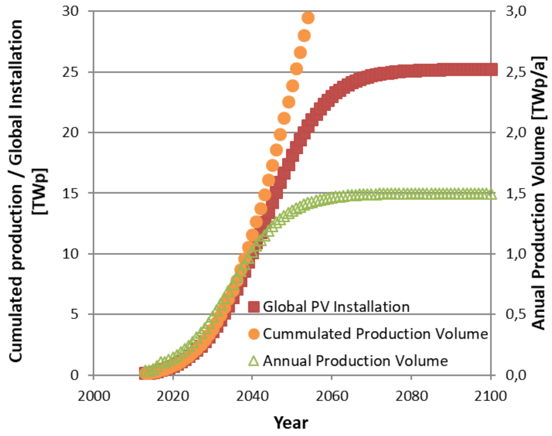

Figure 6: Logistic growth curve (medium case) for annual production volume (25-year module lifetime assumed). Annual Production Volume (year) = 1,500 GWp/a / (1+exp(0.15*(2035-year)))

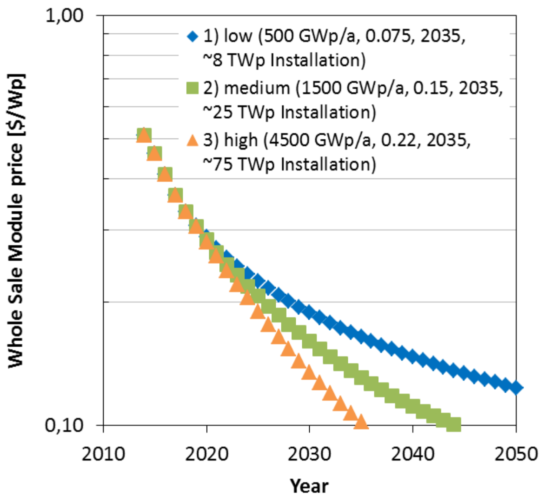

Figure 7: Whole sale module prices for different growth scenarios.

The 10 $ct/W are reached for our medium growth case in ~2044 (not shown but calculated is the ex-works price which arrives at 10 $ct/W in ~2040 at ~10TW cumulative volume). Even for the very ambitious "high growth case" the 10 $ct/W are only reached in ~2035. For the low growth case the necessary volume to reach the 10$ct is not reached within this century.

3.5 Comparison with historical PEC for modules

Fig. 8 shows the history of module prices until 2018 (blue diamonds) together with the calculated PEC (blue line). The modeled whole-sale module prices from Fig. 5 are also shown (yellow area). A calculation for a PEC including these modeled prices until 30 TWp cumulated volume (dashed blue line) shows that the PEF of 23.9% is within uncertainty the same as the PEF until today (23.3%). It will be interesting to see whether this is confirmed with the further development. If so the deviations seen in the past (upwards at ~10 GW and downwards at today times) are caused simply by market conditions: higher prices when Si was short and supply limited and lower ones with oversupply influences which still exist today. As the PV industry will move to a real big one – (1.5-4.5) TWp/a correspond to ~ (150-450) bn $ module turnover – major market distortions should be limited and the market prices should come close to fair calculated ones. This of course implies that the future world will be a free and fair market place.

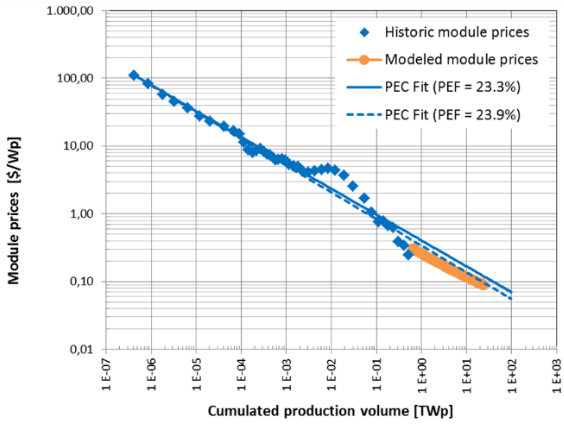

Figure 8: Price Experience Curve for PV modules based on actual prices until today (blue squares). The calculated prices from Fig. 4 for future years are also included (yellow: whole sale prices). The dashed blue line is the calculated PEC including the yellow modeled prices.

4 CELL EFFICIENCY DEVELOPMENT – DRIVER FOR LOWEST LCOE IN THE FUTURE

Until the 1980s, solar cells were manufactured predominantly by using off-spec mono-Si wafers from the semiconductor industry, evaporated contacts and neither a passivation on the back side nor on the front side, where AP-CVD TiO_2 AR-coating was used. This cell architecture limited the efficiency of the solar cells at a level of ~10%. The screen-printing of the contacts with continuously optimized pastes and the introduction of PE-CVD SiN resulted in a significant increase due to passivation on the front side. The limiting efficiency range caused by the BSF was now at around 18%. The PERC and PERL cell structures, demonstrated in laboratories in the 1990s are now introduced in mass-production and reached by today efficiencies around 22%. PERC based bifacial cell concepts will enable "effective" cell and module efficiencies depending on the albedo of the module mounting. The ultimate level for single junction silicon solar cells of about 26% will be reached with back contacted and heterojunction (HIT) solar cells. While all these new technologies are already in industrial production, the next wave for further efficiency increase is already intensively looked at in many laboratories worldwide: dual junction silicon wafer based solar cells with cost efficient thin film additions will be the next step towards 30(+)% solar modules in the market. Like in the satellite business, where 3-junction (and more in the laboratory) devices with III-V compound solar cells are the mainstream products, we may also see in the longer run 3-junction tandem solar cells still based on silicon wafers added with suitable thin film devices for the terrestrial business. When and at which efficiency level (40+/-%) this will happen remains to be seen; but the major driving force to decrease the LCOE for PV electricity will be increased efficiencies as they allow to decrease area related cost (module add-on cost, BOS, installation). In Fig.9 the past and potential further development of cell efficiencies are summarized.

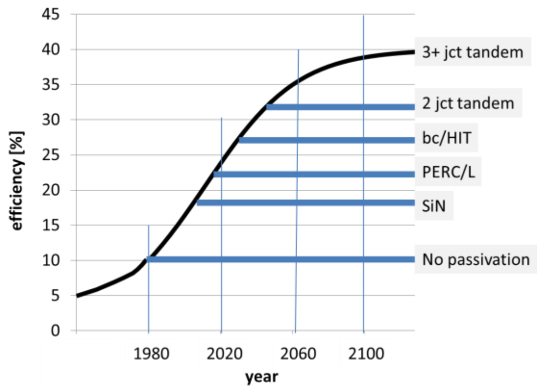

Figure 9: Evolvement of cell architectures for global mainstream production from the past until today and into the future; the horizontal lines indicate the efficiency limits with the given cell technologies.

5 OUTLOOK

Beside the importance for shining light on future module prices it is equally important to highlight the fact that even today with mainstream modules available at ~20 $ct/Wp we are capable to produce electricity with the lowest cost compared to all other technologies, be it fossil, nuclear, wind or any other. This is easily seen with Power Purchasing Agreements (PPAs) open to the public for various technologies: while contracts for PV systems (typically for 20 years) are below 4 $ct/kWh in less sunnier places like Germany (~1kWh/Wp) and below 2$ct/kWh in the sunbelt (Portugal, Chile, middle East at ~>2kWh/Wp), we have more than 20$ct/kWh for a PPA for newly built nuclear power stations (Hinkley Point in Great Britain, including annual adjustment for inflation). This situation as of today together with the prospect of further declining prices for PV as demonstrated in this paper (and other renewable sources) pave the way to quickly change our global energy system – including sector coupling (electricity, heat and mobility) – towards 100% renewable energy sources. The growth of PV towards ~75 TW cumulated installations (see scenario 3 in Fig.7) corresponding to ~90 PWh electricity annually would be highly welcome. The price for this quick change is much less compared to the one which has to be paid for repairing the damage caused by a global temperature rise of >2°C. Only the full decarbonization until 2050 will allow us to keep the global temperature rise below this critical level of 2, better 1.5°C as agreed in the Paris deal

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