LESSONS LEARNED FROM 25 YEARS PRODUCTION TECHNOLOGY RESEARCH & DEVELOPMENT

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ABSTRACT: In 1997, a visionary study addressed limitations of the cost reduction potential for high efficiency solar cell devices. The results of this study triggered increased efforts for the development of production technology at Fraunhofer ISE. Many new approaches with substantial impact have been developed to the demonstration level. Economic analysis and a technology readiness terminology have been established to aid in assessing technological approaches, while the set-up of the PV technology evaluation center (PV-TEC) allowed for testing equipment, processes and materials on a higher maturity level. Reference processes building the backbone of the technology have been developed consistently further and device efficiencies follow a roughly 0.5%/a progress gradient since 2005, which is in good agreement with reports for an industrial pilot line. Today, we can rely on reference processes for PERC, TOPCon and SHJ in the PV-TEC with total and large area efficiencies of up to 22.7%, 24.0% and 24.1%, respectively. Further learning includes that for production technology R&D for PV devices high average power conversion efficiencies must be targeted and that scaling should be combined with thorough testing of products along the value chain. All cost and value determining parameters like production efficiency distribution, yield, capital and operational expenditure as well as degradation and performance under field conditions have to be monitored.

1 INTRODUCTION

The last decade of the last century was decisive for the future development in photovoltaics (PV) and many milestones were achieved. The German Feed-In-Law from 1990 was extended to the renewable energy law with attractive fixed tariffs in 2000. In the late 1990s, for the first time, 100 MWp/a nominal PV module power were sold globally [1], and single junction silicon solar cells close to 25% efficiency were demonstrated, applying the passivated emitter and rear cell (PERC) concept with local diffusion under the rear contacts (PERL) in laboratory [2]. In 1997, PV production in Europe was based on approx. 20 MWp/a production of solar cells, mostly following the concepts of the laser grooved buried contact (LGBC), the screen-printed Al-BSF (Back-Surface Field) and metal-insulator-semiconductor (MIS) approach. Just then, a study by leading PV companies and institutions for setting up a visionary 500 MWp/a production line was published at the EU-PVSEC with seven different approaches being used [3]. The cell technologies under investigation were Al-BSF, LGBC, MIS and the LBSF (local BSF) approach from Fraunhofer ISE, with a design structure and process sequence similar to that of the PERL device. Most approaches were calculated to similar anticipated production costs on a module level. A substantial advantage of 20% vs. 16% conversion efficiency on cell level was assumed for the LBSF approach, but the approximately seven times more expensive cell processing could not be compensated, leading to substantially higher module cost. A main cost driver was the photo-lithographical structuring used to allow for the fine contact and selective diffusion structures in these cells. The increased cost could be attributed to both high material consumption but also low productivity of the used equipment. Based on this analysis, other techniques were to be developed at Fraunhofer ISE with the main objective to realize device features for efficiency increase, high productivity, and low material cost. Thus, a team was formed to focus on production technology development for highest efficiency solar cells, setting up a first lab. Moreover, an industry consortium was built to investigate cost saving potential for PV fabs. For the latter, techno-economic assessment based on bottom-up cost analysis was implemented at the institute. Our methodology has been then tested in our production research and development platform PV-TEC with high quality standards and allowing for in-depth characterization and the objective to support the industry targeting efficiency increase, productivity scaling and economical use of resources. Our methodology focusses on the reduction of the photovoltaic electricity generation cost, applying advanced techno-economic metrics.

This paper is to present the findings of this work on production technology over a period of 25 years and highlight important general results and their impact.

2 AIM AND APPROACH

The aim of the research and development work was guided by the relevance of efficiently bridging the gap between new ideas and concepts achieving outstanding laboratory results to the introduction of industrial pilot processing and mass production. Therefore, the efforts have been focussed on developing innovative equipment and new functional materials feasible for high throughput.

Compared to many state-of-the-art institutional R&D environments, a higher industrial maturity of the technologies was addressed, frequently assessed by its technology readiness level (TRL), which is commonly known to be introduced by NASA for flight missions. In 2016, we have released a first draft of a TRL-methodology specifically defined for devices like PV cells, including a review and more detailed discussion on the TRL-terminology [4]. We have further extended this draft to the version shown in Table I. Such a more specific TRL-methodology allows to be also used as quality gates for further budget decisions throughout technology development.

Table I: TRL stages for PV cell production. The definitions are an advanced version of the one published in [4].

TRL	Phase: Description
0	**Creation**: Idea of a new approach with beneficial features or potential, typically based on findings from modelling and/or experiment.
1	**Early proof-of-concept**: Laboratory process, idea works and is reproducible on small/reduced area.
2	**Advanced proof-of-concept**: Demonstrating potential in lab environment and reaching performance benchmarks using adapted or standardized measurement procedures.
3	**Early scaling**: Laboratory process, functional and reproducible on industrial standard large and complete areas / substrates. Demonstration of a product with essential features allowing for standardized measurement procedures.
4	**Early feasibility**: Laboratory process, efficiency potential demonstrated on industrial standard large and full areas. Successful first feasibility testing in next value chain step.
5	**Advanced scaling**: First high-throughput tools with still high parameter variability are tested and show successful throughput scaling of a process on large and full area. Products from the next value chain step are manufactured and first performance tests are successfully performed.
6	**Feasibility**: Industrial throughput level is reached for all equipment of the approach, but not set-up in a production-oriented mode. Cost drivers are identified, manufacturing can be performed at high throughput. Critical tests for certification have been performed, field tests are prepared.
7	**Pilot**: Process used in temporarily continuous industrial pilot, with operational throughput, yield and efficiency distribution targets met. Substantial quantities of next value chain step are manufactured, and fully certified, successful field tests are performed.
8	**Industrialization**: Process used in mass production with 24 hours/7 days on production tools. More equipment being sold, but still less output compared to benchmark approach. Still substantial potential in equipment and material productivity and resource efficiency. Field application becomes standardized and reliability parameters are monitored.
9	**Maturity**: Thorough production, a standard and dominant technology/product in its application field. Development is focused on further improvements of materials and equipment, where high output ensures continued learning.

3 RESULTS

3.1 Technology milestones

In the beginning, the production technology work was addressed to set up a solar cell process to produce Al-BSF cells and to be able to test technological approaches to achieve higher efficiencies on these cells. Based on this, the knowledge and technical infrastructure has been developed continuously to address the given targets. Today, many different technologies are tested based on reference processes for PERC, TOPCon and SHJ cell device features. If approved on lower technology readiness levels, technologies were typically developed until the pilot level. For complete devices this was obtained for example for screen-printed PERC and MWT (metal wrap through) solar cells. MWT was transferred to TRL 7 with an industrial partner. In 2010, the production technology know-how for screen-printed PERC devices was transferred to industrial partners and their pilot lines with TRL 7 and further matured to TRL 9, according to Table I. An overview of contributions including work of other groups in the development of PERC devices is given in [5]. We also developed an MWT-PERC hybrid and produced cells in a pilot at the PV-TEC, which have been manufactured to modules and installed at a building at the Fraunhofer ISE.

3.2 Findings

Most of the learning has naturally occurred for the respective production technologies, including device structures, processes, materials and respective equipment. Nevertheless, there are a few general learnings. First the establishment of reference processes for relevant device structures is very important. For the selection, we typically focus on device types which have a major share of production volume or show the highest prospects indicated by the gradient in production capacity or new installations. Such device structures allow for the most value for the development in the intermediate TRL levels 4-6. Another learning is the importance of high quality standards for a research and development line, as PV-TEC today includes more than 30 large process tools. Due to this high number of tools, the number of operators including engineers and PhD students also rises. Thus, advanced methods for quality management must be developed compared to lab type processing, including e.g., traffic light procedures, which define how to deal with sudden or drifting changes of control parameter values. This also implies to set parameter value boundaries, which ensure successful processing. In 2017, PV-TEC was re-built and extended to two parts for front-end and back-end processing, with adequate infrastructure for the respective technologies. Since then, we have focused to establish reference processes for the currently most important cell technologies PERC, TOPCon and SHJ, with representative structures of specific variants shown in Figure 1.

One general finding is visualized in Figure 2. For fast market introduction, it is essential to develop technologies to higher technology maturity while simultaneously pushing the development along the value chain. Benefits from an innovative approach must be validated on the system level. Thus, if the development of cell production technology on medium throughput level is conducted, it is essential to manufacture modules from the cells, too. The most relevant pull for introducing new technologies comes

eventually from the motivation of reduced electricity generation price (€/kWh). To reflect this fundamental relevance, the initial development of in-depth cost assessment has been continuously extended. Today, we can calculate levelized cost of electricity for a new technological approach, based on thorough cost data and metrics. We also perform life cycle assessment and address criticality of resources to evaluate the sustainability of different technologies.

Table II: Milestones of solar cell production technology development at Fraunhofer ISE

Period	Milestones in production technology development at Fraunhofer ISE	Ref
1997-1998	Production technology group and expert round founded, set-up of in-depth cost calculation, first screen-printed solar cells manufactured.	[6]
1999-2001	Reference process for screen-printed solar cells set up, first attempts to include PERC features, including laser ablation and laser firing.	[3] [7–9]
2002-2004	First innovative alpha-tools set-up: e.g. galvo-scanner based laser tool, inline plasma etching tool, inline sputtering tool, low contamination inline diffusion furnace.	[10–12] [13]
2005-2007	Set-up of PV-TEC: Full pilot Al-BSF reference process (TRL 5-6), target >100 wafers/h, metal-wrap-through variant, 125-210 mm edge length.	[14] [15, 16]
2008-2010	PERC in PV-TEC: high-throughput oxidation, PECVD-AlOx, fully screen printed, PVD and Al-foil metallization.	[17, 18, 18, 19, 19, 20]
2011-2013	Transfer of PERC to industrial pilot line, MWT-PERC, PERC pilot process in PV-TEC, advanced quality management, modelling and assessing the technical and economical potential (TRL 6).	[21–23]
2014-2016	Set-up of n-type technology in the new PV-TEC Select, bifacial PERC/PERT, dispensing, ultrafast regeneration, machine-learning-enhanced inline PL characterization demonstrated.	[24–29]
2017-2019	PV-TEC front- and back-end, green manufacturing, development of PERC, TOPCon and SHJ reference processes, edge passivation, shingled cells, high-throughput, ultra-fineline metallization.	[30–32, 32, 33]
2020-2022	Highly stable PERC reference line, pilot processes for TOPCon/SHJ and shingled cells (TRL 5-6), first silicon tandem cells in PV-TEC (TRL 3-4 upscaling).	[5]
2023-2025	Pilot process for leading (production and/or growth rate) Si single junction cell technologies (TRL 6), production technologies for Si-tandem technologies (TRL 5-6).	

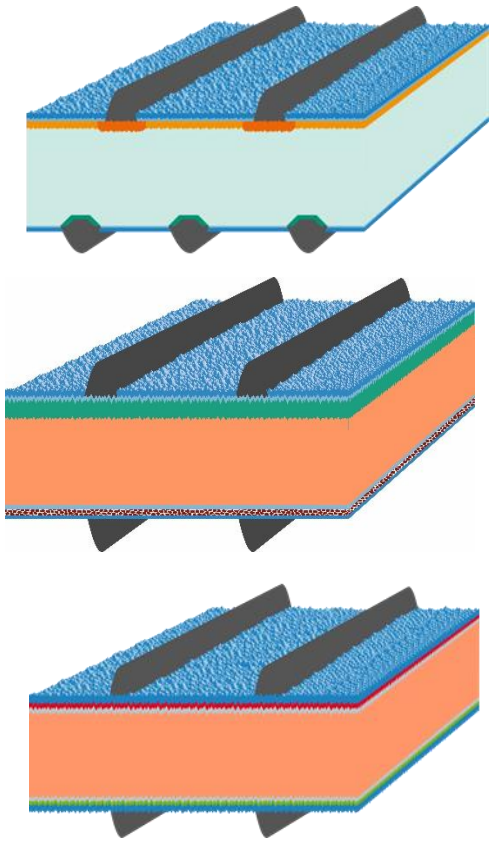

Figure 1: Representations of cell structures of the devices currently produced in PV-TEC in their bifacial versions (PERC with selective emitter, upper graph, TOPCon, center graph and SHJ, lower graph). For PERC devices most cells have been processed applying a lean process with homogeneous front emitter and full area aluminum paste coverage on the rear.

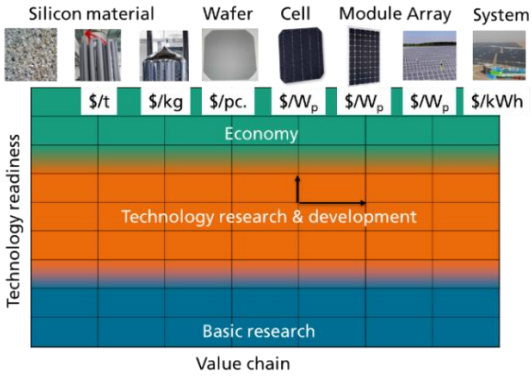

Figure 2: Technology readiness vs. value chain. The arrows indicate that technology development must consider both, TRL of the product but also the subsequent steps.

3.3 Reference process development for current devices

In the early years of the production technology development at Fraunhofer ISE, reference processes for screen-printed cells were developed but not sufficiently often repeated to work as a reference. With the set-up of the PV-TEC, we learned the importance of reliable reference processes based on well-established quality management features. The development of efficiencies is shown in Figure 3 for the first solar cells processed in PV-

TEC in December 2005 to the currently highest, independently confirmed (Callab PV Cells, Fraunhofer ISE) values of 22.7%, 24.0% (both with homogeneous emitter) and 24.1% for our reference processes of PERC, TOPCon and SHJ devices, respectively. Remarkably for PERC solar cells, the deviation of our best to the worst cell is less than 0.4%$_{abs}$ within a batch of 250 cells. Such high reliability with relevant efficiencies ensures valuable research and development for the currently dominating cell structures.

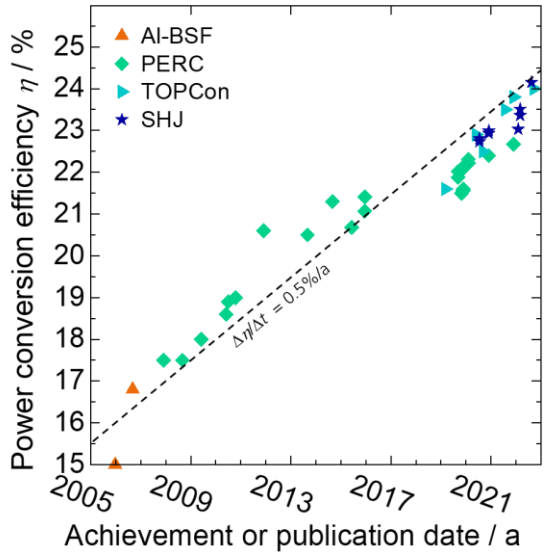

Figure 3 Development of power conversion efficiencies within the PV-TEC for different cell structures independently determined at the Callab PV cells (extended from [5]. The two cells which yield the highest efficiency values for SHJ and TOPCon feature a second MgF_2 anti-reflection layer. All TOPCon and most PERC cell results are prepared with a homogeneous emitter, only. The efficiency progress gradient of approx. 0.5%/a (dashed line) is similar to the report from industrial pilot lines [34].

4 TRAINING AND DISSEMINATION

One of the most important results is the training of scientifically, technologically but also economically qualified individuals who disseminate the knowledge. Within the 25 years, almost 100 PhD students and several 100 master and diploma students have performed their scientific work within our production technology environment. It was mandatory to install high standards for scientific quality, which have resulted in several hundred of conference and journal publications within this period, contributing to the knowledge, which set the unforeseeable pace in the industrial deployment of photovoltaics. For all this work, the general approach to set-up a respective technology environment and to combine this with in-depth techno-economic analysis has proven to be a very powerful and stringent approach.

5 SUMMARY

This paper gives a summary of findings of the work on production technology research and development performed at Fraunhofer ISE. It further introduces an advanced technology readiness scheme, which allows to evaluate maturity and support budget decisions.

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