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CAST-MONO SILICON WAFERS FOR A SUSTAINABLE PV MARKET GROWTH

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ABSTRACT: The economic and ecologic sustainability of using cast-mono silicon wafers in comparison to Czochralski silicon wafers for the production of PERC solar cells and their subsequent application in a photovoltaic system has been studied within a cost and carbon footprint analysis for the whole value chain. The cast-mono growth technology has been modelled based on a G8 industrial furnace system compared to a Cz-growth systems with 36” crucible size and recharging process. The carbon footprint and cost per wafer were evaluated for M6 and M12 wafer sizes. A PV system with cast-mono wafers shows a 9 % reduced carbon footprint for a use phase of 25 years with the assumed properties. On wafer level the cost profiles for both technologies show a cross over point at around 5-7 $ct per kilowatt hour of electricity with lower cost of cast-mono wafers in case of higher electricity prices. An increase of brick yield from actual approx. 53 % to over 60 % would result in a wafer cost decrease of up to 0,4 $ct per Watt peak thus enabling a competitiveness for the future wafer market.

Keywords: Crystallization, Cast-mono, Life Cycle Assessment, Sustainability, CO_2 Emission, Photovoltaic

1 INTRODUCTION

The silicon wafer market for the production of solar cells has strongly changed over the last years due to the successful evolvement of the Passivated Emitter and Rear Contact (PERC) solar cell structure into the mainstream solar cell product. With ever increasing cell efficiencies significantly above 20% the demand shifted from low cost multicrystalline silicon (mc-Si) wafers towards high quality monocrystalline silicon wafers (mono-Si). Thus, the market share for Si wafers for mc-Si has shrunk from above 60% in 2017 to about 32% in 2019 and is expected to fall below 10% in the next five years [1].

In addition, the total PV market is expected to grow from about 740 GW total installed capacity worldwide in 2020 to about 2840 GW in 2030 [2]. For this growth, the market share of mono-Si wafer based PV is assumed to stay at around 95% thus giving rise to a demand for mono-Si wafers equivalent to approx. 2000 GW of PV capacity over the next 10 years.

Improvements for the crystal growth technology based on the Czochralski method have already been successfully implemented such as an increase of growth velocity by using an active cooling of the grown crystal in close distance to the Si melt surface and recharging of the crucible and thus pulling of multiple ingots from one crucible as the so called Recharged Czochralski growth process (RCz). This has led to significantly increased production throughput and thus cost reduction.

The advancements for the directional solidification methods known also as “block cast” methods focused on the growth of ingots with over 90% of monocrystalline ingot volume by using a structured setup of monocrystalline plates as seed material in combination with an adapted thermal process. The wafer material from this type of processes is known as “cast-mono”, “quasi-mono” or “mono-like” silicon (further abbreviated as “CM-Si”) [3–5].

The wafer sizes had been constant with a standard size of 156 mm side length for quite some time until new wafer formats appeared on the market [1]. The format M6 with side length of 166 mm has been introduced in 2018 closely followed by the introduction of the M12 wafer format with 210 mm side length [5].

The enormous PV market growth expected for the next decade will consume high amounts of raw materials and energy in the production process. Therefore, it is preferable to achieve this growth with as low as possible environmental impacts and energy consumption in order to reach a fast decarbonisation of the energy sector in accordance to the Paris Climate Agreement [6].

2 APPROACH OF STUDY

In this study we assess the future potential of wafer production by the cast-mono technology for a sustainable PV market growth in the next decade in comparison to the actual dominant RCz technology. After a thorough study of the parameters and assumptions for each technological process step the individual wafer cost and the ecological impact for the production of electricity are given for M6 and M12 wafer formats following both the RCz-Si and the CM-Si technology routes. The expected costs of the CM-Si wafers are analysed with respect to the impact of electricity price and brick yield as crucial parameters.

Wafers of both routes are assumed to be processed into PERC solar cells and modules with a half or third cut cell approach. The calculation of the Greenhouse Warming Potential (GWP) given in kilograms of CO_2 equivalent emissions per produced kilowatt hour of PV electricity, delivered to the grid, enables the comparison of the potential impacts of the investigated technology routes.

Finally, an assessment of the technological prospects of the cast-mono technology based on the results is given to point out the opportunities of this route.

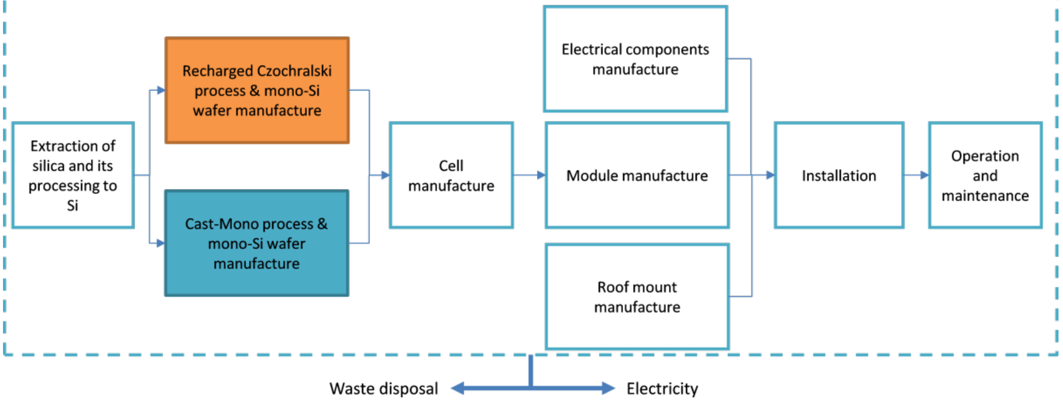

Figure 1: Scope of cost and carbon footprint analysis framework for the RCz-Si and CM-Si routes starting from Si raw material via crystallization, wafering, solar cell and module production until the final PV system is installed and under operation for 25 years.

2.1 Framework of cost and carbon footprint analysis

The framework of the analysis is composed of separately modelled production steps as distinct subunits of the whole value chain as depicted in Figure 1. It starts with the extraction of silica and the production of high quality poly-silicon feedstock of assumed 9N+ quality for the subsequent crystal growth processes as a first subunit. As the next step the crystal growth processes in combination with subsequent preparing of bricks and final wafering by diamant wire sawing have been analyzed.

In order to compare the cast-mono growth technology with actual recharged Czochralski growth technology, both routes have been modelled bottom-up including actual industrial data as well as assumptions for production equipment, growth parameters and production related data such as cycle time, recycling and specific equipment cost. The accounting for all investigated properties and the calculation of the related material flows and costs up to the wafer level have been realized by use of the S-Cost tool developed at Fraunhofer ISE [7]. Thus, the effect of specific input parameters on wafer cost can be calculated in form of “cost of goods sold” COGS per single wafer. As wafer formats the M6 format defined as quadratic wafer with 166 mm side length as well as the M12 format with 210 mm side length have been investigated. All wafers were assumed to have a thickness of 170 µm.

The following subunits of the analysis framework such as the cell processing, module production, system installation and use phase including operation and maintenance have been modeled in an analog way. For all steps, the usable output of the preceding subunit is used as input for the following subunit including modeling of recycling loops. The principal data for these subunits and the modeling of the various steps rely on results from previous work and external references[1, 7, 8].

All data from the examined process steps and the overall bill of materials are used as input for a Life Cycle Assessment (LCA) following the evaluation rules given by the IEA Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity [9] and the general recommendations in ISO Standards 14040 and 14044. The calculation of the Global Warming Potential in terms of CO_2 equivalents was performed with IPCC 2013 GWP 100a using Umberto LCA+ software with data from Ecoinvent 3.6 and Fraunhofer ISE. A detailed description of the methodology and the precise analysis for a complete study for Czochralski based silicon wafers will be published in a separate paper.

2.2 Model assumptions for cast-mono process

The cast-mono technology data used in this work is based both on experimental data for the growth of CM-Si via the SMART seeding approach [5] and industry information on equipment and process parameters. In order to study the potential of CM-Si technology for the next decade, data from state of the art G8 furnace concepts (SCU 1500, ALD Vacuum Technologies) was used for the analysis. For the material quality distribution, data from growth experiments utilizing laboratory processes with G2 sized ingots equivalent to 75 kg of Si feedstock and G6 sized industrial processes with 650 kg of Si feedstock and SMART seeding concept were evaluated. Based on these results main assumptions for material quality distribution and thus potential yield were derived for a G8 system with crucible sizes adapted to an optimal ingot side length for either M6 or M12 wafer production. It has to be pointed out that the number of experiments was limited and thus the experimental data not validated on a statistical base. An overall electricity consumption of 6,8 kWh/kg of crystallized silicon is assumed [8].

Further input values for the CM-Si process model are shown in Table I.

Table I: Input Data for CM-Si growth process.

Wafer product		M6	M12
Feedstock charge	kg	1500	1500
Seed height	mm	20	20
Ingot side length	mm	1420	1350
Brick side length	mm	166	210
Number of bricks		64	36
Growth velocity	mm/h	12	12

A general width of 30 mm for ingot side cuts and 1 mm grinding loss per brick was accounted for. After cropping of top and bottom of the brick including the seed, a maximum usable brick height of 85 % of total ingot height was calculated for all bricks. The brick yield defined as the brick mass meeting the required material quality after squaring and polishing strongly depends on the quality assumptions of the investigated growth process and the material requirements of the succeeding cell process. Since no experimental data of a G8 growth experiment could be used, a material quality distribution was assumed for this process based on lifetime and solar cell studies of M2 wafers from an experimental G6 ingot.

In order to model a more realistic yield for CM-Si material meeting the quality requirements for further cell production, a usability of 70 % of the outer and 80% of the inner brick material was calculated resulting in overall brick yield values of 53,1 % for the M6 and 54,1 % for the M12 process.

2.3 Model assumptions for RCz process

For the RCz-Si growth model the input data based on an industrial Cz furnace including a recharging unit, a 36” crucible and a receiving chamber of more than 4 m height and an average of 4,5 pulls of 4 m long ingots per crucible. An overall energy consumption of 30 kWh/kg of crystallized silicon has been assumed [8]. Further input values for the RCz-Si process model are shown in Table II.

Table II: Input Data for RCz-Si growth process.

Wafer product		M6	M12
Feedstock charge	kg	360	650
Ingot height	m	4,0	4,1
Ingot diameter	mm	226	300
Pulling speed	mm/min	1,7	1,2

A maximum ingot usability of 85 % after cutting of seed, shoulder and endcone is assumed for all ingots without accounting for any remelting processes. The usable brick mass considering the geometric constraints of a square wafer out of a round ingot was thus calculated to 58,8 % for the M6 and 54,7 % for the M12 format.

2.4 Model assumptions for Cell, Module and PV System

As for the following steps input data were mostly the same for both CM-Si and RCz-Si wafers with an exception for the cell efficiency and subsequently the module power. A PERC solar cell process was assumed to have an average efficiency of 22,3 % for the CM-Si in comparison to 22,5 % for the RCz-Si material. All cells were cut prior to module manufacturing into half cells for the M6 format and third cells for M12 format. The modules were modeled as glass-back sheet modules with 138 half-cells for the M6 size and 130 third-cells for M12. Thus the average module power for RCz-Si material was calculated to 421 W_p and 425 W_p for M6 and M12 wafer size, respectively. For the CM-Si this translated into 419 W_p and 421 W_p for analog modules.

The modules are combined with the necessary electronic and roof mounting equipment to form a residential rooftop PV system at Freiburg i.Br., Germany, with a rated power of 15 kW_p, a performance ratio of 90,6 %, 25 years of use phase and a global horizontal irradiation of 1173 kWh/m^2 year. A detailed description of the cell, module and system modeling will be published in a future work.

3 RESULTS

3.1 Cost Analysis - Electricity Price Sensitivity

The calculation of the wafer cost according to the aforementioned framework has been performed in order to enable an analysis of the CM-Si and RCz-Si technology cost structure and a comparison to the actual market conditions. The calculated wafer cost for both technology routes and formats is shown in Figure 2.

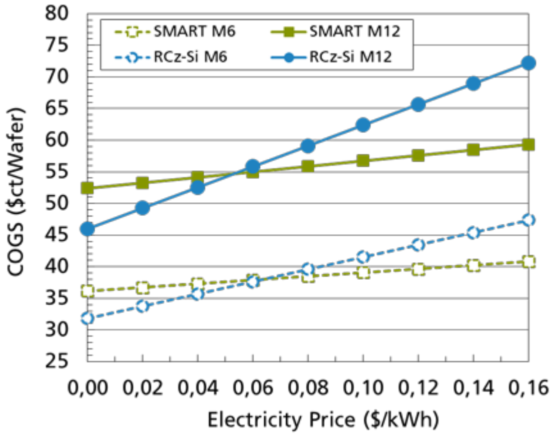

Figure 2: Cost per wafer for RCz-Si and SMART CM-Si wafers of M6 and M12 format in dependence on the electricity price.

The wafer costs are linearly depending on the electricity price. For the assumption of an average price range between 0,05-0,07 $/kWh, the model predicts costs between 0,36-0,38 $ per M6 RCz-Si wafer. This is in good accordance with 0,40 $ for a 175 µm thick M6 wafer as observed by EnergyTrend for September 2020 [10].

The curves of CM-Si and RCz-Si are crossing each other at an electricity price of about 0,06 $/kWh with different slopes due to the differing energy intensities of the crystallization process. That means that the production cost per wafer is lower for RCz-Si wafers when being able to purchase electricity for less than 0,06 $/kWh. For higher electricity prices, the CM-Si would have a significant cost advantage.

The cost per wafer for M12 format is a factor of about 1,5 higher than for M6 format in comparison to a gain in wafer area of a factor of 1,6 translating in a relative cost reduction per wafer area. This relative cost reduction can be seen as well in the wafer cost per W_p as shown in Figure 3. By increasing the format from M6 to M12 for both technologies, a cost reduction of almost 10 % is calculated.

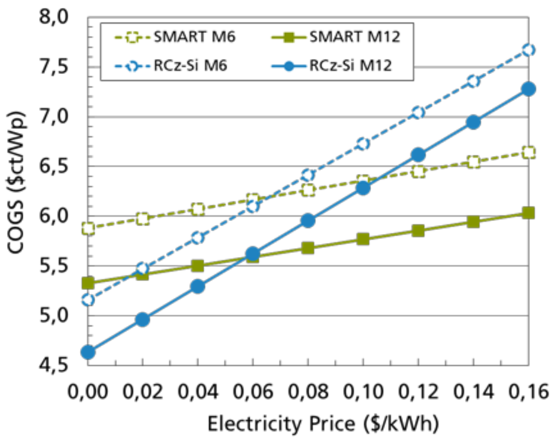

Figure 3: Cost per Watt peak for RCz-Si and SMART CM-Si wafers of M6 and M12 format in dependence on the electricity price.

3.2 Cost Analysis – Brick Yield Sensitivity

A crucial parameter for the CM-Si technology is the brick yield as described in section 2.2. In the model an average brick yield of 53% for M6 and 54 % for M12 has been considered. The cost dependence of the CM-Si wafers on this brick yield is depicted in Figure 4 with the assumed actual range shown as a red bar.

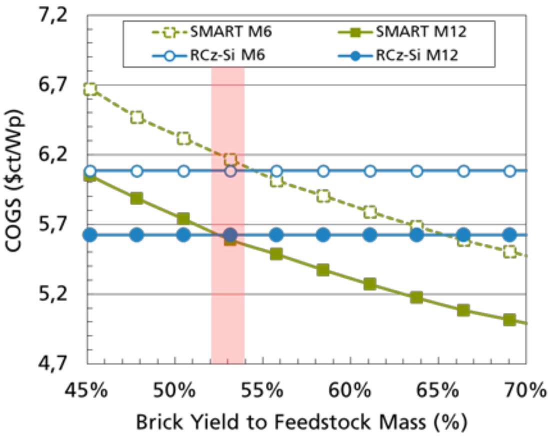

Figure 4: Cost per Watt peak for SMART CM-Si wafers of M6 and M12 format in dependence on the brick yield with an assumed electricity price of 0,06 $/kWh.

By increasing the yield to e.g. more than 60 %, a significant cost reduction and thus cost advantage in comparison to RCz-Si could be reached on a cost per W_p basis.

3.3 Carbon footprint

The carbon footprint, estimated as Global Warming Potential including the CO_2 equivalent emissions which are associated to the production of poly-silicon, wafer, cells, modules, balance of system components and the assembly and use of a PV system is shown in Figure 5.

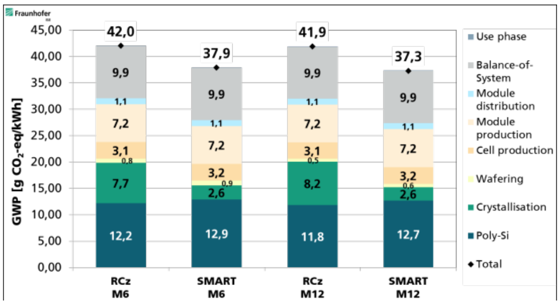

Figure 5: Global warming potential GWP of a kilowatt hour electricity produced by the calculated PV system after 25 years of use including RCz-Si and CM-Si based solar cells

The results show that the values for the M6 and M12 variants of the same crystal growth technology vary only to a small amount. The GWP for the RCz-Si wafer based technology is about 42 g CO_{2eq}/kWh for the M6 size and the M12 size. In contrast the resulting GWP values for the CM-Si wafer based technology are in the range of 37 g CO_{2eq}/kWh giving a 9 % reduction over the whole system lifetime. The difference in total is a combination of a lower energy impact for the crystallization of CM-Si in comparison to RCz-Si due to the lower energy intensity for the crystal growth counterbalanced by a higher GWP amount for the higher need of Si-feedstock due to the effect of lower brick yield and recycling quota. An increase of the difference in solar cell efficiency by 0,2 % absolute resulted in a slight increase in GWP for the CM-Si technology, still significantly lower than for the RCz-Si technology.

4 DISCUSSION

The cost and carbon footprint analysis of the two crystal growth technologies throughout the whole value chain still show a principal advantage for the lower environmental impact of the cast-mono growth technology by up to 10 % absolute for a PV system after its use phase. The main parameters for that are the energy intensity of the crystal growth process, the brick yield and the average efficiency for the PERC solar cells produced on these wafers. The latter parameters are connected via the material quality of the cast material with a focus on the amount of dislocations and impurities limiting the material quality and thus the yield of usable brick mass.

A very significant parameter regarding the cost projection is the future development of the electricity price. Whereas for a low electricity price regime the RCz-Si technology has an advantage already on the cost level, the CM-Si technology has the potential to be the better choice for production in a high price environment. In order to account for the detrimental climate effects of CO_2 emissions various states have introduced carbon pricing schemes such as carbon tax or emissions trading systems. For the near future this could contribute to a rise in electricity prices translating into a principal advantage of the CM-Si technology due to the lower energy intensity.

Further technology development for CM-Si resulting in a significant increase in brick yield and thus wafer throughput would give the CM-Si route again a cost advantage already on wafer level. For this, new technological solutions for higher ingots, less impurity intake and lower dislocation densities have to be introduced on industrial scale. This could be done e.g. by feeding technologies, more sophisticated cooling systems and advanced crucible systems. The introduction of industrial solutions for these technological aspects into the established Cz technology has triggered the transformation into the actual RCz technology. By doing so for the casting technologies a significant improvement would result in a technology base for a sustainable growth of the Si wafer based PV market.

5 CONCLUSION

The cost and carbon footprint analysis for a Si wafer based PV system with large wafer sizes of either M6 or M12 format shows a significant reduction of the carbon footprint by up to 10 % for the use of wafers produced by the cast-mono growth technology in comparison to the actual dominant RCz technology. For regions with electricity prices higher than 6 $ct/kWh for industrial applications a cost advantage for cast-mono wafers has been found. An increase in brick yield to over 60 % would give the opportunity to reduce wafer cost per W_p up to 0,4 $ct. To make this possible further technology and process development for the CM-Si technology is needed thus enabling future competitiveness for the PV market growth yet to come.

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