INFLUENCE OF FEEDSTOCK ON C-SI MODULE COST

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ABSTRACT: This paper analyzes the impact of solar silicon feedstock alternatives on the wafer-based crystalline silicon photovoltaic (PV) module cost. As the impact of feedstock affects the whole manufacturing chain of a PV technology, its technological steps need to be defined. This is done with a number of roadmap scenarios that have been defined in the *CrystalClear* project. Advanced Basepower is defined as the reference technology, developed in a high throughput plant (300-500 MWp/a) which is built now with state-of-the-art technology, and ready to operate in 2011. Six more advanced technologies, two multicrystalline, two monocrystalline, one ribbon technology, and one wafer-equivalent technology are also defined. Regarding Advanced Basepower technology, the cost advantage of using low-cost feedstock (10€/kg) instead of high-cost feedstock (30€/kg) is lost if the cell efficiency is reduced, due to quality degradation, by an absolute 1.7%.

Keywords: Cost assessment, Crystalline silicon, Silicon feedstock

1 INTRODUCTION

The photovoltaic community is working on solar grade silicon (SoG-Si) feedstock alternatives, aiming at a reduction of the energy consumption in the production processes and of the cost [1-3]. It is important to analyze the entire manufacturing chain, from feedstock to the module, considering the fact that the influence of SoG-Si alternatives on the module cost is related not only to the feedstock cost, but also to the efficiency of its utilisation and the quality of the material.

The assessment described in this work has been carried out within *CrystalClear* (CC)[4], a European Integrated Project carried out in the 6th Framework Programme which ended in June 2009. CrystalClear gathered expertise from 9 industries, 3 universities and 4 research centres, aiming at "research, development, and integration of innovative manufacturing technologies that allow solar modules to be produced at a cost of 1€ per watt-peak in next generation plants".

CrystalClear research has been guided by technology roadmapping and cost analysis. Since the initial CC roadmap scenarios were based on 2005 technology and 30-50 MWp/a plants [5], a thorough revision of these scenarios was recently carried out. The updated scenarios, and their cost breakdown, correspond to high throughput plants (300-500 MWp/a) producing in 2011 or beyond, and they are presented in section 2.

Then, the impact of different silicon materials is analyzed considering effects of material cost and quality. The assessment has been carried out for the updated scenarios based on mono and multicrystalline technologies.

Note that we refer to cost and not to price. This makes the analysis independent of external and temporary factors influencing PV prices.It should also be noted that the impact of Si feedstock on the generation cost of solar electricity is determined not only by the influence on the module cost, but also on other aspects such as Balance-of-System (BoS), performance ratio, global solar radiation, etc. Therefore expensive but more efficient modules may lead to lower generation costs.

	Advanced Basepower	Multistar	MultistaR	Superslice	SuperslicE	Ribbon-champ	Epi.c
Feedstock type	Solar Grade	Solar Grade	Solar Grade	Semicon. Grade	Semicon. Grade	Solar Grade	Deposited
Silicon	p-type mc-Si	p-type mc-Si	p-type mc-Si	p-type Cz	p-type Cz	p-type ribbon	p-type umg-Si
Wafer thickness	180 μm	120 μm	120 μm	120 μm	120 μm	120 μm	120 μm (substrate) + 20 μm (layer)
Cell concept	Front & Rear	Front & Rear	MWT	Front & Rear	EWT	MWT	Front & Rear
Module assembly	soldered intercon-nects	low stress interconnects	integrated conductive pattern & low stress intercon-nection	low stress interconnects	integrated conductive pattern & low stress intercon-nection	integrated conductive pattern & low stress intercon-nection	low stress interconnects
Encaps. cell efficiency	15.8%	16.7 %	17.0 %	18.7 %	18.5 %	16.0 %	15.8 %
Si utilisation [g/Wp]	6.5	4.5	4.4	3.9	4.0	2.1	-

Table 1: Technology description for the updated CC roadmap scenarios.

€/Wp	Advanced Basepower	Multistar	MultistaR	Superslice	SuperslicE	Ribbonchamp	Epi.C
Feedstock	0.10	0.07	0.07	0.10	0.10	0.04	0.02+0.08
Ingot growth	0.07	0.05	0.05	0.10	0.10	-	0.04
Wafering	0.13	0.09	0.09	0.08	0.08	0.09	0.09
Cell process	0.30	0.33	0.34	0.33	0.37	0.33	0.26
Module	0.54	0.47	0.51	0.42	0.48	0.50	0.49
Total €/Wp	**1.15**	**1.00**	**1.06**	**1.03**	**1.13**	**0.96**	**0.98**
g/W	*6.5*	*4.5*	*4.4*	*3.9*	*4.0*	*2.1*	-

Table 2: Cost breakdown of the updated CC scenarios. Feedstock includes the epitaxial growth for the Epi.C scenario.

2 UPDATE OF COST MODELING OF THE CC ROADMAP SCENARIOS

In the deployment of the CC project, there has been a continuous update of the cost figures, introducing some new assumptions, refining the cost breakdown of particular steps, or benchmarking with other cost studies disseminated within the PV community.

Costs are related to those of a factory producing in 2011 and beyond, with production sizes in the range of 300-500 MWp/a.

Advanced Basepower corresponds to the standard technology of today's plants: relatively thick wafer, front-and-rear contacted solar cell with full Al BSF, conventional encapsulation.

It is important to note that current technology evolution is by no means spontaneous; on the contrary, it is the result of many efforts to solve a number of technological problems, to which CrystalClear has contributed to a great extent: the processing of thinner wafers, the optimisation of screenprinted metallisation schemes or the improvements in cell interconnection, to mention some of them [6].

Six other technology scenarios have also been considered in CC: two advanced multicrystalline technologies (Multistar, MultistaR), two advanced monocrystalling technologies (Superslice, SuperslicE), one ribbon technology (Ribbonchamp) and one wafer-equivalent technology (Epi.C). The technology description for the updated CC roadmap scenarios is presented in Table 1.

3 COST RESULTS

Cost figures for Advanced Basepower are calculated according to the following procedure:

-Taking the cost results for Basepower 2005, i.e., the technology defined averaging data from the CC industrial partners according to their production levels by the end of 2005 (30-50 MWp/a) [5].

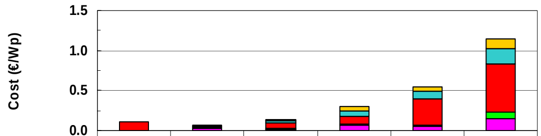
-Implementing the changes in the technology to update it (180 µm thick wafer instead of 220 µm, 15.8% encapsulated cell efficiency instead of 14.5%, etc.).

-Scaling those numbers according to the “large scale estimates” discussed in [5], following the line of reasoning of other works [7].

Advanced Basepower cost is 1.15 €/Wp and silicon utilisation 6.5 g/Wp, distributed as shown in the Figure 1.

The cost modeling of each CC updated scenario has been performed by describing it in terms of the impact of technological improvements, with respect to the Advanced Basepower technology, in the cost structure. The cost of technological steps not included in Advanced Basepower technology, such as laser drilling, have been estimated extrapolating data from pilot plant production to industrial production. The cost breakdown of the updated CC scenarios is shown in Table 2.

A range should be incorporated in our cost results to account for uncertainties in our estimates. Taken that into account, a more aggressive scenario brings down costs to 0.83-1.07 €/Wp, depending on the roadmap scenario, showing the potential for crystalline silicon based PV technology.



	Feedstock	Ingot Growth	Wafering	Cell processing	Module Assembly	Total
Equipment		0.01	0.01	0.06	0.04	0.13
Labour		0.01	0.02	0.06	0.10	0.19
Material	0.10	0.02	0.06	0.10	0.33	0.61
Yield losses		0.01	0.02	0.02	0.02	0.08
Fixed		0.02	0.01	0.06	0.05	0.15
Total	0.10	0.07	0.13	0.30	0.54	1.15

Figure 1: Cost breakdown of Advanced Basepower.

4 IMPACT OF FEEDSTOCK COST, QUALITY, AND EFFICIENCY OF UTILIZATION

The cost modeling allows to analyze the impact of the use of new (solar grade) silicon feedstock materials on the manufacturing cost of wafer-based crystalline silicon photovoltaic modules considering effects of material cost, efficiency of utilization, and quality.

The impact of new silicon feedstock materials on the module cost is quantified by describing the new materials in terms of cost (€/kg) and quality (cell efficiency). Silicon feedstock cost varies for different production processes, from Near Semiconductor grade (Near SeG-Si, around 30 €/kg) to Upgraded Metallurgical Grade (UMG-Si, around 10 €/kg) [8] and the impact of this variation is quantified. What the PV community understands as quality of silicon is not easy to state, since it is not only related to the amount of impurities within the material [9] but also to the chemical compounds and the distribution of them within the crystal after crystallization process [10, 11]. Thus, the cell efficiency has been considered in this assessment to represent the silicon quality.

The efficiency of utilization can be analyzed considering the yield of every technological step, from silicon feedstock production to module assembly, the material loss in ingot growing and the wafer thickness and kerf loss.

This work is focused on the impact of feedstock cost and cell efficiency for Advanced Basepower technology. A more comprehensive analysis can be consulted elsewhere [12]. Considering a certain technology, alternative Si feedstock cost and cell efficiency will impact on its module total cost (in terms of €/Wp) according to the following expression:

$$C_{total} = A \cdot \left(€ / kg\right) \cdot \eta_{rel}^{-1} + B \cdot \eta_{rel}^{-1} \qquad (1)$$

Where η_{rel} stands for relative efficiency (ratio of the cell efficiency with a new material and the cell efficiency of considered technology). A and B are constants, calculated as follows:

$$A = g / Wp \cdot 10^{-3} \qquad (2)$$

$$B = C_i + C_w + C_c + C_m$$

Being C_j the fully-integrated processing cost of ingot growth, wafering, cell processing and module assembly respectively (in €/Wp). Analyzing Advanced Basepower technology, where A equals to $6.5*10^{-3}$ and B equals to 1.02, and considering the cell efficiency and the feedstock cost as independent variables, it can be seen from Eq. (1) that if the cell efficiency decreases by relative 10% (from absolute15.8% to 14.2%) the module cost increases by 11%. Likewise, if the feedstock cost were 0 €/kg, the module cost would decrease by 11%.

Nevertheless, an alternative feedstock might change the cell efficiency. Thus, analysis of the impact on module cost regarding a combination of variables is needed. The iso-cost curve for feedstock cost *vs* relative cell efficiency is presented in Figure 2, showing the combination of feedstock cost and relative cell efficiency values that yield a constant total module cost.

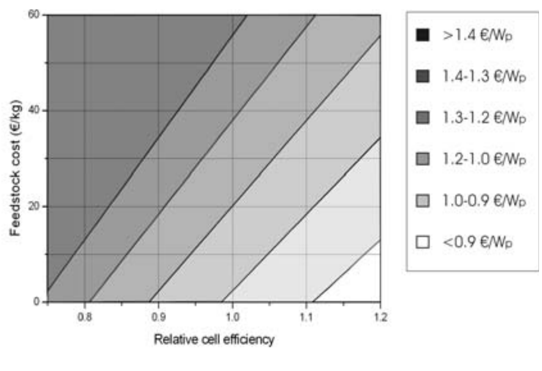


Figure 2: Iso-cost curve for Advanced Basepower technology regarding cell efficiency and feedstock cost.

As it can be seen in Figure 2, coming from a situation of 20 €/kg and relative efficiency 1, if the feedstock cost increases to 30 €/kg (50% up), increasing efficiency by a relative 6% (from 15.8% to 16.7%) neutralizes the cost increase, and the module cost remains constant. Likewise, if the efficiency decreases a relative 10% (from 15.8% to 14.2%), the feedstock cost should decrease to 2 €/kg (90% down) to keep the module cost constant.

The feedstock production yield must also be taken into account, since when the effect of lowering the feedstock cost is combined with lowering the feedstock production yield, the result can be an increase in the module cost. Generally speaking, if the feedstock yield reduction is higher than the feedstock cost reduction, the module cost increases. Thus, coming from a situation with 20€/kg of feedstock cost, if it decreases to 10€/kg (50% down) the feedstock yield could be relaxed a relative 50% yielding constant module cost.

5 CONCLUSIONS

Cost model in CC has been updated. The technologies now take into account the levels of production expected for next generation factories, which are in the range of 300-500 MWp/a. The cost of the different technologies is in the 1 €/Wp range, as compared to the typical c-Si PV cost in 2006 (in the range of 2 €/Wp), a cost reduction that is a combination of large scale effects and technology improvements.

Advanced Basepower cost is 1.15 €/Wp. It already incorporates technological developments which have been addressed in CC (such as ingot weight increase, wafer thickness reduction, cell processing optimization).

Regarding the cost modeling presented for Advanced Basepower technology, if the cell efficiency decreases by relative 10% the module cost increases by 11% and if the feedstock cost were 0 €/kg, the module cost would also decrease by 11%. The variation of feedstock cost, from Near SeG-Si to UMG-Si, for Advanced Basepower technology changes the cost of c-Si modules by 13%, if the efficiency can be maintained. However, the cost advantange of low-cost feedstock alternative is lost if the cell efficiency is reduced, due to quality degradation, by an absolute 1.7%.

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