SEMI INTERNATIONAL TECHNOLOGY ROADMAP FOR PHOTOVOLTAICS (ITRPV) – CHALLENGES IN C-SI TECHNOLOGY FOR SUPPLIERS AND MANUFACTURERS

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ABSTRACT: The photovoltaic (PV) industry has to provide power generation products that are competitive to conventional and other renewable sources of energy. A technology roadmap helps to identify trends and to define requirements for necessary improvements. Significant parameters along the crystalline Silicon (c-Si) PV value chain are discussed in this work with respect to commercially available solutions. A cost of ownership consideration for c-Si crystallisation, wafering, cell and module manufacturing reveals that the current drop of poly-Si prices to ≈20 \$/kg puts the focus back on technology improvements that increase module output power by a more efficient use of all materials including Silicon. New technologies have to be implemented without significantly increasing cost per piece and despite necessary more complex manufacturing processes. The historic learning rate of about 21% can be maintained over the next years by introducing new double side contacted cell concepts with improved Si-wafers, improved cell front side, improved cell rear side and improved module technologies. This will result by 2020 in modules with an average output power of about 300Wp (60 cell modules). The combination of increased cell and module performance in conjunction with significantly reduced manufacturing costs will secure the long-term competitiveness of PV power generation.
Keywords: PV roadmap, PV learning curve, PV value chain, cost reduction, module performance.

1 INTRODUCTION

The photovoltaic (PV) industry has to provide power generation products that are competitive to conventional and other renewable sources of energy. A technology roadmap helps to identify trends, to define requirements for necessary improvements, and is essential in order to be successful in this competition. The SEMI international technology roadmap for photovoltaics (ITRPV) aims in this spirit to inform suppliers and customers about expected technology trends in the field of crystalline silicon (c-Si) photovoltaic and provides a basis to intensify the dialog on required innovations and standards. The 3rd edition covers the PV value chain from crystallisation, wafering and cell processing downstream to module manufacturing. The ITRPV identifies parameters and discusses emerging trends in the c-Si based PV industry that support the PV learning curve [1].

All topics are discussed along the value chain in three areas: materials, processes, and products. Data are collected from the participating companies and are processed anonymously by SEMI. All companies jointly agree about the results to be reported in the roadmap publication. The maturity of a technology is characterized by colour marking: green (technology is in use), yellow (industrial solution is known but not in mass production), orange (interim solution exists, but to expensive), red (no industrial solution is known).

2 PV LEARNING CURVE AND COST REDUCTION

2.1 Historic learning curve

Cost reduction in the PV production process has to result in price reductions [2]. Fig. 1 shows the learning curve for PV modules displaying the average module sales price (in 2011 US\$/Wp) as a function of module shipments from 1976 until 06/2012 (in MWp) [3]. Module shipments have been ahead the installed capacity for years [4]. Displayed on a log-log scale the plot becomes approximately linear despite a kink at around 100MW and reveals that for every doubling in cumulative PV module shipments the average selling price decreases with a learning rate (LR) of about 21%. A definition of the LR is given in [2]. The first point below 1\$/Wp indicates the average module price end of 2011 at 0.95 \$/Wp with 77.3 GWp shipped. The last data point represents the price in June 2012: 0.83 \$/Wp with 92 GWp shipped, an estimated increase by 15 GWp with respect to the end of 2011.

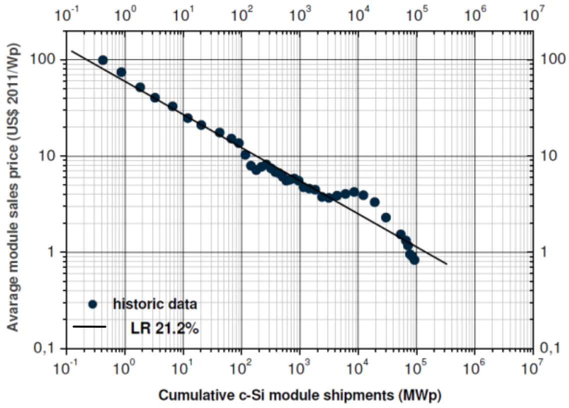

Figure 1: Learning curve of module price as function of the cumulative PV module shipments.

2.2. Cost considerations

Fig. 2 shows the price development for modules from 2010 until June 2012 with separate price trends for poly-Si, multi crystalline (mc) wafers and cells respectively [5]. The price erosion in 2011/2012 was mainly caused by huge over capacities along the PV value chain [6]. The poly-Si price dropped from ≈ 70\$/kg at the end of 2010 to ≈ 20 \$/kg in September 2012 [5]. This data represents the all-in cost level of top tier suppliers [7]. Further cost reduction may only be realized by continues improvements of the classic Siemens process or by introducing new mass production technologies like fluidized bed reactor (FBR) [8]. The share of silicon in the price and therefore in the cost of modules dropped in this time frame from 27% to 15%. A similar reduction is visible for wafering. Cell conversion cost remained at a similar share level while the price share of module conversion more than doubled from 20% to 44% as shown in Fig. 3. The relative cost distribution of all PV value chain elements in the ITRPV [1] reveals that non-Si material costs are the main cost driver.

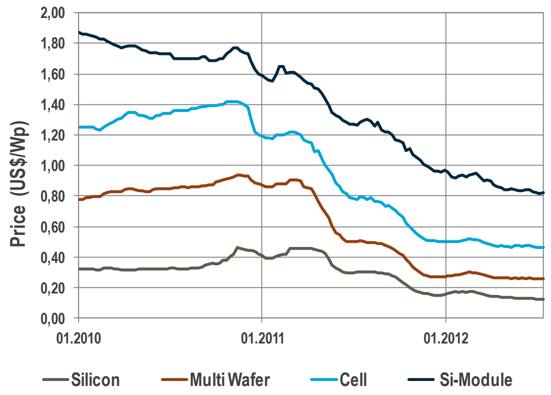

Figure 2: price trends for poly-Si, mc Si wafers, cells, and c-Si module [5]. (Assumption: 42 Wafer/kg poly-Si with ~23,8 g/Wafer and average mc-Si cell power of 4,09 Wp)

In order to continue cost reduction per Wp, focus is put again on the efficient use of Si and of non-Si materials as well as on cell efficiency improvements. Efficiency improvements have to be implemented with lean processes requiring minimum invests in new tool sets in order to avoid significant increase in depreciation costs.

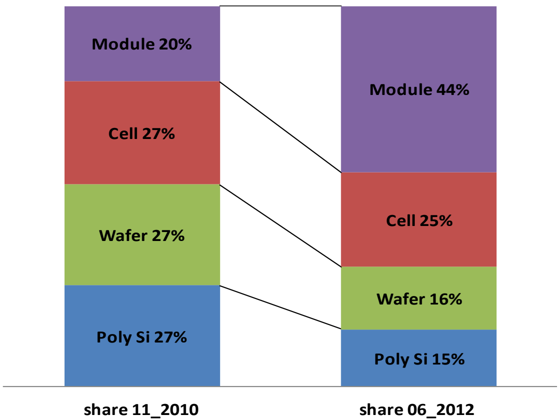

Figure 3: Comparison of the share of module price elements between 11/2010 and 06/2012 (1.86 and 0.82 $/Wp absolute respectively).

3 ITRPV MATERIAL REQUIREMENTS

3.1. Materials – cell processing

The Si wafer causes today about 55% of the cell cost as shown in Figure 2. Reducing the Wafer thickness will result in a more efficient use of silicon. The ITRPV predicts a thickness reduction trend shown in Figure 4.

Wafer thickness reduction has the following technological implications: i) improved wafer sawing technologies + reduced kerf loss and Total Thickness Variation (TTV), ii) innovative handling concepts, iii) new high eta cell concepts suitable for thinner wafers, and iv) new interconnect and encapsulation technologies at module level. Possible upgrades to existing machines to enable new sawing techniques for thin wafers are structured wire techniques for slurry based processes and diamond wire sawing, which enables further cost reductions by eliminating the slurry [9].

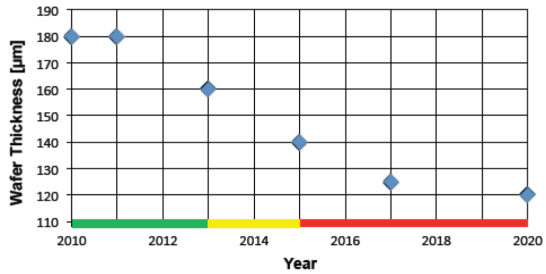

Figure 4: Trend of minimum as-cut wafer thickness processed in mass production of solar cells.

About 50% of cell conversion costs are caused by non Si materials and consumables as discussed in ITRPV Cost of Ownership (CoO) considerations [1]. Silver (Ag), used for front side and bus bar metallization, is the far most expensive material.

Fig. 5 shows the trend of Ag remaining at the cell as published by the ITRPV. An average Ag price of 880$/kg in 06/2012 causes costs of about 4 $cent/cell or 20% of the non-Si price as shown in Fig. 2. Cells cannot be produced at today's cost level with this cost of silver.

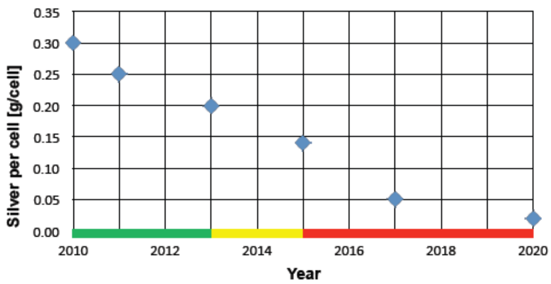

Figure 5: Remaining portion of silver per cell (156 x 156 mm^2).

Therefore the reduction of Ag consumption is mandatory in a first step and its replacement by a more cost effective material around 2015 will be the second step. Copper (Cu) is intended to be the substitute.

3.2. Materials – module processing

Module add-on costs are sensitive to all materials (except solar cells) used in module manufacturing at approximately equal share as discussed in [1]. Improvements in module performance and reductions in material costs are required to reduce the module add-on costs. Approaches for performance increase include the reduction of optical losses e.g. absorption and reflection of front cover glass (see Fig. 6) as well as reduction of interconnector losses. Approaches for material cost reduction include: i) reduction of material volume e.g. material thickness, ii) replacement of expensive materials, and iii) reduction of waste material. To improve the transmission of the front cover glass the use of antireflective (AR) coated or surface structured glass becomes more and more common. The transmission over the relevant range of the solar spectrum and hence the module performance can be increased by up to 2.5% as shown in Fig. 7.

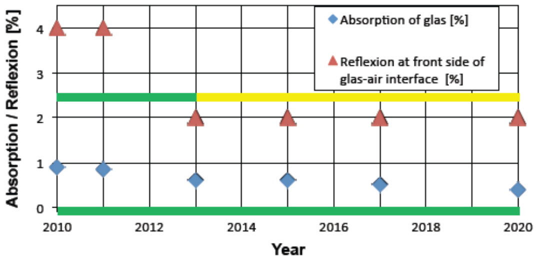

Figure 6: ITRPV requirements for the absorption of glass, as well as reflection of the front side of the module glass-air interface.

Furthermore, the transmission of encapsulant materials in the UV-range of the spectrum can be significantly improved by shifting the UV cut-off to lower wavelengths in order to use the improved blue response of advanced cell structures, e.g. low doped and selective emitters, effectively.

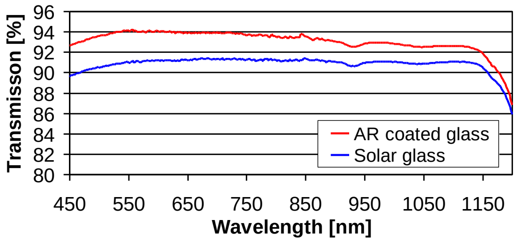

Figure 7: Transmission curves of standard solar glass and AR coated glass [10].

With respect to current cost reduction measures for module materials the front cover glass thickness has been reduced from 4.00 mm to 3.2 mm. However, below 3.0 mm challenges in the glass manufacturing process are expected [1]. Also thickness reductions for the encapsulant material are currently under investigation. A significant cost driver in module manufacturing is the commonly used aluminum frame. Cost reduction possibilities are improved frame designs or the substitution of aluminum by plastic materials. Optimizing the junction box and the module interconnection offers further potential for cost reduction.

4 ITRPV PROCESS CHALLENGES

In order to reduce the manufacturing cost the ITRPV describes several “must haves” for the manufacturing processes along the value chain. A key for progress in reducing production costs per piece is the economy of scale. Increasing tool throughput, tool up times, and yield combined with reduced investment per MWp for new production lines are thereby a matter of cause [1]. Increasing the efficiency and module power has to be granted by technology improvements.

4.1. Process – cell technology

Cell efficiency improvements are directly linked to reductions of the recombination current in the cell bulk (J0bulk), at the front side (J0front), and at the rear side of the cell (J0rear). Fig. 8 shows the ITRPV trend for these parameters. The color coding in Fig. 8 indicates that solutions for this requirements are in production evaluation phase.

Material improvements reducing J0bulk are especially available for mc-Si material. Mono-like Si (i. e. mono-cast Si) and high performance mc-Si (HPM) are available from several wafer manufacturers. Those wafers combine the cost advantage of the Si casting process with significant reduced recombination losses [11 - 13].

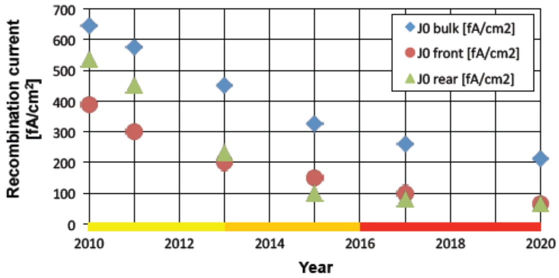

Figure 8: Trend of recombination currents J0bulk, J0front, and J0rear.

Reductions in J0front can be realized by increasing the emitter sheet resistance resulting in an increased blue light response of the solar cell [14]. The ITRPV expects for n-type emitters the values shown in Fig. 9.

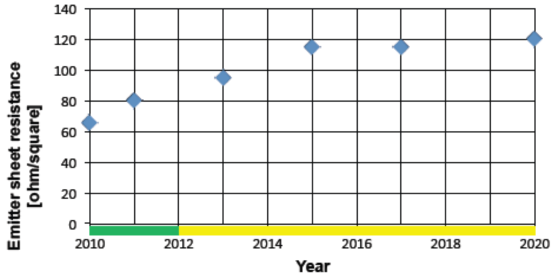

Figure 9: Trend of n-type emitter sheet resistance.

Several commercial solutions with and without additional processing steps have been available for the last years to contact these low doped regions with standard Ag metallization. Selective emitter techniques are available with etch back or laser doping processes, with ion implantation, or with Silicon inks. Solutions for homogenous doped emitters are disposable with techniques that combine fine-line metallization with Ag plating as well as with screen printing techniques using advanced Ag-pastes. Cell manufacturers have therefore the choice to apply the most cost efficient solution for their production environment.

Rear side recombination currents below 200fA/cm² cannot be reached with conventional Al Back Surface Field (BSF). Rear side reflection also needs to be improved in order to increase the near infrared (IR) response of the cell [15]. Techniques for the deposition of dielectric rear side passivation layers available are i) Al_2O_3 atomic layer deposition (ALD), ii) Al_2O_3 plasma enhanced chemical vapor deposition (PECVD) as well as iii) silicon nitride (SiNxOy) PECVD. Process equipment with optimized CoO will be implemented in manufacturing lines for next cell generation with these technologies.

4.2. Processes – module technology

An important performance parameter for module process development is the module-to-cell power ratio, which describes the ratio of module output power in relation to the sum of the power of all cells used in the module. As shown in Fig. 10 the module to cell power ratio is expected to rise according to ITRPV, while the gap between modules from mono- and mc-Si cells is expected to remain.

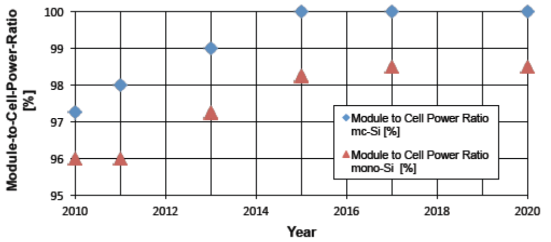

Figure 10: Expected trend of module-to-cell power ratio

Solutions to improve the module to cell power ratio are based either on the reduction of the optical losses or the interconnection losses. Besides the use of AR-coated glass and encapsulants with an improved transmission in the UV-range, structured cell interconnector ribbons and back sheets with optimized reflection behavior are available. The resistive losses in the module can effectively be reduced by increasing the cell interconnector thickness. However, this approach is limited by soldering issues if conventional soldering processes are applied. Alternatively the number of interconnectors per cell can be increased to four or five. If wires are used instead of conventional interconnectors the number of interconnectors can be increased even further to above 10.

5 PRODUCT TRENDS

5.1. Products – crystallization and wafering

The material landscape for c-Si solar cells is expected to change over the next years. Fig. 11 shows the ITRPV

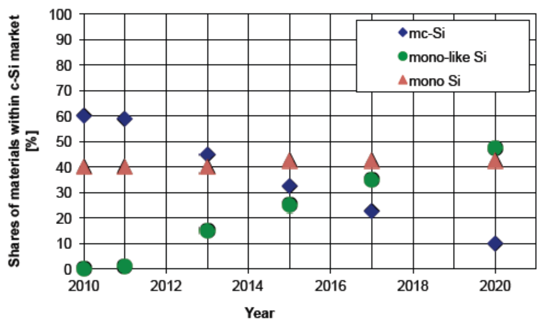

Figure 11: Expected share of mc-Si, mono (Cz)-Si, and mono-like Si material for c-Si Solar cells.

view about the share of c-Si materials used during the next years. Mono-like Si is expected to get an increased share comparable to Cz-Si in the disadvantage of mc-Si.

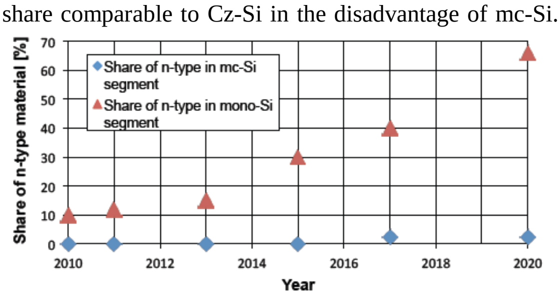

Figure 12: Expected share of n-type material on world production of c-Si solar cells.

A big advantage of this technology is the usage of standard equipment for casted ingots. Increasing the share of Class 1 material is possible e. g. by using Class6 crystallization equipment. A general advantage of casting technology is the lower light induced degradation (LID) compared to Boron doped p-type Cz-Si due to lower Oxygen concentrations [15]. Nevertheless, mono-like Si as emerging material is not yet in a mature production phase [12]. The need for high efficiency cells will increase the share of n-type mono-Si wafers from about 10% today to above 60% in 2020 as shown in Fig. 12.

5.2. Products – cell and module

Cell efficiency of p-type Si solar cells will increase over the next years due to the measures described in 4.1.

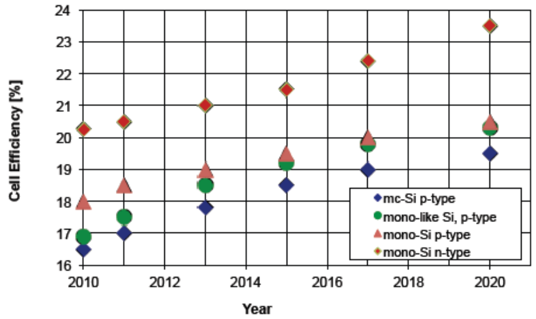

Figure 13: Stabilized efficiency trend of mc-Si, mono-like Si and mono-Si cells in mass production.

Fig. 13 shows the stabilized cell efficiencies of double-sided contact cells in state-of the art mass production lines as predicted by the ITRPV. N-type cells show significantly higher efficiencies.

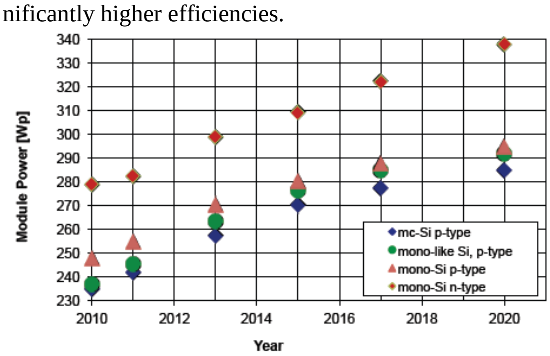

Figure 14: Trend of mc-Si, mono like and mono-Si module power with cells corresponding to Fig. 13.

The corresponding development of module power for modules with 60 cells (156x156cm²) is shown in Fig. 14. A transition from semi square to full-square mono material starting in 2013 and the trend of module-to-cell power ratio as shown in Fig. 10 are considered in the calculation of this chart. A switch to rear side contacted cells

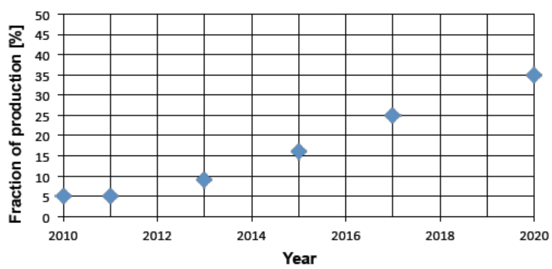

Figure 15: Share of modules using rear contact cells as fraction of the worldwide production.

seems not to take place immediately because of the high efficiency potential of current cell concepts and due to the need for advanced, cost efficient module assembly for such cell concepts. Fig. 15 shows the expected share of modules using rear contact cells as fraction of worldwide c-Si module production.

6 CONCLUSIONS

Taking into account all improvements discussed above the presented roadmap can give an outlook about the future of the PV learning curve despite the current distortion of prices due to an overcapacity situation. Tab. 1 shows assumptions for three different scenarios and Fig. 16 shows the resulting learning curves. Shipped volumes are estimated with an annual growth between 30 and 50 GWp, based on the predictions in [16].

	06/12	**12/13**	**12/15**	**12/17**	**12/20**
Cum. volume (GW)	**92**	**110**	**210**	**310**	**460**
Avg. Wp increase	-	7.5%	5%	3%	10%
Scenario 1 ($/Wp)	**0.83**	**0.76**	**0.73**	**0.70**	**0.63**
Increased complexity	-	2.5%	0%	-2%	0%
Scenario 2 ($/Wp)	**0,83**	**0.86**	**0.85**	**0.87**	**0.87**
Cost reduction	-	10%	15%	10%	10%
Scenario 3 ($/Wp)	**0,83**	**0.69**	**0.55**	**0.48**	**0.38**

Table 1: Comparison of different cost scenarios based on the ITRPV predictions.

Scenario 1 considers a reduction of the avg. module price corresponding to the cell-efficiency-driven average increase of module power (see Fig. 14) – "Avg. Wp increase". Other costs and the equivalent prices are assumed to remain stable. The higher Wp increase between 2017 and 2020 is due to the switch to n-type cell concepts (see Fig. 12). Scenario 2 assumes that Wp increase will go along with a cost adder for complexity that almost burns up the cell efficiency benefits – "Increased complexity". Scenario 3 assumes on top of scenario 1 price reductions due to continuous cost improvements – "Cost reduction". The introduction of Cu-metallization around

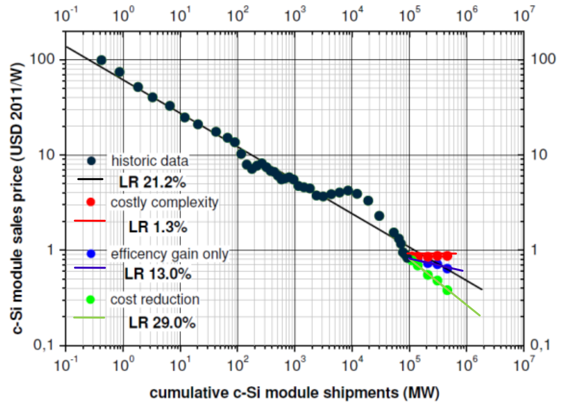

Figure 16: Learning curve of module price as function of the cumulative PV module shipments with historic data and scenarios shown in Tab.1.

2015 is assumed to reduce the material cost more significant than over the other periods indicated (see 3.1.).

Scenario 1 describes a return to the price trend predetermined by the historic data and a continuation with the LR of about 21% as described in Fig.1. The pure efficiency improvement results in a LR of about 13%. This is much higher than the historic efficiency increase LR of 3% found in [2]. Scenario 2 is a pretty unlikely case because it would repulse c-Si PV competitiveness. In contrast, it seems possible that there could be an accelerated learning rate of over 25%. This will be enabled by combination of efficiency improvement and continuous reduction of cost per piece as described by the ITRPV over the coming years. The described c-Si modules price reduction will reduce the c-Si based PV system cost and furthermore it will influence the LR [2] and the cost structure of those PV systems [17]. So the PV Industry will continue its "learning" and will be able to provide power generation products that are competitive to conventional and other renewable sources of energy.

7 ACKNOWLEDGEMENTS

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