

Next-generation high-throughput cell production technologies – impact on equipment CAPEX, footprint and labour requirements for a 10GWp PV cell factory

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Abstract

With the expected increase in annual photovoltaic production capacity beyond 1TWp/a (terrawatt-peak per year), the emphasis on novel, next-generation production technologies gains significance from the perspective of potentially lowering production costs as well as increasing sustainability by reducing the resources required in manufacturing.

The focus of this work is to analyse the impact of high-throughput (HTP), next-generation silicon solar cell production technologies, as developed within the framework of the NextTec research and development project, on the required i) amount of equipment, ii) capital expenditure (CAPEX) and iii) labour, herein termed as key performance indicators (KPIs), for a solar cell production facility with an annual capacity of 10GWp. Current throughput values (reference year 2022) for the industrial manufacturing of M10-sized solar cells range from 4,000 wafers per hour (wph) to 18,800wph, depending on the process step involved. Considering the possible realisation of an increase in throughput by a factor of two to three for next-generation cell production processes, the impact on the investigated KPIs as well as the total cost of ownership (TCO) for a 10GWp PERC production factory is analysed and presented here against the reference state-of-the-art values.

The process sequence considered is based on the established PERC solar cell structure. Within the NextTec project, new HTP production technology has been developed, focusing on almost all PERC production steps, such as wet chemical, thermal, printing, continuous furnace, laser and inline characterisation processes. As such, a novel, conceptual analysis for a 10GWp production facility with a HTP processing sequence, termed PERC-HTP, can be formulated. The results show that an increase in throughput leads to a reduction in each KPI and the TCO for the PERC-HTP route when compared to the reference PERC processing route, with the relative advantages being:

- 50% reduction in the number of tools on the production line (in tools/GWp)
- 32% reduction in overall equipment CAPEX (in €/m²/GWp)
- 44% reduction in gross manufacturing area (in m²/GWp)
- 54% reduction in labour requirement (shift-FTE/GWp)
- 34% reduction in TCO (in eurocents/Wp).

An important outlook of this work is that although the results shown here are focused on a PERC-HTP production sequence, the same can also be replicated and further extended to different cell technology types, such as TOPCon, HJT and IBC along with their associated HTP equivalents. This is possible considering the overlap in some of the considered production HTP processes across different cell technology types, as long as the requisite changes in the equipment type and process recipes for the respective cell types are considered.

Introduction

With the expected increase in annual photovoltaic (PV) production capacity beyond 1TWp/a [1], the emphasis on novel, next-generation production technologies gains significance from the perspective of potentially lowering production costs as well as increasing sustainability by reducing the resources required in manufacturing. As is the case in any industrial mass production, optimising productivity is essential to be cost competitive, and the PV industry is no different. One way of achieving greater productivity is by increasing the throughput of the processing equipment (in wafers processed per hour, or wph), which in turn increases the output capacity of the tool and thereby reduces the cost per wafer or cost per Watt-peak (Wp).

Figure 1 shows the current and expected development trend for PV cell equipment throughput rates for the front-end (chemical processes, annealing and diffusion) and back-end (metallisation, laser and characterisation) PV production steps taken from the ITRPV report [2]. The development trend is plotted along with the maturity of the process (see colour scheme within Figure 1) in terms of whether the process already exists in mass production, whether an industrial solution is known, whether an intermediate solution is known or whether the process is still in feasibility testing. What can be clearly seen from Figure 1 is the expectation of a two-to-threefold increase in throughputs for both front-end and back-end PV production processes within the next decade. In some cases, there is already a known industrial solution (yellow) to increase the throughput rates, whereas in others there is only an interim solution (red) without a clear industrial implementation path.

To overcome the challenges of interim and unknown industrial solutions, several high-throughput (HTP) concepts for PV cell production

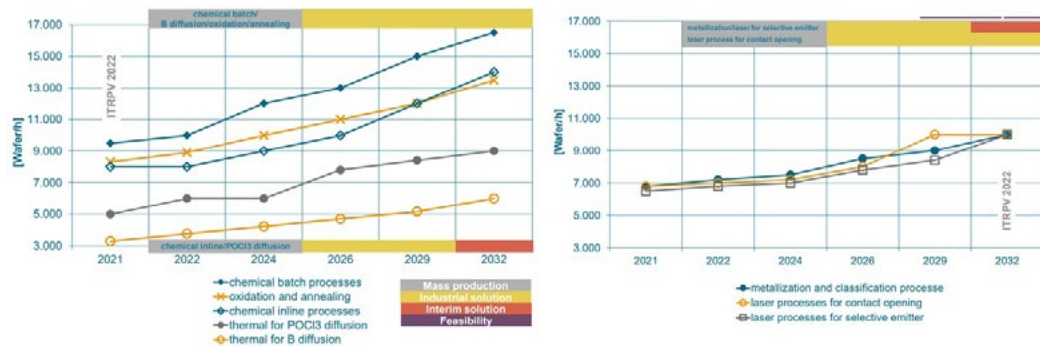


Figure 1. Expected development trend for equipment throughput rates for front-end and back-end PV cell production processes [2].

were developed and realised over the course of the NextTec research and development (R&D) project [3], which provided a proof of concept confirming a potential two-to-threefold increase in throughput compared to today's production rates. Analysing the impact of this increase in throughput with quantifiable metrics allows for a better understanding of the drivers for the economic feasibility of the developed HTP production technologies. To the authors' knowledge, such an exercise involving novel HTP production processes applied to an annual 10GWp solar cell facility with an impact on the total amount of equipment, overall equipment capital expenditure (CAPEX), required labour and production costs has not yet been presented. Therefore, this paper holds significant relevance for both the scientific and industrial PV communities, even more so now with the prominence of regional energy security, cost and sustainability.

The focus of this work is to analyse the impact of next-generation HTP PERC cell production technologies on three key performance indicators (KPIs) – namely i) the required amount of equipment, ii) CAPEX and iii) required labour – and their impact on the total cost of ownership (TCO) for an M10 PERC solar cell production facility with an annual capacity of 10GWp, alongside comparing the results against the standard PERC cell production route as a reference. The calculation entails data collection from industrial partners based on industrial equipment and process parameters. The data was then fed into Fraunhofer ISE's in-house bottom-up cost model [4], which is aligned to the SEMI standards E35 [5] and E10 [6].

Figure 2 shows an established process sequence for a PERC solar cell in the market today on the left, with the NextTec project-based high-throughput

sequence, termed PERC-HTP, on the right. The yellow highlighted processes represent the HTP processes with a throughput demonstrated to be two to three times higher than the standard reference processes. The herein analysed NextTec HTP production technologies are briefly described below (more details can be found in [3]):

Wet chemical processes: A significant increase in efficiency and throughput is demonstrated by combining batch and inline production processes, where the silicon wafers no longer travel horizontally but vertically through an inline wet chemical system. In this case, 50-100 tracks can be

p-type M10 Cz wafer	p-type M10 Cz wafer
cell line loader & WIS	cell line loader & WIS
SDE + texture + clean	SDE+texture+clean (HTP)
diffusion LP-POCl ₃	diffusion LP-POCl ₃ (dep. only)
LDSE	LDSE on-the-fly
chemical edge isolation	chemical edge isolation
thermal oxidation	stack oxidation
PECVD Al ₂ O ₃ / SiN _x (rear)	PECVD Al ₂ O ₃ / SiN _x (rear)
PECVD SiN _x (front)	PECVD SiN _x (front)
LCO	LCO on-the-fly
SP Al grid (rear)	RSP Al grid (rear)
SP Ag contact pads (rear)	RSP Ag contact pads (rear)
SP Ag grid (front)	RSP Ag grid (front)
contact firing	contact firing (20 m/min)
cell tester & sorter	shuttle cell tester & sorter

Figure 2. Analysed sequences for standard "PERC" cell process and corresponding HTP production process (PERC-HTP).

realised instead of the usual five. Thus, at a belt speed of 3m/min, a throughput of 40,000wph can be realised [7].

Thermal processes: Here, the high-temperature stack oxidation (HiTSOx) [8] approach combines an adapted low-pressure POCl₃ diffusion and HTP thermal oxidation using stacked wafers (greater than 5,000 wafers per stack). Consequently, a 1.8- and 2.4-times higher throughput is realised for the diffusion and thermal oxidation, respectively. The thermal oxidation process in this case provides both the formation of the final doping profile, i.e., the phosphorus drive-in, and simultaneous surface passivation, while reaching energy conversion efficiencies similar to the state-of-the-art processing.

Printing processes: For metallisation processes, rotary printing methods like rotary screen printing and flexographic printing represent a highly promising approach to overcome the throughput limit of conventional flatbed screen printing. Using a newly developed demonstrator machine at Fraunhofer ISE, a high-speed metallisation process for bifacial silicon heterojunction solar cells with throughput rates of 7,000-8,000wph using rotary screen printing was demonstrated [9]. For bifacial PERC solar cells, considering two printing lanes/stations per tool and two imprints per rotary screen per station, a potential throughput rate of 32,000wph was considered for the calculations of the PERC-HTP sequence, with a similar footprint as today's flatbed screen printers.

Drying/sintering processes: For these processes, ultra-fast firing processes yielding similar power-conversion efficiency levels up to a belt speed of 20m/min were demonstrated [10]. With a belt speed of 20m/min, yields for a double-lane furnace, M10-sized solar cells and a cell distance of 25mm, a technical throughput of 11,600wph was demonstrated, which was significantly higher than the 8,000wph for thermal processes in the PV industry predicted by the ITRPV roadmap.

Laser processes: Novel inline laser processes with precise laser beam control allowed the development of a high-throughput approach to create LCO patterns using a simple conveyor belt and on-the-fly laser processing. A polygon scanner was used for fast on-the-fly laser processing. The wafer's location was determined using an optical sensor and a laser process was automatically triggered upon arrival of the moving wafer, which enables HTP rates of up to 25,000wph [11].

Inline characterisation processes: For inline defect analysis, an on-the-fly electroluminescence measurement system with a throughput of 12,000 cells/hour was developed. A deep neural network corrects the motion blur to enable a proper and

fast defect inspection. For IV measurements, two concepts were developed to increase the throughput of cell testing: ultra-fast contacted [12] and newly developed non-contacted IV measurements [13].

Technical throughput of inline and batch processes

When calculating the technical throughput λ_{tech} of process equipment, a distinction can be made between continuous and discontinuous production according to the continuity of the production process or material flow. Continuous production occurs when the product units pass through the production process without any interruption in time. In PV production, this is referred to as an inline process in which, for example, wafers or solar cells pass through the production systems on several conveyor belts or processing lines in parallel. In a discontinuous process, the product units are fed into the equipment with time interruptions and processed in batches. A special case of discontinuous production is batch production, in which a certain quantity of material (batch) is fed into the process as a whole and removed again as a whole. In PV production, discontinuous production processes are usually represented as batch processes.

The technical throughput of an inline process $\lambda_{\text{tech,inline}}$ is calculated from the ratio of conveying speed v_{inline} and distance s_{inline} of the product units, as shown below. If the product units are processed in parallel on several processing lines within one piece of equipment, the throughput is scaled with the number of lines $l_{\text{pl,inline}}$.

$$\lambda_{\text{tech,inline}} = \frac{v_{\text{inline}}}{s_{\text{inline}}} \cdot l_{\text{pl,inline}} \cdot r_{\text{oi}}$$

$\lambda_{\text{tech,inline}}$	technical throughput of inline production equipment with trouble-free operation (units per hour)
v_{inline}	conveyor speed of the product units in the continuous production process (m/h)
s_{inline}	distance travelled by the product units on the conveyor line (m)
$l_{\text{pl,inline}}$	number of parallel conveyor belts or manufactured product units in the production process (number)
r_{oi}	ratio of the number of outgoing product units to the number of incoming product units of the production process (output-input relation)

The technical throughput of a batch process $\lambda_{\text{tech,batch}}$ is calculated from the ratio of the batch size l_{bat} that is processed within a process cycle to the tact time t_{tct} , which is the time interval between two successive batches completed by the production line:

$$\lambda_{tech, bat} = \frac{l_{bat}}{t_{tct}} \cdot r_{oi}$$

$\lambda_{tech, bat}$ technical throughput of a batch process with trouble-free operation (pieces/h)
 l_{bat} lot or batch size processed within a process cycle (pieces/batch)
 t_{tct} interval between two consecutive batches completed by the production line (h/batch)

If the equipment can process several batches in parallel, the tact time differs from the cycle time of the process, which is the actual processing time of the product units in the production process. If the number of product units entering the equipment does not correspond to the number of outgoing product units, e.g., when a full solar cell is cut into half cells, this must be taken into account when calculating the technical throughput λ_{tech} by multiplying the technical throughput with the ratio of the number of outgoing product units to incoming product units, termed as the output-input relation r_{oi} .

Tact time (t_{tct}) and cycle time (t_{cyc})

According to the REFA association [14], the tact time (also known as work-tact or tact) is defined as “the time in which a quantity unit is completed so that the flow system produces the target quantity output”. One quantity unit in the REFA definition corresponds to one production batch. The calculation of the tact time t_{tct} results from the ratio of the processing time of the batch, here referred to as cycle time, and the number of

batches processed in parallel by the production line $l_{pl, bat}$:

$$t_{tct} = \frac{t_{cyc}}{l_{pl, bat}}$$

t_{cyc} cycle time of the production process (h)
 $l_{pl, bat}$ number of batches processed in parallel by the production line (number)

The cycle time t_{cyc} is calculated as:

$$t_{cyc} = t_{out} - t_{in}$$

t_{in} time of entry of a product unit into the equipment (h)
 t_{out} time of exit of a product unit from the equipment (h)

In production planning, the cycle time is the time it takes for an entire production programme or process to run through once. Thus, the cycle time t_{cyc} is calculated according to the time difference between the input of a product unit t_{in} into the process and its output t_{out} .

Cost modelling methodology and data collection

Fraunhofer ISE has collected relevant cost data throughout the whole value chain for over 20 years. During that time, a sophisticated cost analysis tool, “SCost” [4], covering the entire PV value chain has been developed, which enables economic comparisons of different technology options. The economic analysis features a bottom-up calculation of the industrial PV value chain with the adaptation for individual production

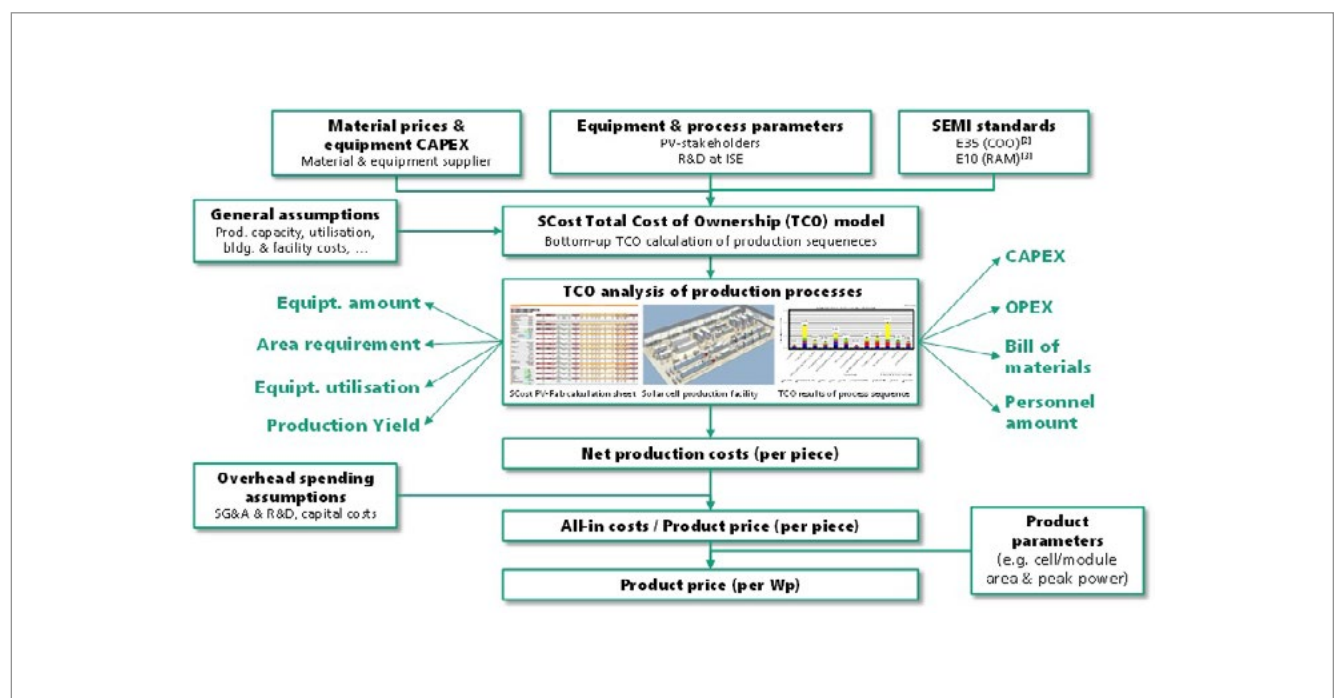


Figure 3. Simplified methodology for cost calculation with the SCost TCO tool developed at Fraunhofer ISE.

Parameter	Value	Unit
PV cell production output	10,000	MWp/a
Factory capacity utilisation (350 days per year, 24 hours per day)	8,400	h/a
Shiftdependent staff deployment at production line	5	FTE*/position
Average FTE employee salary	65,000	€/year
Depreciation period		
Equipment CAPEX	7	years
Facility CAPEX	10	years
Building CAPEX	20	years
Overhead costs		
Sum SG&A and R&D	4	€/ct/cell

*FTE: full-time equivalent

Table 1. General model assumptions and calculation parameters.

technologies. The underlying cost model is aligned with the SEMI standard E35 [5] for the calculation of cost of ownership (COO) or semiconductor and PV production equipment, as well as the SEMI standard E10 [6] for reliability, availability and maintainability. The equipment and process-related input parameters (e.g. process throughput or material consumption), as well as equipment CAPEX, are primarily gathered from various PV stakeholders, such as the equipment manufacturers, but also from PV companies using the equipment in production and especially for newly developed production technologies from conjoint R&D activities with Fraunhofer ISE. Material input prices are primarily collected directly from the suppliers of the material. With the SCost bottom-up TCO model, the process information of each process step is put into entire process sequences, together with general production assumptions like the envisioned capacity and planned utilisation of the production facility, as shown in Figure 3.

The result of the SCost TCO analysis of the process sequence is the “net production costs” per manufactured piece of product, which include all costs of production. The net production costs are divided into cost categories, with their cost components distributed into the following:

- Equipment: production equipment and automation, including delivery, installation and qualification.
- Buildings and facilities: CAPEX, cost of capital and OPEX of factory buildings and facilities – HVAC, gas farm, DI water production, chemical supply, waste disposal, warehouse, offices, canteen, infrastructure personnel etc.
- Utilities: power, cooling, CDA, exhaust, DI water, water, N₂, etc.
- Parts: spare and wearing parts.
- Process consumables: solids, liquids, gases, etc.
- Waste disposal: materials for factory internal disposal and costs of external disposal.

- Labour in production: operators, technicians, supervisors, engineers etc.
- Cost of yield loss (CYL): breakage and pieces not meeting quality requirements.

Not included within the net production costs are overhead costs for selling, general and administrative expenses (SG&A) and for R&D, as well as the cost of capital for the corporate unit. For SG&A and R&D, market benchmark values are taken (as the share of revenues from annual reports from PV manufacturers).

Table 1 gives an overview on the general assumptions and calculation parameters used within the cost model for a greenfield PERC cell production facility with an annual capacity of 10GWp located in Germany. The output cell efficiency for both the PERC reference and the

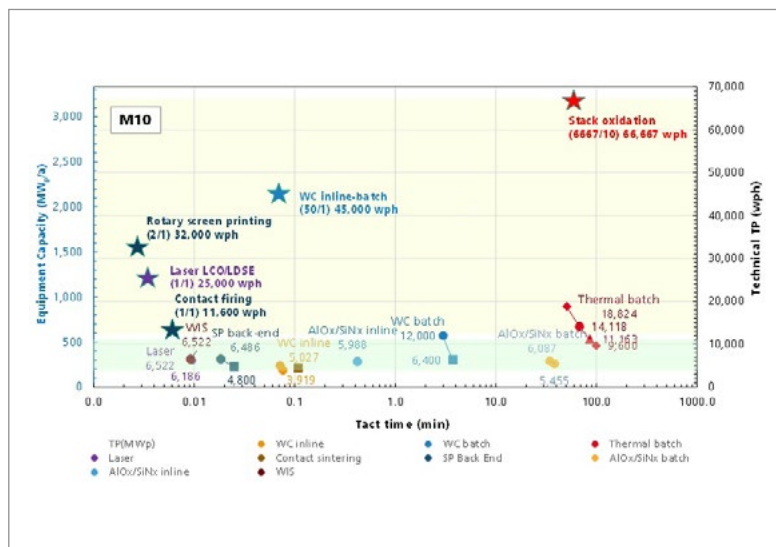


Figure 4. Throughput comparison of next-generation HTP versus current cell production technologies for M10-sized wafers. Depicted are both batch and inline processes and their respective number of wafers processed at the same time, e.g. (6,667/10) for the stack oxidation process means 6,667 wafers per batch and 10 batches per tool processed simultaneously. For inline rotary screen printing, (2/1) means the use of two parallel conveyor lines per tool.

Process PERC reference/PERC-HTP	TP PERC reference (wph)	TP PERC-HTP (wph)	% increase in TP	% increase in equipt. CAPEX per tool
SDE + texture + clean / SDE + texture + clean (HTP)	4,800	45,000	+ 838%	+ 131%
Diffusion LP-POCl ₃ /POCl deposition only	11,200	21,300	+ 90%	-
Laser selective emitter (LDSE)/LDSE on-the-fly	6,200	25,200	+ 307%	+ 213%
Thermal oxide/stack oxidation	18,800	66,700	+ 255%	+ 30%
Laser contact opening (LCO)/LCO on-the-fly	7,200	25,200	+ 250%	+ 215%
Screen printing/rotary screen printing	7,200	32,000	+ 344%	+ 50%
Contact firing/contact firing (HTP)	3,600	11,600	+ 222%	-
Tester and sorter	5,000	16,900	+ 238%	+ 25%

Table 2. Process-specific throughput rates and equipment CAPEX.

PERC-HTP sequences was assumed to be 23.5%. Apart from the values provided in the table, the building and facility costs were based on benchmark values for a German case. The material prices were collected based on an internal, established data warehouse of PV materials, as well as updated spot prices of key materials such as the silver paste for metallisation. Specific equipment parameters (uptime, yield, etc.) and process parameters (process recipe, material consumption, etc.) were collected from both PV stakeholders (OEMs) and R&D at Fraunhofer ISE.

The first step in data collection was to gather an understanding of the current throughput rates (year 2022) for standard, industrial mass-manufacturing cell production processes of an M10-sized wafer. Further to this, the throughput of processes developed within the NextTec project were included in the same figure to compare the possible increase in technical

throughput and the corresponding equipment capacity (in MWp/a).

Figure 4 shows the technical throughput (TP, not including equipment downtime) of production equipment for the M10 wafer format as a function of the tact time (t_{tct}) for the different technologies of the state-of-the-art (green area) and HTP technologies (light-yellow area). The technical throughput is calculated based on the formulas provided in the previous section. The equipment capacity in MWp/a is calculated based on an overall equipment efficiency (OEE) of 100% ($365 \text{ d/a} \times 24 \text{ h/d} = 8760 \text{ h/a}$ operation with 100% equipment uptime and 100% yield) and an M10 solar cell efficiency of 23.5%. Clearly evident from the figure is the significant increase in throughput for HTP technologies in the range of 11,600 wph to 67,000 wph (light-yellow region) compared to current production technologies in the range of 4,000 wph to 18,800 wph (green region).

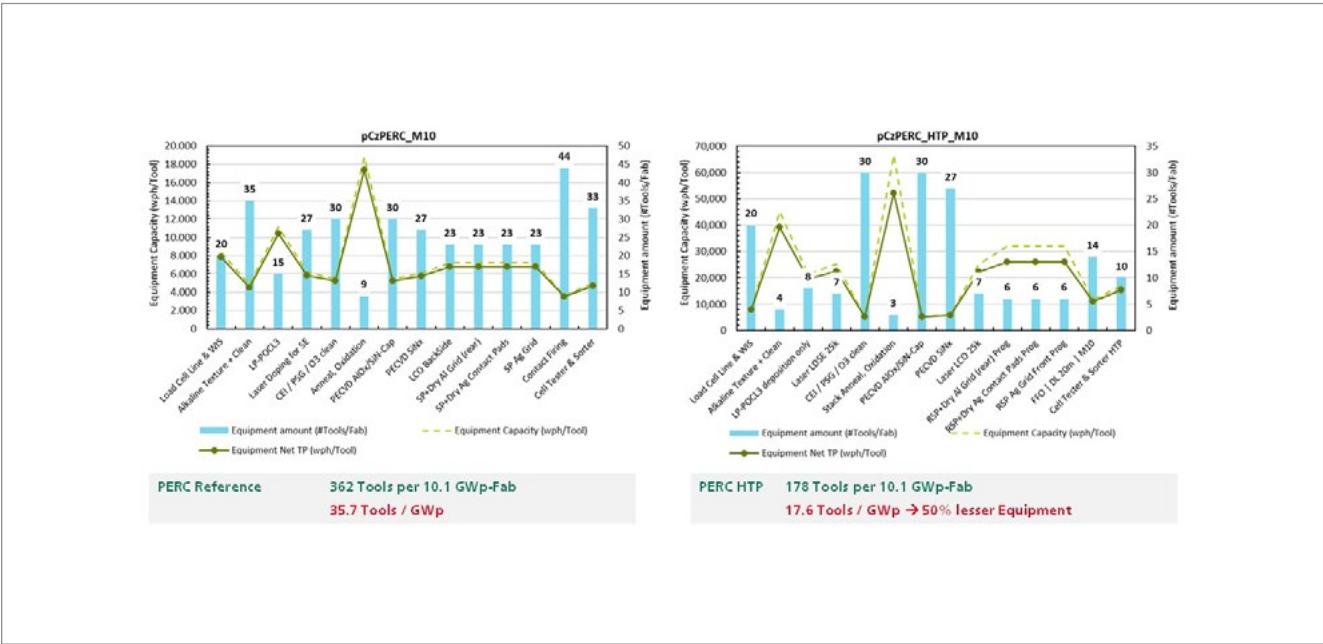


Figure 5. Equipment capacity comparison of next-generation versus current cell production technologies for a 10GWp production line.

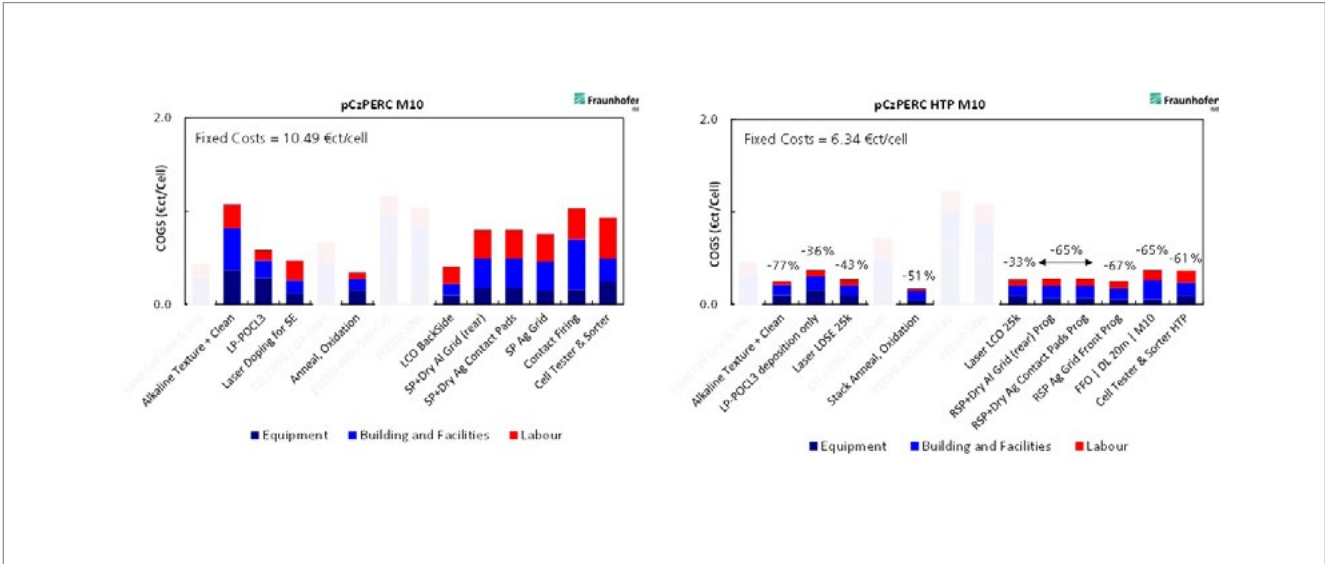


Figure 6. Comparison of fixed production costs (equipment, building, facilities and labour), showing a reduction of 40% for the HTP case of next-generation versus current cell production technologies for a 10GWp production line.

Following the collection of the throughput rate of the production processes, each process was looked at in terms of an estimated increase in the equipment price (CAPEX) due to modifications required for the tool (higher load requirements, additional processing stations, new laser sources, etc.) or in some cases, a more expensive, new tool. The impact on the increase in both the throughput and CAPEX per tool is shown in Table 2.

Results

Based on the collected data on throughput rates and the increase in equipment CAPEX per process step, a process sequence for the standard PERC reference and the PERC-HTP route was modelled with Fraunhofer ISE's SCost tool [4]. The objective was to compare the defined KPIs for the PERC-

HTP route against the PERC reference process, to determine potential advantages that the developed HTP processes offer when implemented in an industrial mass-production facility with an annual capacity of 10GWp.

Figure 5 shows the comparison of current reference process steps (left) with next-generation HTP production technologies for a 10 GWp PERC cell production facility. The bars in the chart relate to the number of tools required per production step for the 10GWp factory. The solid lines represent the calculated average net throughput (after line balancing) and the dashed line is the equipment capacity for one single piece of equipment, each in wafers per hour per tool (wph/tool). The difference between the

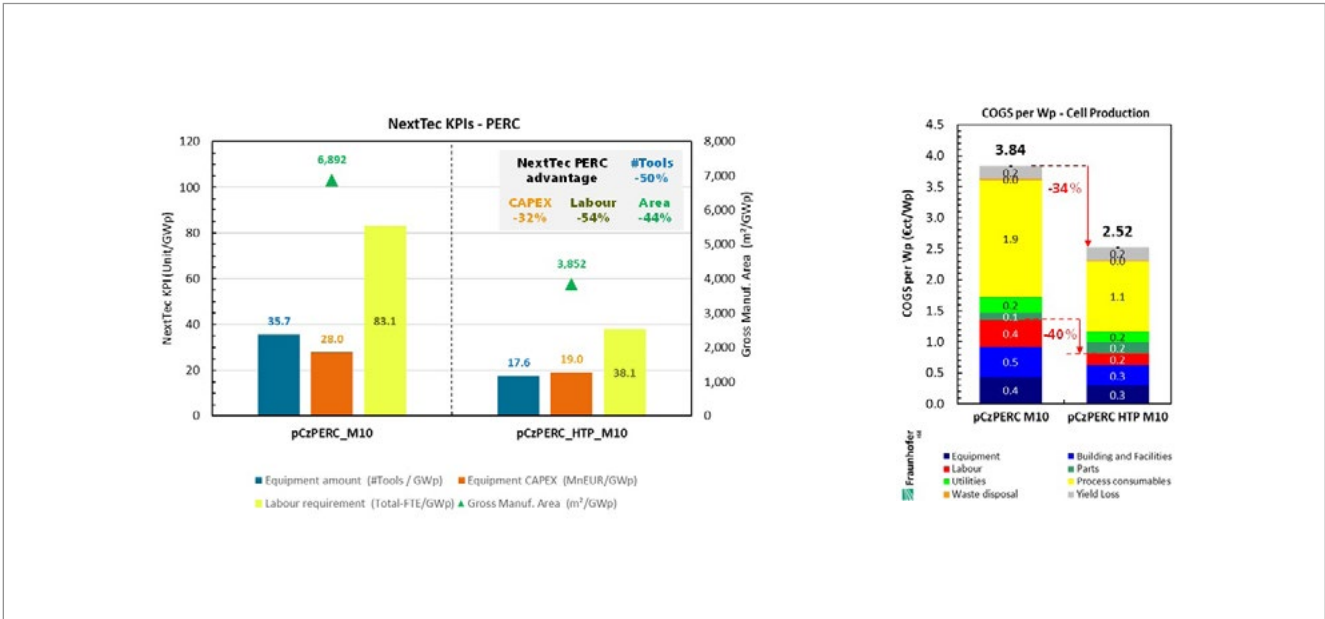


Figure 7 (left) and Figure 8 (right): Resulting KPIs and TCO results for standard PERC versus PERC-HTP production sequences for a 10 GWp facility (FTE in Figure 7 refers to full-time equivalent).

dashed and solid lines represents the utilisation rate for each tool – the larger the gap between the two lines, the lower the utilisation rate of the tool after line balancing. Thus, the bottleneck process for the production sequence can also be identified – the process where the dashed and solid lines meet is the bottleneck process within the respective sequence. The graphs in Figure 5 show that utilisation for most of the equipment in the HTP sequence is lower than for the PERC reference, which is a result of the less equipment as well as higher step-wise capacity difference. Nonetheless, for the analysed PERC-HTP production sequence, the number of tools for the entire facility is reduced by 50% compared to the reference production sequence.

The increased throughput from the PERC-HTP sequence that results in the 50% reduction in the number of tools required for a 10GWp factory mainly impacts the fixed production costs, i.e., the equipment, building, facilities and labour. This is because the number of tools directly determines the area required for the factory and thereby the facilities required to supply the tools, primarily related to the temperature and humidity control of the factory. Also, the number of workers (operators, technicians and supervisors) to run the tool is directly dependent on the number of tools within the factory. In addition to the area required for the equipment, working space considerations were included within the model to account for maintenance and installation of the tool. Correspondingly, the lower the number of tools for the PERC-HTP sequence, the lower the fixed production costs.

Figure 6 shows the fixed production costs (equipment, building, facilities and labour) reduced by 40% for the PERC-HTP route versus the reference, from 10.49 €/cell to 6.34 €/cell. The impact on each of the fixed production cost components can be seen for each individual process step for the reference against the corresponding HTP process. The greyed-out bars represent the processes for which no HTP process was modelled within this work and thus no change in the fixed production costs was determined between the reference and the HTP route, specific to those processes.

Figure 7 and Figure 8 consolidate the results of the cost model in terms of the previously defined KPIs and production costs. The figures show that an increase in the throughput leads to a reduction in each KPI and the TCO when compared to the reference PERC processing route. In the case of the TCO or cost of goods sold (COGS) Figure 8 shows the impact of the reduction in the fixed production costs (40%), as shown in Figure 6, as well as the overall reduction in the production costs of 34%. It

is important to highlight that most (~60%) of the reduction in the COGS for the PERC-HTP route comes from the reduction in materials (yellow bar in Figure 7), from 1.9 €/Wp to 1.1 €/Wp. This result is mainly driven by the assumed reduced silver and aluminium paste requirement (40% and 30% reduction, respectively) for metallisation with the rotary screen-printing process in the HTP route as reported in [9].

Overall, the relative differences between the PERC-HTP and reference routes are:

- number of tools in the production line (in tools/GWp) reduced by 50% for PERC-HTP versus reference PERC.
- overall equipment CAPEX (in €/m/GWp) reduced by 32% for PERC-HTP versus reference PERC.
- gross manufacturing area (in m²/GWp) reduced by 44% for PERC-HTP versus reference PERC.
- labour requirement (shift-FTE/GWp) reduced by 54% for PERC-HTP versus reference PERC.
- TCO (in €/Wp) reduced by 34% for PERC-HTP versus reference PERC.

Discussion and outlook

Considering the material flow analysis of an HTP production line, the focus was on determining the amount of equipment required for a 10GWp production line. Other aspects of the material flow analysis relating to the handling of wafers between production steps and the provision of various chemicals, gases, etc. required for the process on the scale of an HTP production line were not analysed as part of this work. Here, it can be assumed that autonomous guided vehicles (AGVs) in the future with greater capacity than today's AGVs, or direct transport on conveyer belts with sufficient buffer stations could be a possible solution for handling the increased number of wafers. Also, the increased demand for chemicals and gases is not considered to be a technical challenge for any HTP process.

An important consideration remains of the technology readiness levels (TRL) of between three and five of the most considered HTP processes, as they so far lack industrial maturity and are rather at the stage of conceptual processes and/or demonstrations on industrial-like equipment. This highlights the need for implementation of the developed HTP technologies within pilot lines for successful transfer to an industrial mass-production scale. It is noteworthy that although the results shown within this work are focused on a PERC-HTP production sequence, most of them can also be replicated and further extended to different cell technology types such as TOPCon, HJT and IBC along with their associated HTP equivalents. This is possible because of the

overlap in some of the considered production HTP processes across different cell technology types if the requisite changes in the equipment type and process recipes for the respective cell types are considered.

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