Challenges of the gigawatt fab

Michael Kostwald, Turner & Townsend GmbH, Germany; **Hans Mahrenholtz**, Linde Gas, Linde AG, Germany; & **Anish Tolia**, Linde Electronics, U.S.A.

This article first appeared in *Photovoltaics International* journal's first edition in August 2008.

ABSTRACT

Thin-film solar cell manufacturing is poised to make a giant leap in scale with the birth of the gigawatt fab. Commercial thin-film plants are typically sized based on the capacity of the production line from the chosen equipment supplier. In most cases, initial investments have been for a single line, typically with an output capacity of no more than 60MWp. This period of initial development has allowed the industry to prove the robustness of the technology and capabilities of the equipment, as well as to understand the significance for the cost-per-watt of key cost drivers such as materials reduction, cell efficiency increases, and productivity. While large-scale manufacturing will positively impact costs, it presents a unique set of challenges for equipment and material suppliers, as well as the engineering and contracting companies tasked with designing, building, equipping and running a facility on this scale. In this paper, we present the insights of two specialty companies in the solar industry. Turner and Townsend, a design and project management consultancy, and Linde, glass manufacturer and gas and chemical company – share their views of the challenges of the gigawatt fab in three dedicated sections.

Methods and considerations in designing and building a gigawatt fab – Turner & Townsend GmbH

As project sizes increase, and time-to-market demands fast-track construction, careful consideration must be given to the project management model that will successfully deliver gigawatt fabs on time, without compromising cost targets or technical performance.

Frequently, traditional project management methods fail when carrying out these fast-track projects, which contain high risks with regards to function, quality, cost and schedule. Traditional execution is characterised by a sequence of mostly individually-developed, separate planning steps. After defining the program, the owner starts to select architects and engineers based on their qualifications. The architects and engineers develop the preliminary and detailed designs and prepare the procurement procedure for selecting a General Contractor or Work Package Contractor. On being awarded the contract, the General Contractor or Work Package Contractor step into the project with no prior knowledge of – and little subsequent control over – the basic objectives. This precludes the possibility of providing valuable input to optimise the design, cost structure or time schedules. The other extreme, i.e. the development of the entire planning and design by a management contractor, will generate a solution that is optimal for the contractor but will not adequately match the need of the project sponsor.

Better suited to the demands of the task is an Integrated Project Design & Management (IPDM) model (see Figure 1), already proven in the semiconductor industry. Adopting such an integrated approach, and forming a core team of experts to design, co-ordinate and manage all efforts from the very start of the project to the final delivery of the completed facility, brings significant benefits and sees the client form a key component of the team.

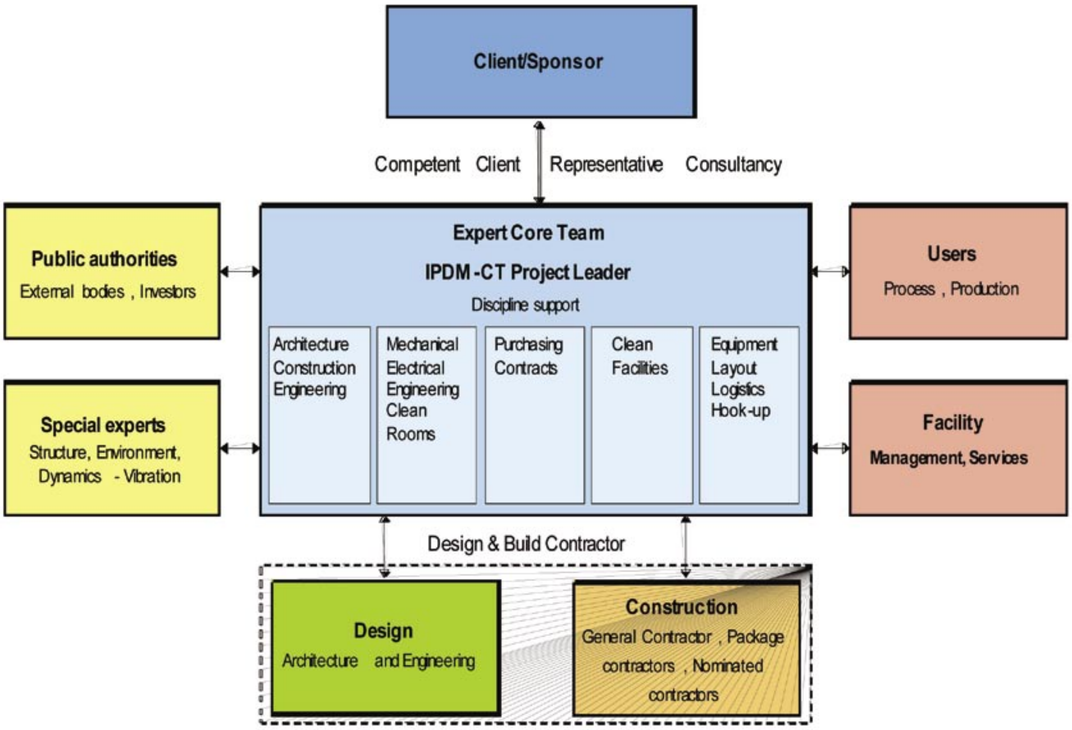


Figure 1. Integrated Project Design & Management (IPDM) model.

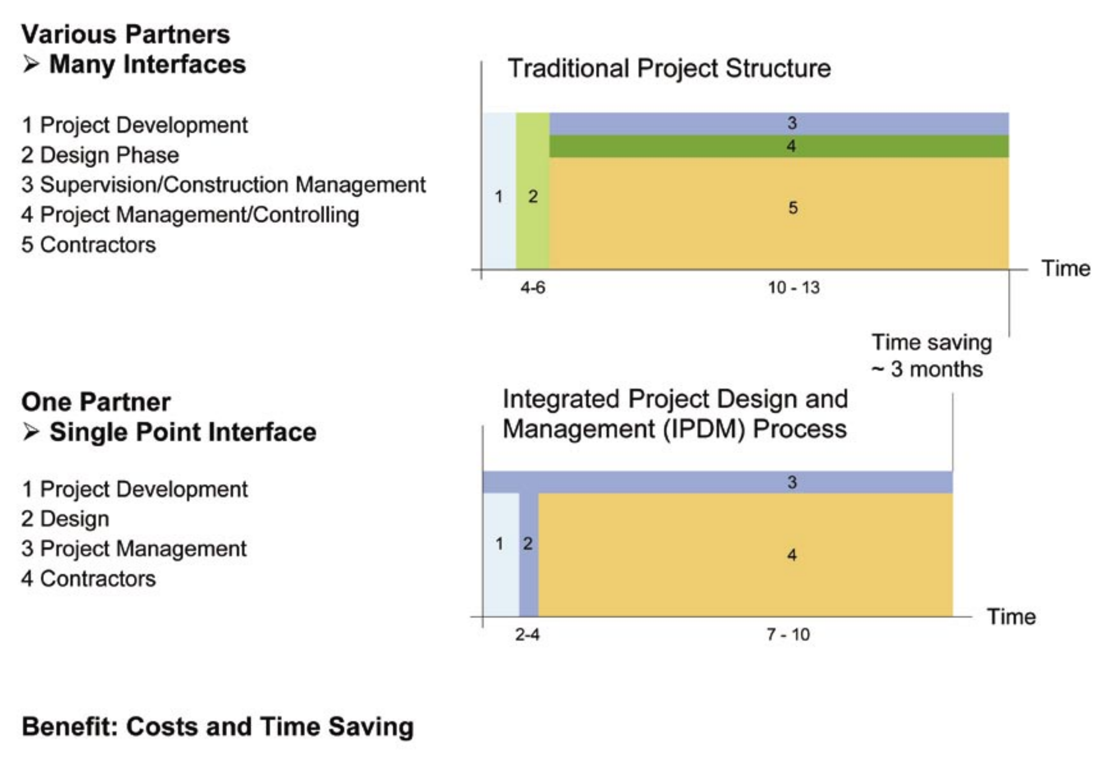


Figure 2. Comparison between traditional Project Structure vs. Integrated Process.

The core team begins to work in the project definition phase. Many key decisions are made during this early phase and cost-saving potential is at its highest. Changing key decisions very often affects costs, schedule or quality. The project is developed in close co-operation with the client/project sponsor, reflecting in detail the objectives and needs of the sponsor. In the next step those needs are transformed into a "Conceptual Design" which acts as a robust tender document to find a Design and Build Contractor in a competitive procedure. The Design and Build Contractor is then controlled and monitored by the core team throughout the entire project.

The risk for the client is reduced and the strict and optimised planning phase saves valuable time through:

- integration of all experts in an interdisciplinary mode from the start
- strong focus on an intensive programming phase to define the needs and objectives
- sequential but integrative progression leading to parallel work
- controlled change order procedures

and reduces project costs through:

- improved competition for detailed design and execution
- innovative concepts by early expert integration, less changes due to the strict and optimized planning phase.

Design challenges

Often, for warranty reasons, the facility planners will not work with "true" design parameters but with "worst-case" design parameters, which frequently result in higher-than-necessary costs.

The question of how the building and facility requirements are impacted by the scale-up will be answered in the IPDM Programming Phase. An intensive workshop, lead-managed by the core team, is held with the owner, equipment vendors, user and representatives of all technical disciplines with the main target to set up qualified requirements for the entire building and infrastructure scope. To ensure the design is state-of-the-art, the core team's role is to verify the redundancies, spare capacities, standards, specifications, qualities and quantities for each system with the help of "best practice" – reference data and benchmark figures, which reflect real design and operational experience. Compared to semiconductor manufacturing, purity specifications for process materials for PV manufacture such as ultra pure water (UPW) and nitrogen (N_2) may be less stringent, but the facility systems will be just as complex, and uptime requirements just as rigorous. System risk assessments and HAZOPs (hazardous operations) are equally as critical, and in some cases are dealing with significantly larger quantities of hazardous materials.

For example, wafer-based PV manufacturers will potentially require a high consumption hydrofluoric acid supply and discharge system, which therefore requires an engineering task force. The n+1 redundancy of cooling machines depends on the system capacity and on the diversity factor. Consideration of modular concept of production area, facility and infrastructure may not have any impact on the production but have to take into account a well-balanced ratio between operational cost and investment, with the target to reduce the overall production cost. Separation of central heating, cooling, gases and power station on site has to be considered to change to alternative business models in the future (e.g. lease-back).

> Utility consumption values for sub-100MW production facilities cannot simply be scaled up to gigawatt facility capacities.

PV manufacturers have not yet gained operational experience at industrial scale over long periods; hence utility consumption values for sub-100MW production facilities cannot simply be scaled up to gigawatt facility capacities. Additionally, facility requirements from equipment vendors are still under evaluation due to:

- Process technology optimization
- Production equipment layout optimization
- Efficiency improvements
- New thin-film clean gas technology under development
- Critical thin-film gas impurities not yet understood

In the programming phase, equipment vendor data are challenged to achieve qualified requirements, and these

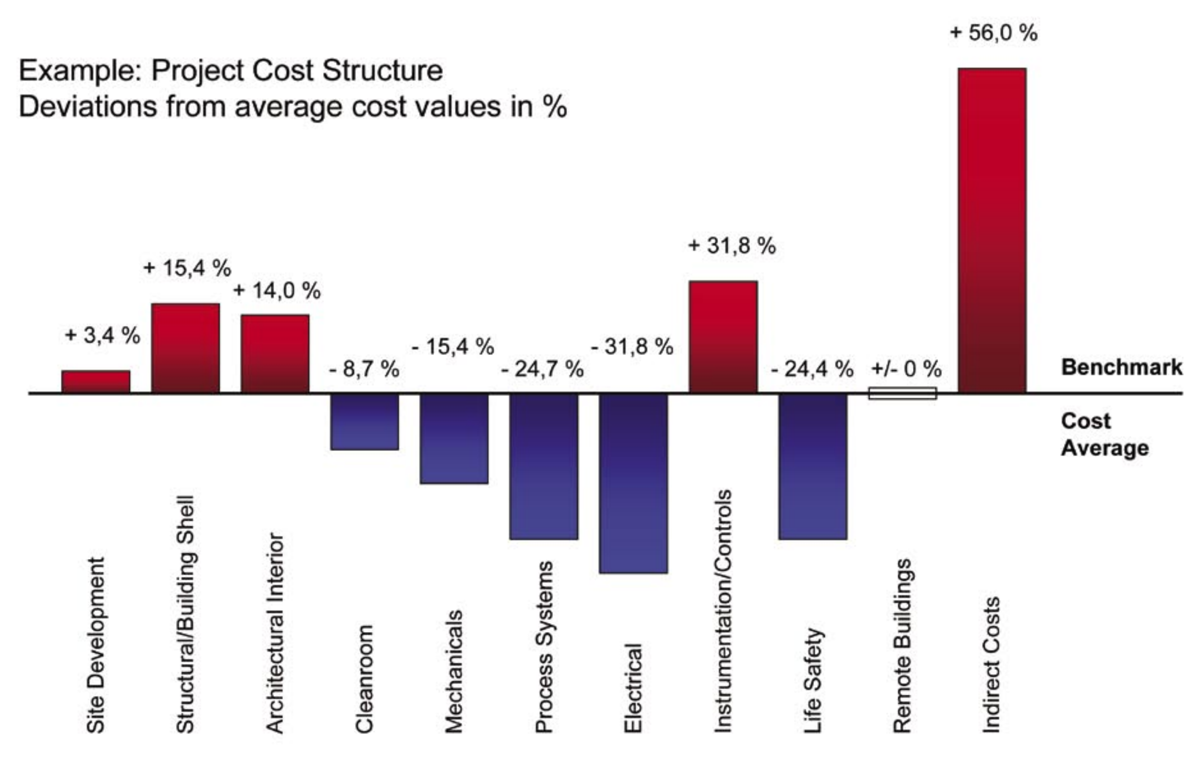


Figure 3. Example benchmark exercise for target costing.

requirements are monitored on an ongoing basis to ensure planning accuracy.

Energy and carbon challenges

With increasing energy supply costs and carbon tariffs, low CO_2 power generation will become more important. From a rational point of view, PV manufacturers should focus on the production optimization and minimization of the energy demand, e.g. by preferring equipment with lower specific consumption figures. Cooling demand should be investigated very carefully. All actions to reduce energy demand should be taken, as well as determining measures of utilisation of waste heat.

Due to the very complex and sensitive cost structure of co-generation plants, power supply should be left to the professionals. At that time, the development of the whole energy price scenery is not convenient for high investment into any power generation system – this is not the core business of a PV manufacturer. The evaluation of the energy and carbon issue is part of the programming phase.

Target costing

Target costing is the basis to achieve savings by evaluating the individual cost targets of scaling factors such as equipment, material, utilities, personnel and building as well as other factors such as area, process complexity and productivity. Using benchmarking and value engineering, the proposed technical solutions can be optimized. The process should start top-down – a critical input for this exercise is the revenue forecast for the product, which should be net of any government subsidies. It is recommended that any such subsidies be treated as additional benefit.

> Due to the very complex and sensitive cost structure of co-generation plants, power supply should be left to the professionals.

As an example, Figure 3 illustrates the deviations per work package from client's budget based on average costs from benchmark data. The analysis shows that the client's overall cost budget was approximately 4.6% (€11million) higher than a budget based on average values.

However, the detailed comparison revealed significant cost differences for nearly all items. Considering the client's cutting-edge technology and future requirements, the costs for the process infrastructure were strongly underestimated, and budgets could be re-allocated accordingly to critical quality-related work packages in order to avoid major changes and claims after contract award.

Glass for PV applications – Hans Mahrenholtz, Linde AG

In the move towards gigawatt-scale manufacturing, greater understanding of the materials used – such as glass substrates – will be required. Key areas of concern include cost, transportation and dedicated supply, especially when photovoltaic production is expanded into regions with fewer glass manufacturing facilities.

Consideration of greater quality control and lower emissions in glass production while controlling costs is also vital in dealing with such a scale of production. Importantly, the number of glass plants will eventually need to be increased, plants that are high in capital expenditure and long in construction.

Currently, both patterned (rolled) and float glass (see Table 1) are used for all types of photovoltaic cells - crystalline silicon and thin-film, as well as in other solar energy systems such as concentrator modules and solar thermal. However, while crystalline cells require only a single sheet in the form of the transparent protective cover, thin-film modules require an additional glass sheet as the substrate. In the case of thin-film, where glass quality requirements are the highest, float glass is the most widely-

Solar Technology	Preferred Glass type	Application
Crystalline silicon PV	Patterned glass	Front cover
Thin-film silicon PV	Float glass	Front cover & substrate

Table 1. Preferred glass types for different solar cell types and applications.

used type. This increased use of glass for thin-film modules means that about 24% of the overall manufacturing BOM is related to glass and TCO coating.

The current annual demand for glass by the solar industry is approximately 37 million m^2. In global terms, this represents less than 0.5% of the current available capacity for high-quality float glass, with most of the output from a typical float glass plant destined for architectural and automotive applications. As you would therefore expect, glass industry expansion is largely aligned with the growth of those large industries.

Given that solar glass is currently such a small share of global float glass output, the demand is largely met by existing glass plants on a batch basis. Notwithstanding the predicted PV industry growth, there are inherent issues with this approach:

- Consistency in key parameters between batches are hard to achieve, leading to varying cell performance
- Inefficiencies due to set-up times when switching from regular float to solar specific sizes and thicknesses add plant downtime and hence unwanted cost
- In many cases the geographical location of PV manufacturing facilities leads to high logistical costs to ship the product from the nearest available source
- "Fresh", recently manufactured glass is preferred to ensure high quality solar cells, so building stock on a batch basis is not necessarily the solution.

Based on projections for PV industry growth of 35% pa, the overall requirement for PV glass by 2011 will be about 84 million m^2, or the output from 22 typical pattern and float glass plants. Table 2 shows the projected development in demand for glass to 2020.

Based on historical investments within the industry, it is unlikely that the top four glass manufacturers alone will cope with the required expansion, especially with the current trend toward gigawatt-scale fab construction activity. Thus, a glass feedstock shortage similar to that of crystalline silicon is a real possibility if additional investment, potentially from new manufacturers, is not forthcoming. It is also worth noting that a new float glass plant can take up to two years to complete, and can cost up to €150M.

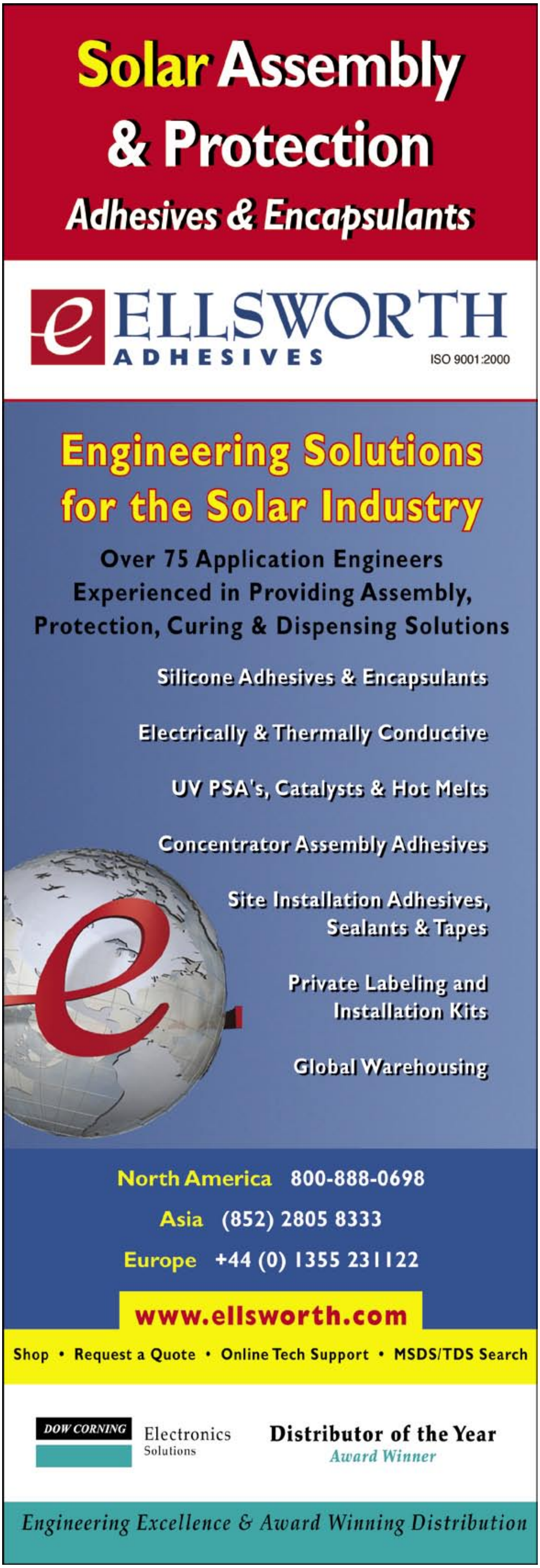
Currently, there are no float glass plants in the world specifically designed for, or dedicated to, thin-film PV glass. For optimum glass properties, PV float glass plants require specific designs for the batch plant to prevent contamination by iron particles, and in areas such as the furnace due to the increase of melt temperatures and the tin bath and the lehr due to an increased cooling effect. The plant output must also be tuned to meet the specific thickness, dimensions and properties demanded for PV applications. Table 3 gives key parameters for float and pattern glass plants.

Environmental challenges

Glass production (and PV float glass in particular) is an energy-intensive process and consideration should be given to optimizing the manufacturing to as great an extent as possible. One area of development is through the use of oxygen instead of air within the melting process. Fuel consumption and CO_2 emissions can be reduced by about 25%. Additionally, the NOx emissions can be reduced by up to 70%.

Depending on a large number of parameters, there are many advantages associated with the use of oxygen in glass melting furnaces and in the glass melts:

- Reduced CO_2, low NOx and particulate emissions
- Improved heat transfer with enhanced glass quality
- Lower capital costs, no air preheating necessary, reduced filtration and furnace requirements
- Increased productivity
- Better control over operations, reduced variation
- Energy savings.



	2006		2011		2020	
	GWp	Million m^2	GWp	Million m^2	GWp	Million m^2
cSI modules	2	14	4	26	50	300
Patterned glass lines (@250t/day)	2		10		35	
TF cells	0.3		7		50	
Front glass		0.5		84		550
Back glass		0.5		78		528
Front glass float lines (@400t/day)			6		40	
Back glass float lines (@400t/day)			6		38	
Total glass lines needed to support PV development	2		22		113	

Table 2. Glass lines needed to support PV developments until 2020.

Parameter	Float line	Pattern line
Typical capacity	400 to 800 tpd	240 tpd (2 x 120 tpd)
	~40,000 to 80,000m^2, 3.2mm	
Land requirements	200 x 600m	100 x 150m
CAPEX	€80 to 150 million	€30 to 45 million
Energy requirements	1,500 kcal/kg of glass	1,000 kcal/kg of glass
	1,125 kcal/kg of glass – oxygen melting	900 kcal/kg of glass – oxygen melting
	70,000 to 140,000 Nm^3/d of natural gas	28,000 Nm^3/d of natural gas
	52,000 to 100,000 Nm^3/d – oxygen	25,000 Nm^3/d – oxygen
Operation	365 days a year, continuous	
	10 to 18 years	8 to 12 years
Time from order to start-up	20 to 24 months	15 to 18 months
Manpower	~ 250 persons	
Major applications	BIPV, TF substrate and cover	transparent protective cover

Table 3. Key parameters for different glass lines.

Gas Technology	$/Watt Impact	$/Year per 65MW line (based on > 500MW scale)
Replace NF_3 by fluorine (material savings only)	$0.03/Watt	$2,000,000
Silane cost reduction	$0.015/Watt	$1,000,000
Optimized hydrogen and nitrogen on-site production	$0.03/Watt	$2,000,000
Dopant blending	$0.001/Watt	$50,000
Helium recycle or removal from process	$0.007/Watt	$450,000
Total	$0.087/Watt	$5,500,000
Potential throughput advantage of F_2 clean	$0.05/Watt	$3,250,000

Table 4. Gas consumption cost reduction approaches.

Performance optimization

There are several known projects where newcomers are planning to build PV solar glass plants and overcome the issues identified by incorporating the following features:

- Production of high-quality ultra-bright float glass for solar applications (3.2mm/4mm) only
- Manufacturing process is optimized for one type of glass to ensure consistency and high quality
- Located close to the PV manufacturer to minimise transport costs and risks
- Provide a feedstock of fresh glass, do not build for stock
- Use latest technologies to reduce costs and emissions

Further development is needed to optimize key glass properties such as optical transmission, mechanical strength, and chemical and environmental resistance to minimise performance degradation over an expected 25 years' lifetime, while ensuring economic manufacturing costs.

Some performance improvements may be achieved through the adoption of on-line functional coatings. Aside from TCO, other coatings such as self-cleaning and anti-reflective are likely to increase the cell performance.

While the major glass manufacturers will no doubt figure highly in the growth of the PV glass market, new manufacturers will emerge, including PV manufacturers, either directly or through co-investment.

Thin-film materials for gigawatt fabs – an insight by Anish Tolia, Linde Electronics

Thin-film silicon-based solar cells have attracted a great deal of attention and investment in the last year. Several companies have recently embarked on large-scale projects ranging from 500MW to 1000MW production capacity.

Reaching this aggressive target for fabs of gigawatt scale depends in large part on reducing the associated direct materials costs associated with the process. Direct material costs in the thin-film silicon

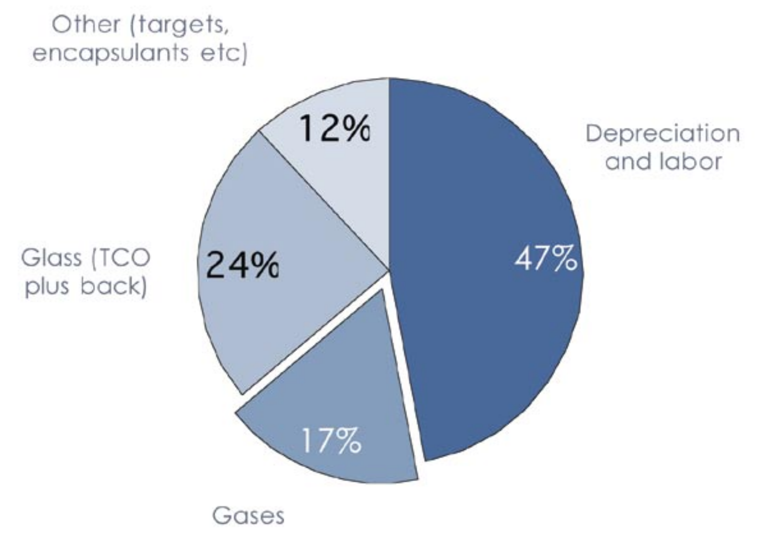


Figure 4. Thin-film cost considerations.

process, particularly tandem junction, can represent over 50% of the cost of production of the module (see Figure 4). Among the direct materials, gases can account for nearly 20% of the cost of module production. Therefore, reducing cost of these critical materials is essential for the success of this technology.

Large-scale manufacturing of solar cells, thin-film silicon in particular, requires very large quantities of gases and chemicals. Figure 5 shows typical consumption of key gases used in a gigawatt-scale fab. While bulk gases have historically been supplied via on-site plants or pipelines from ASU for large industrial users, specialty gases such as silane and NF_3 have never before been used in such large quantities. Gas companies must therefore invest in logistics solutions to supply large quantities of specialty gases. Additionally, large-scale adoption of solar cell production will severely tax the global production capacity of critical gases such as silane. Gas companies must also be willing to invest in additional capacity to meet the growing demand.

In order to successfully impact the cost per watt, gas companies must move from a traditional "supplier" model to becoming an integral part of the solar industry. They must think in terms of overall cost-per-watt reduction and use innovative technologies to lower overall cost per watt.

The critical process step in all thin-film silicon technologies is deposition of doped silicon film from a silane (SiH_4) precursor in a Chemical Vapor Deposition (CVD) system. The result is a thin film of silicon on the glass. Typically, hydrogen (H_2) is also introduced at high flow rates to control the kinetics of the film growth. Dopants are incorporated through precursors such as Trimethyl Boron (TMB), Diborane (B_2H_6) and Phoshphine (PH_3).

This process also results in amorphous silicon deposition on other surfaces in the process chamber, such as the showerhead and chamber walls, which must be periodically cleaned. A fluorine-based etch process using NF_3, SF_6 or F_2 is usually used for this purpose. Finally, nitrogen (N_2) must be used to dilute the pump lines.

Another critical step is the deposition of a transparent conductive oxide (TCO) film on the top glass. This is typically tin oxide or zinc oxide deposited via sputtering or

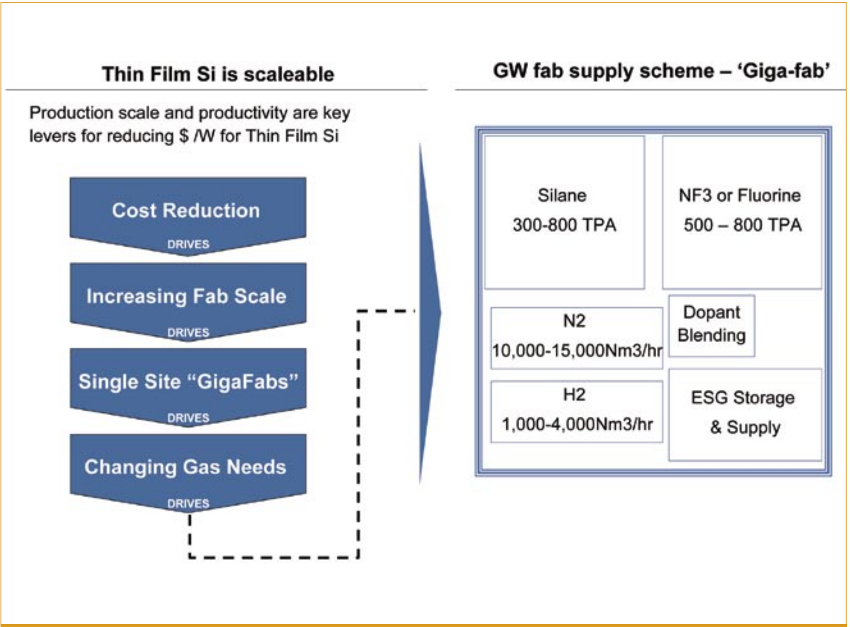


Figure 5. Availability, supply logistics and cost challenges

using an organometallic precursor such as Diethyl Zinc (DEZ).

Figure 6 shows relative consumption of the various gases used for three of the most common types of thin-film manufacturing equipment. Reducing the cost of gases can be achieved in various ways.

On-site generation of bulk gases

Due to the large scale of gigawatt fabs, the economics favour on-site generation of major bulk gases such as hydrogen and nitrogen. This eliminates the transportation and delivery cost and enhances security of supply. Hydrogen is provided through Steam Methane Reformers or electrolytic cells. On-site hydrogen is the preferred delivery method for flows exceeding 150Nm^3/hr.

Nitrogen can also be generated on-site via packaged N_2-generators such as the one shown in Figure 7. Minimum consumption of 1500 Nm^3/hr makes this a cost-effective solution.

Lowering cleaning costs

Approximately 70% of the capital cost and over 40% of the direct materials cost are related to the CVD process that deposits the active silicon layers. The CVD chambers require frequent cleaning of silicon residue. Replacing current methods (NF_3 or SF_6) by using fluorine (F_2) can cut cleaning costs by up to 40%. Fluorine can be generated on-site using packaged fluorine generators such as those shown in Figure 8. The cost benefit breakdown is illustrated in Figure 9.

Increasing throughput

By utilizing F_2-based cleaning, the throughput of the CVD process may be increased by up to 6% at no additional cost. Additionally, additives in the silane gas may increase deposition rates and thereby increase throughput as well.

Improving cell efficiency

The cell efficiency is strongly affected by the composition of the active p-i-n layers in the amorphous and microcrystalline steps. Cell efficiency may be improved by controlling critical impurities or through additives such as disilane.

Silane cost reduction

Silane is the largest contributor to the cost of gases and one in potentially short supply. Silane cost reduction can be achieved through recycling, reducing film thickness and improving film quality and device efficiency by the control of critical impurities. Since these changes impact critical process steps, the impact must be evaluated and the benefits weighed against potential risks.

Dopant management

While dopants (PH_3 and TMB) are used in relatively small quantities, they are very expensive and are typically shipped as 0.5% mixtures in H_2. Since on-site H_2 generators are part of the gas supply solution, costs may be reduced by shipping pure dopants and making the blends on site.

The net effect of all of these programs can result in a significant cost-per-watt reduction. Table 4 shows quantitative cost reductions that can be achieved through this strategic approach to gas use. The cumulative impact of these cost reduction initiatives is illustrated in Figure 10.

Conclusion

While there are many opportunities to drive down cost of production for fabs of large scale, realization of the cost savings will require coordination and partnerships between gas suppliers, equipment suppliers and module manufacturers. Such partnerships must form the new business model in the supply chain if thin-film silicon solar technology is to reach its potential.

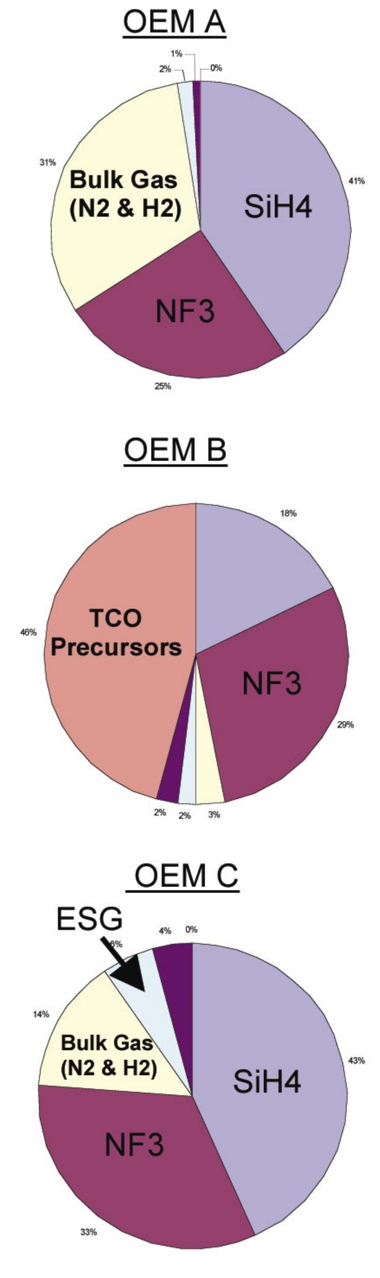


Figure 6. Commonly-used gases for thin-film manufacturing equipment.

Figure 7. On-site nitrogen generation (courtesy of Conergy AG).

Figure 8. On-site fluorine generation.

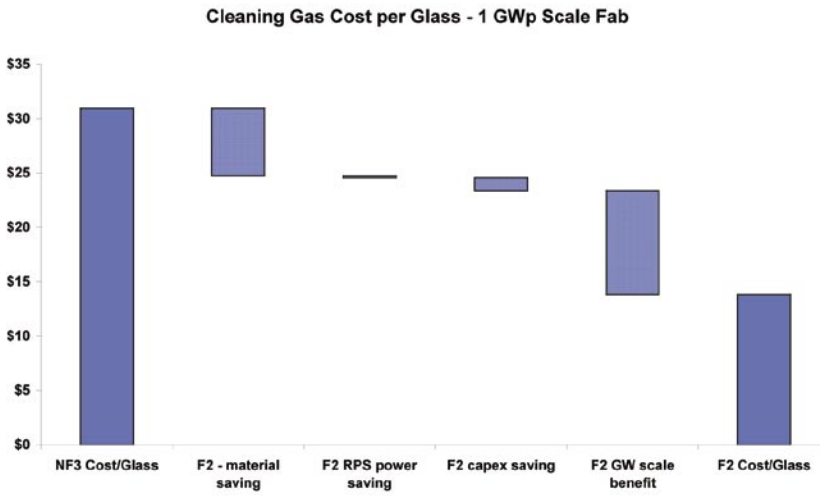


Figure 9. Cleaning gas cost per glass at 1GWp-scale fab.

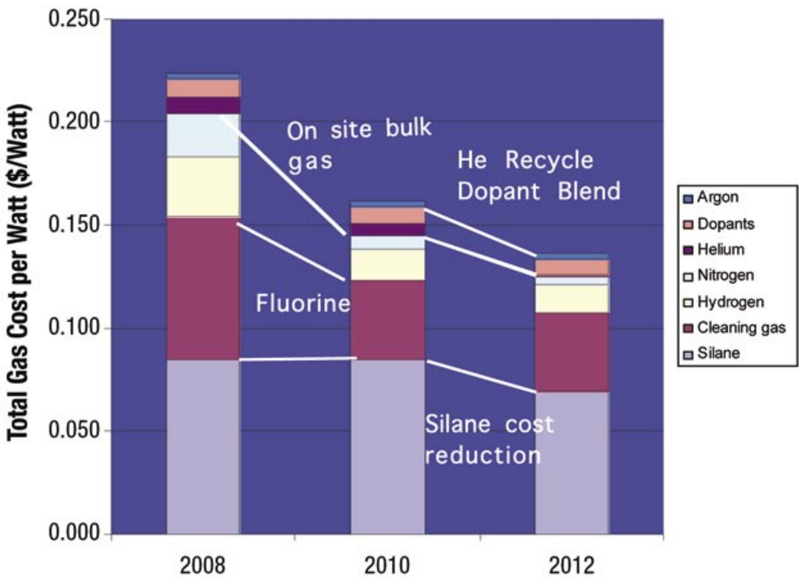


Figure 10. Cumulative cost reduction strategy impact.

About the Authors

Michael Kostwald is Senior Consultant of Turner & Townsend GmbH, within the business unit Design & Management Solutions.

Turner & Townsend GmbH, based in Munich, Germany, covers the high-tech sector within Turner & Townsend and offers independent Design and Management Services for high-tech, high integrated construction projects.

Hans Mahrenholtz is Head of Application Development for the glass market sector in Linde Gas, where he specialises in furnace design and improvements in glass manufacturing technology. Mahrenholtz has a degree in energy, glass & ceramic engineering, and was previously with The SORG Group, a global glass technology company.

Anish Tolia is market development manager for the solar industry for Linde Electronics. He is responsible for strategic marketing, planning, forecasting and business development in the U.S. Prior to joining Linde in early 2008, Tolia spent several years with Applied Materials in technical development. He also served as senior product manager for Photon Dynamics, a market leading inspection and test OEM for the TFT-LCD industry. Tolia has a doctorate in chemical engineering from Purdue University, Indiana, and holds numerous patents that have been published widely in technical journals and presented at conferences.

Enquiries

Michael Kostwald
Turner & Townsend GmbH
St.-Martin-Strasse 76
81541 München
Germany
Tel: +49 (0)89 636 83000
Direct: +49 (0)89 636 86916
Email: michael.kostwald@turntown.com
Web: www.turnerandtownsend.com

Hans Mahrenholtz
Linde AG
Carl von Linde Strasse 25
85716 Unterschleissheim
Germany
Email: hans.mahrenholtz@linde-gas.com

Anish Tolia
The Linde Group
4935A Southfront Road
Livermore
CA 94551
USA
Email: anish.tolia@linde.com