Scaling challenges for photovoltaic manufacturing facilities

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ABSTRACT

The photovoltaic market is currently experiencing a rapid decline in the average selling price per module, resulting in a new era of challenges to reduce the investment and operational costs of manufacturing facilities. Subsequently, PV modules are rapidly gaining acceptance for industrial applications in the renewable energies sector. The PV industry will therefore need to progress toward high volume production of the established process technologies to meet future demand after the current inventory base has been installed. This paper addresses the potential impact of process technology, manufacturing and automation considerations, as well as the appropriate building concepts for large-scale crystalline silicon cell manufacturing. The other inherent advantages and considerations regarding fabs with a capacity approaching one gigawatt peak are also evaluated and discussed based on comparisons between two actual production facilities.

Introduction

The PV module market is in a state of oversupply. Much of the excessive inventory, estimated at close to 3GWp in total (Fig. 1), will be installed while the existing manufacturing base starts to ramp up to the available production capacity. Nevertheless, investments in new manufacturing facilities may occur due to other factors such as emerging PV technologies or changes in national incentives, including tax breaks, subsidies or feed-in tariffs for the generation of power from renewable energy sources. The technology split between silicon-based and thin film (CdTe, a-Si/µ-Si and CIGS) is forecasted to develop from 80% to 20% by 2012.

Therefore, a continued downward trend in the average selling price (ASP) per module is visible, which is expected to increase demand and renew growth in the mid-term.

Renewed market demand for new PV modules is forecasted to grow at a compound annual growth rate (CAGR) of between 20 and 30% over the next few years. In addition to improvements in module efficiency through technological progress and increased manufacturing throughput, photovoltaic manufacturers will also need to reduce the investment and operational costs of their buildings and facilities as a second contributor to reducing the manufacturing cost per watt peak. Both are key factors in attaining grid parity as early as possible.

Process technology outlook

The first focus area to reduce manufacturing cost is still the development of alternative PV technologies and the optimization of existing processes, thereby

Process	Gases, Chemicals & Materials	Layer	Elements in Layer	Elements in Cell
Current Status				
N/A	N/A	Doped Si wafer	Si, B	Si, B, P, N
Doping, dry	$POCl_3$	Active layer doping	P	Ag, Al
Doping, wet	H_3PO_4	Active layer doping	P	
SiN_x – CVD	SiH_4, NH_3	ARC Si_3N_4	Si, N	
SiN_x – Sputter	Targets	ARC Si_3N_4	Si, N	
Metallization	Ag – Paste	Front contact	Ag	
Metallization	Ag / Al – Paste	Back contact	Ag, Al	
Metallization	Al – Paste	Back area	Al	
Base-Metallization	Current Process: Ag, Ni			
Future Trends				
Antireflective Coating		ARC SiO_2	Si, O	O, Ti,
Antireflective Coating		ARC TiO_2	Ti, O	Mg, Ni, Sb,
Metallization	AlMg / Al – Paste	Contacts	Al, Mg	Cu
Metallization	AlMg / NiSb – Paste	Contacts	Al, Mg, Ni, Sb	
Metallization	Cu – Paste	Contacts	Cu	
Future Processes				
P-Doping	In-line technology combined with SEP			Cu, Sn
Selective Emitter Process	In-line technology			
Ag-LIP Process	In-line metallization			
Base-Metallization		Cu-Sn		
Nano-Technology				

Table 1. Current and future elements used for wafer-based PV cell manufacturing.

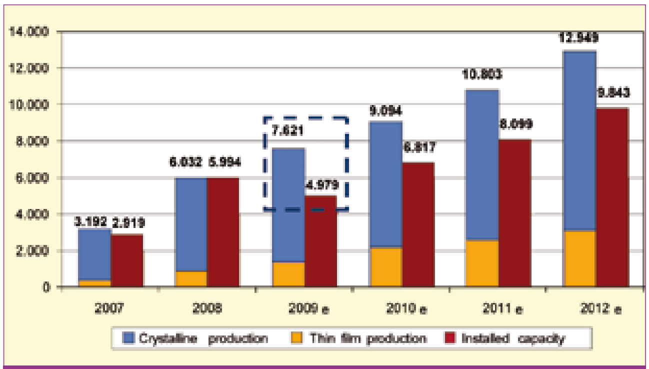

Figure 1. Forecasted gap between global module production capacity and demand [1].

improving average cell and module efficiency and/or simplifying the manufacturing process. Table 1 summarizes the most commonly used elements for wafer-based PV module production in the Periodic table and provides an outlook of elements that are currently being evaluated for new silicon-based process technologies, such as alternative metallization processes by substituting other less expensive metals for silver.

Process technology-driven improvements inevitably impact the design and operation of a manufacturing facility. For instance, with the introduction of new processing materials, alternative process material storage, handling, supply and disposal concepts may need to be implemented.

> "Economies of scale are primarily achieved through the dilution of fixed costs that are independent of production capacity, as well as through the improved utilization of building areas, facility systems, process equipment and automation."

The challenges of large-scale manufacturing

Besides the development of new PV technologies and processes, large-scale manufacturing facilities are recognized as part of the second strategy to reduce the overall cost of manufacturing. The economies of scale are primarily achieved through the dilution of fixed costs that are independent of production capacity, as well as through the improved utilization of building areas, facility systems, process equipment and automation. The key factors include:

- Increased productivity of process equipment
- Higher space utilization of manufacturing and support areas
- Increased ratio of manufacturing area to total building area
- Alternative building concepts, including logistics
- Alternative facility system technologies
- Administration, operations and maintenance staff
- Redundancy of facility system plant equipment
- Advanced engineering and design systems
- Large volume utility supply and disposal contracts (power, water and waste)
- Large volume contracts for consumables and spare parts.

Benchmarking case study

A number of these key factors were examined by benchmarking two multi-crystalline silicon-cell manufacturing facilities of differing capacities. Both are actual projects that have been performed by M+W Zander as the General Contractor (Design/Build or EPC) for

	Design Manufacturing Capacity	Building Concept	Facility Concept	Total Gross Building Area (m²)
Project 1	100MWp	Single-level manufacturing	Facilities integrated in fab building	10,000
Project 2	600MWp	Multi-level manufacturing	Separate central utility building	38,000

Table 2. Key features of M+W Zander reference projects.

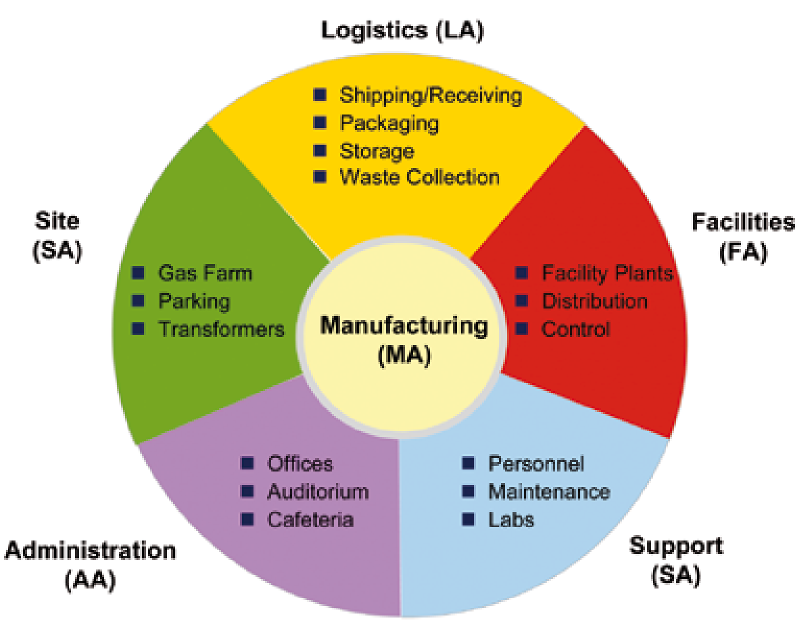

Figure 2. M+W Zander area classification system for PV manufacturing facilities.

the site infrastructure, buildings, facility systems and process tool hook-up. Table 2 outlines the key features of these two projects.

The results of the comparison are discussed by factor in the following sections. For confidentiality reasons, all project-related numbers provided in this article are normalized to arbitrary units where the value for Project 1 (100MWp) was set to 1.

A functional categorization system of the total gross building area is required in order to evaluate the Key Performance Indicators (KPIs) between the projects. Fig. 2 illustrates the building area classification system that was utilized during this investigation.

Productivity considerations

PV cell manufacturing equipment is typically grouped into partial or fully automated production lines of between 80 to 100MWp per line. The automation concepts provide batch or single-substrate transfer and buffering capability between the output loader of a process tool and the input loader of the subsequent equipment. Each line requires a certain level of 'catch-up' manufacturing capacity at the bottleneck tool in order to achieve the average design throughput of the line in the event of unscheduled downtimes. Therefore, other tools may not be fully utilized due to differences in throughput.

In contrast to the 100MWp manufacturing facility, which consists of a single production line as well as all support and facility plant functions, the 600MWp complex within a dedicated manufacturing building can accommodate multiple production lines that are typically installed in linear or U-shape arrangements. To illustrate the comparison, Fig. 3 depicts the linear layout of six individual process lines compared with the integrated 'Smart Farm' approach.

Through improved capacity sharing and implementation of the appropriate automated material handling and manufacturing execution systems, the utilization of process equipment within each dedicated farm can be improved, thereby reducing the overall process equipment count. The decrease in total process tool count in Fig. 2 is 20%, with a corresponding effect on investment and operation costs not only for the process equipment, but also for the required building spaces (manufacturing and support areas) and the facility systems. Another noticeable decrease is the amount of personnel required for operations and maintenance. It should be noted that the Smart Farm concept can also be implemented in a phased capacity ramp strategy.

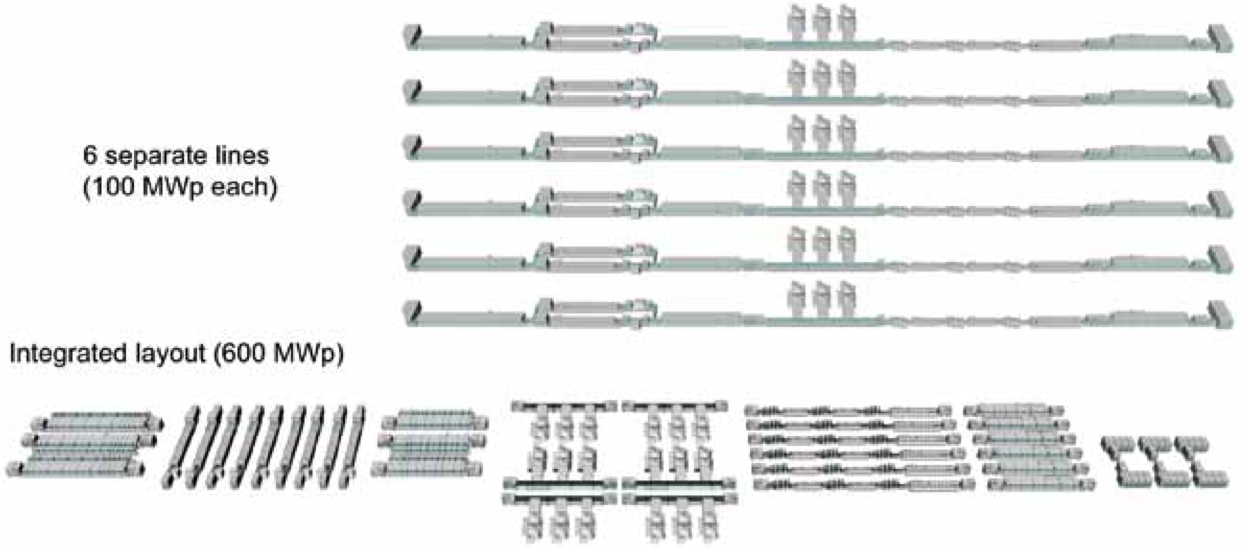

Figure 3. The Smart Farm concept – improving overall equipment utilization through capacity sharing [2].

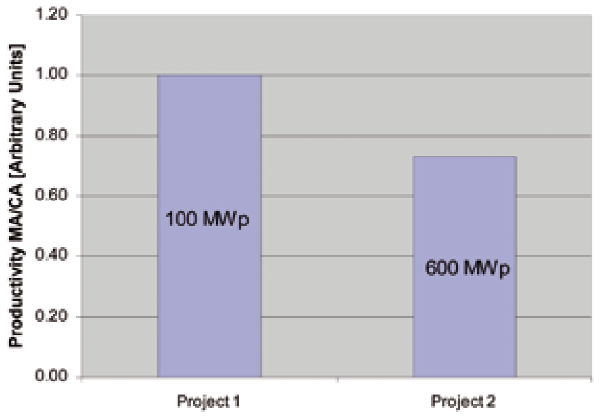

Figure 4. Manufacturing area productivity improvement per capacity in MWp.

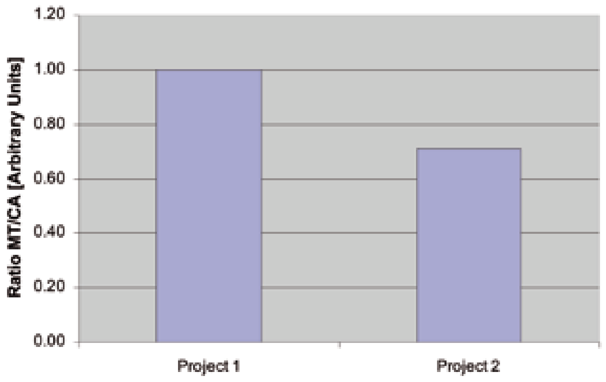

Figure 5. Ratio of tool count vs. manufacturing capacity.

In the selected projects, the productivity enhancement was first determined by evaluating the manufacturing area productivity, a KPI that is calculated by dividing the manufacturing area by the manufacturing capacity. The calculation yields an improvement of 27% in Project 2 (Fig. 4).

The resulting increase in manufacturing area productivity is primarily driven by the reduced process tool count due to the higher overall equipment utilization of Project 2's process equipment set. Additionally, the more efficient utilization of gross manufacturing area between equipment for maintenance, tool move-in and personnel access improves the packing density of the process equipment.

Fig. 5 addresses the KPI Process Tool Productivity, which is determined by dividing the total number of major (value-adding) process equipment by the overall manufacturing capacity.

A reduction of 29% was observed during the evaluation of the reference projects, which again verifies the potential to reduce the overall capital expenditure (CAPEX) for process equipment and the associated facility systems and manufacturing support areas. This benefit may be partially offset by increased investments required for more advanced automated material handling and MES (Manufacturing Execution System) systems.

Redundant plant equipment

Redundant facility plant equipment is installed to ensure that facility system capacity is available around the clock, i.e., even during maintenance or an unplanned shutdown of operational units. A common strategy is to utilize an "n+1" philosophy for all manufacturing-critical systems, but site-specific factors in different countries and regions, such as the reliability of the local electrical power grid, may affect this in order to ensure a sufficiently stable redundancy concept. Table 3 summarizes the redundancy approach for selected large facility plant equipment.

The philosophy selected by the user in Project 1 was to accept a degree of degradation of the HVAC (heating, ventilation and air

	Make-Up Air	Exhaust Fans	Chillers	Transformers
Project 1 (100MWp)	2 + 0 (100%)	2 + 1 (150%)	2 + 1 (150%)	2 + 0 (100%)
Project 2 (600MWp)	4 + 1 (125%)	3 + 1 (133%)	5 + 1 (120%)	2 + 0 (100%)

Table 3. Comparison of the redundancy approach for selected facility plant equipment.

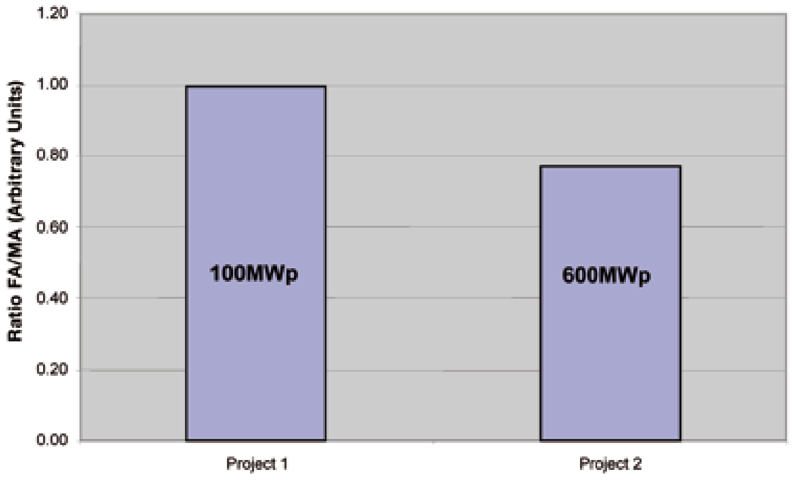

Figure 6. Ratio of facility area to manufacturing area.

conditioning) system with respect to heat removal and temperature stability in the manufacturing area. In most other cases, the percentage contribution of redundant capacity is higher in comparison to Project 2 (600MWp). These differences influence the overall CAPEX of these facility systems on a per MWp basis, thereby favouring the large-scale facility.

The overall effect of reduced redundancy, as well as the installation of larger plant equipment units can be determined by calculating the ratio between the facility area that is required to support the entire PV production complex and the manufacturing area. A lower ratio indicates a lower overall investment per manufacturing capacity by saving building floor space for these functions. An evaluation of the reference projects yielded a reduction of 22.5%, as illustrated in Fig. 6.

> "Process-critical systems drive environmental protection requirements, such as process exhaust systems, gas and chemical storage and waste water treatment."

Alternative building concepts

Photovoltaic manufacturing facilities are purpose-built around the process technology and equipment to be utilized. This affects the specifications pertaining to height development, structural loading, logistics, fire protection zoning, emergency egress concept etc. The process-critical systems drive environmental protection requirements, such as process exhaust systems, gas and chemical storage and waste water treatment.

Fig. 7 depicts the migration of the building concept for cell production facilities. Whereas a 100MWp fab typically consists of a single-storey building with all functions integrated within the building, large-scale manufacturing facilities are often constructed vertically with multiple levels in a similar fashion to flat panel display or semiconductor manufacturing fabricators. This building accommodates the production equipment, selected support functions and the process critical supply systems such as process chemicals, specialty gases, production make-up air handlers and exhaust treatment.

Selected systems such as electrical power supply, chilled and hot water generation, ultra pure water generation, wastewater treatment etc. are centralized and located in a dedicated Central Utility Building (CUB), which may ultimately be shared with a second adjacent fab. The same approach often applies to other site functions, such as an on-site energy supply centre or a logistics building for storage of raw materials or shipping of the final product.

Overall area scaling advantages

The area overhead ratio (also known as the building efficiency factor) is defined as the ratio between the total gross building area and the manufacturing area (Fig. 8). This is a typical KPI for determining the overall efficiency of a building concept.

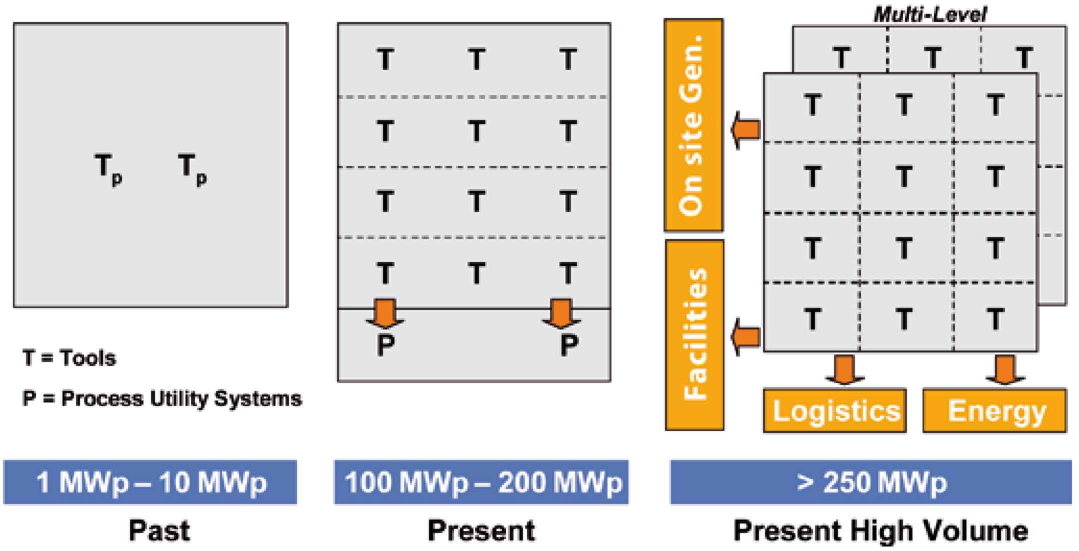

Figure 7. Migration of PV manufacturing building concepts.

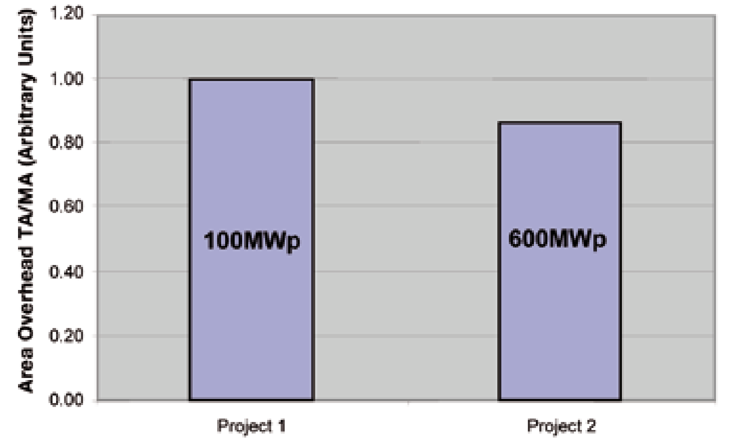

Figure 8. Area overhead ratio comparison.

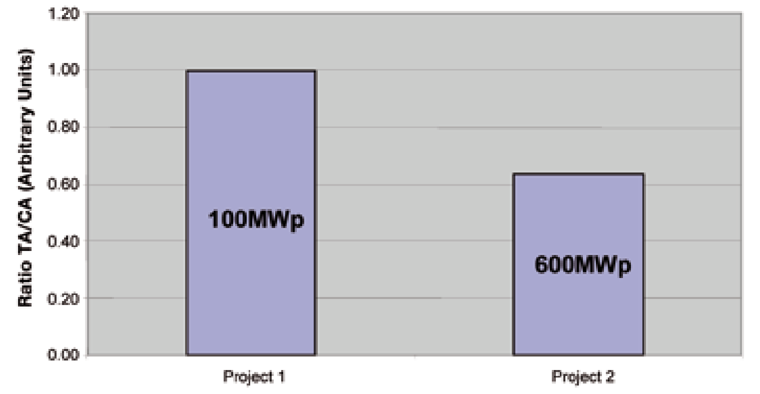

Figure 9. Total gross building area by manufacturing capacity.

A reduction of 13% in the area overhead ratio was observed, which directly reduces the construction cost of the buildings. The reduction is mainly driven by the dilution of administration functions, logistics areas, as well as the higher area efficiency of large facility plant equipment as discussed in the previous section.

A second KPI was calculated to determine the overall reduction in investment for the building and associated facility systems, namely the ratio between the total gross building area and the manufacturing capacity, illustrated in Fig. 9. This KPI is simultaneously influenced by the improvement of the area overhead ratio as well as the manufacturing area productivity.

In this comparison, the required building area per manufacturing capacity was reduced by 36.5%, thereby demonstrating the significant potential to reduce CAPEX for construction of the buildings and the associated facility systems through the migration from medium- to high-volume manufacturing.

Alternative facility system technologies

Large-scale manufacturing facilities also present the opportunity to consider alternative facility system concepts in order to further enhance the energy and environmental efficiency of the overall complex. The implementation of measures such as heat recovery systems is generally

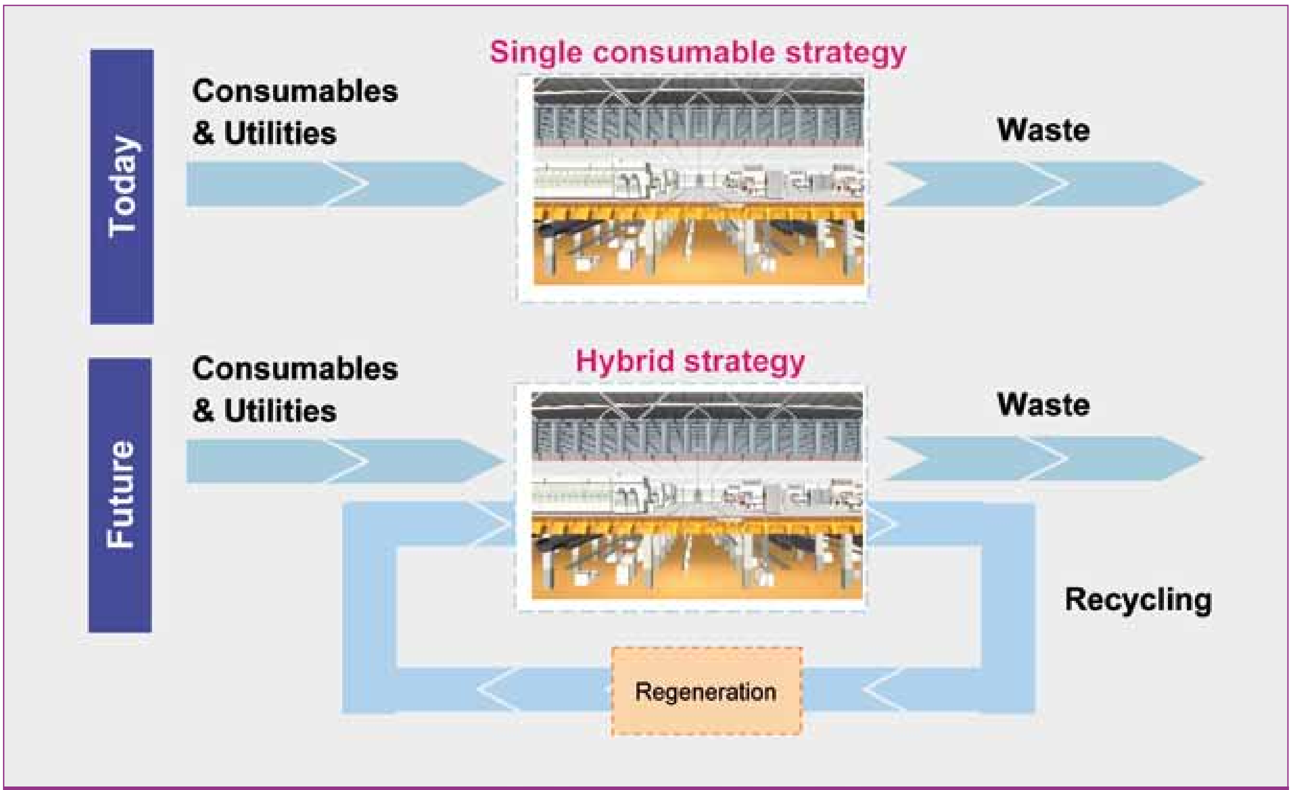

Figure 10. Waste reduction potential – material recycling.

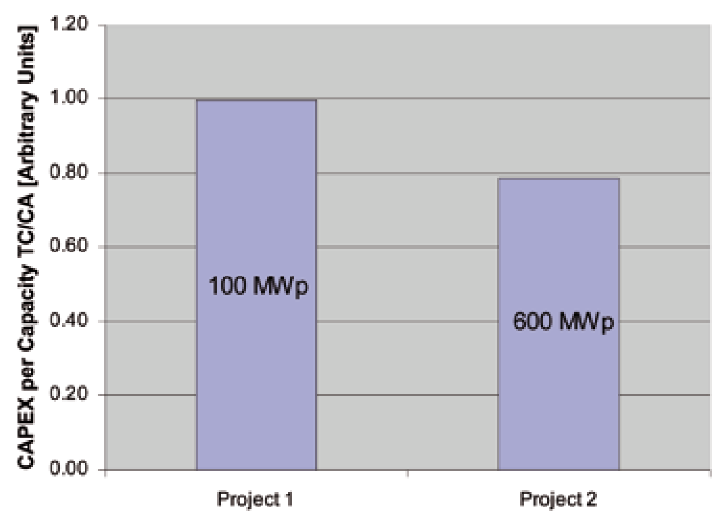

Figure 11. CAPEX per manufacturing capacity for building and facilities.

not viable in smaller manufacturing facilities due to the high specific investment cost on a per MWp basis.

As an example, dual temperature process cooling water (PCW) systems are under evaluation for very large manufacturing facilities. A single system in small factories is designed at the lowest temperature set point required by the process equipment set, although most of the equipment can operate at higher temperature level. A dual temperature PCW system can be designed and optimized according to the actual demand of the equipment, thereby saving cooling capacity and the associated electrical power, which can compensate for the higher initial investment in a secondary system.

The overall electrical demand of a large manufacturing facility complex can favour implementation of a tri-generation power

Figure 12. Architectural impression of the Q-Cells PV manufacturing complex in Malaysia.

plant. Such energy supply centres can simultaneously provide stable electrical power, hot water, as well as chilled water to the campus, and may also be owned and operated by a third party. Compared to conventional power plants, tri-generation plants substantially reduce the primary energy demand of manufacturing facilities. They normally operate with high efficiency gas motors, which further contribute to the overall reduction of the CO_2 footprint of the manufactured product by between 30 to 50% compared to conventional power supply concepts.

Large-scale manufacturing facilities not only promote the implementation of energy-saving measures, but also support waste reduction and material recycling technologies. Such measures often become mandatory in order to minimize the handling and storage volume of hazardous process materials such as HF or other chemicals, which not only reduce manufacturing cost, as shown in the schematic in Fig. 10, but also improve the industry's image regarding environmental compatibility and protection.

On-site bulk gas generation (e.g. hydrogen or fluoride) can be implemented, resulting in lower overall handling and operational costs for gas generation and transport compared to regular shipment of tankers and trailers. For specialty gases, bundle or trailer solutions become feasible compared to bottled systems, thereby reducing gas costs and enhancing handling safety. Furthermore, separate gas shelters can be implemented in lieu of dedicated gas rooms inside a building, thereby reducing the requirements for safety systems.

For ultra pure water (UPW), DIW supply and other process supply systems, savings are primarily driven by the increased system size and higher overall utilization and can be centralized in the CUB building to serve multiple fabs. Secondly, with a linear arrangement of the manufacturing lines (Smart Farm concept), the specific distribution system costs and space requirements are lowered. Particularly for wastewater treatment systems, the Smart Farm concept facilitates the segregation of wastewater flows, thereby enabling the implementation of dedicated treatment methods. Water recycling technologies become more economically viable with increased size of the manufacturing facility, especially if such facilities are located in areas with a limited source of raw water.

In many of the aforementioned opportunities, precise determination of the utility consumption data of all process equipment is essential to enable correct sizing of each facility system and hence minimize CAPEX, which requires improved co-ordination between the process technology team, facility engineering group and the process equipment vendors.

Overall building and facility investment (CAPEX)

In order to evaluate the opportunities of large-scale PV cell manufacturing facilities, the overall CAPEX per manufacturing capacity for the buildings and facilities of the benchmarked projects was evaluated. This comparison includes the investment for site development, building structure, architectural interiors, the mechanical, electrical and process utility systems as well as the electrical control and life safety systems. Normalized values were applied to account for exchange rate differences, local climate and site-specific requirements (such as foundations). A reduction of 21.3% of the normalized CAPEX was determined (Fig. 11). The overall CAPEX reduction would be higher when taking the lower number of process equipment into account, which results from implementation of layout concepts, such as the Smart Farm approach, into account.

As described previously, the major contribution to CAPEX savings is the reduction of required building area by increased area efficiency (production and facilities), lower facility system capacities due to the smaller process equipment set, as well as by the diluted overhead functions (administration, support and logistics). These savings are greater than the additional investment in the sustainability of the complex. Furthermore, the operational expenditure (OPEX) is also substantially decreased through an improved redundancy strategy and higher utilization of less production equipment and the corresponding facility systems.

Figure 13. Side view of the Q-Cells cell manufacturing building in Malaysia.

Figure 14. Overhead utility connections to process equipment in the manufacturing area.

Figure 15. View of the Central Utilities Building (CUB).

Case study: large-scale cell manufacturing facility

One example of a large-scale manufacturing facility is Q-Cells' new cell production building in Malaysia. It constitutes the first phase of a planned gigawatt production complex with various technologies in the future. The location was a greenfield site with no available infrastructure. In order to achieve a fast-track schedule approach, design standardization was critical for all building systems and mechanical, electrical and process systems with a high level of flexibility for future requirements.

Figure 12 illustrates the overall complex, which consists of multiple cell manufacturing buildings, a central logistics building and site functions including a bulk gas yard and energy supply. A particular feature of the design is an interconnecting ('spine') building to enable inter-building material and personnel flow as well as utility distribution.

The Cell Manufacturing building, shown in Fig. 13, is a triple-storey complex consisting of two levels to accommodate the cell production lines, and a ground floor for logistics and building-specific facility systems such as electrical distribution, HVAC and process systems. The Spine building features a similar height development with co-planar floors on all three levels. This concept allows multiple usage of the building, where the major functions on the ground floor (material flow and inter-building facility connections) can be separated from personnel flow on the upper levels. It also contains a large data centre, gowning rooms and office space to support the first cell building.

The Logistics building is a single-storey unit adapted to the requirements of a warehouse. This includes dedicated HVAC and electrical distribution systems as well as the appropriate building height and building column grid spacing for the installation of fully automated high-bay storage systems.

The Central Utilities Building (CUB) supplies the cell building with chilled water, make-up water for the UPW plant and electrical power distribution. The CUB also houses the necessary expansion space of these systems for future manufacturing facilities (Fig. 15).

Centralized site functions for multiple buildings include the primary electrical

Feature	Definition KPI	Ratio	Project 1	Project 2
Capacity (MWp)		CA	100	600
Process Tool Utilization	Major Tools by Capacity	MT/CA	1.00	0.71
Basebuild Investment	CAPEX for Buildings & Facilities by Capacity	TC/CA	1.00	0.79
Area Overhead Ratio	Total Building Area by Manufacturing Area	TA/MA	1.00	0.87
Facilities Overhead	Facilities Area by Manufacturing Area	FA/MA	1.00	0.77
Manufacturing Productivity	Manufacturing Area by Capacity	MA/CA	1.00	0.73
Overall Productivity	Total Building Area by Capacity	TA/CA	1.00	0.64

Table 4. Overview of the Key Performance Indicator (KPI) comparison.

substation, fire protection tanks and pump house, FMCS/Fire Alarm Centre and a wastewater treatment plant.

Construction of the Cell building and associated functions was completed in less than eight months, commencing with the foundations and ending in Ready for Equipment (RFE). The first process line was fully installed, started up and qualified within three months. Production of the first cells commenced in 2Q09 and commercially available cells are scheduled for shipment in 4Q09.

Considerations

Although significant CAPEX and OPEX saving opportunities have been demonstrated with the migration from medium- to large-scale manufacturing facilities, other factors need to be considered when developing a business case, such as the increased upfront investment in buildings and facilities, especially if the ramp schedule between pilot and full mass production is prolonged. In the case of a high volume manufacturing complex, a non-scheduled production shutdown will have a severe impact on overall manufacturing capacity, even for the larger cell manufacturing companies.

Furthermore, the selection criteria for the location of a large-scale production site, such as the adequate availability of water and power utilities, become more stringent. With respect to facility design, the high availability criteria for a broad range of facility systems has become mandatory, thereby driving considerations such as robust design, sufficient system redundancy, and high quality of key system components.

The size of a single factory or site may be limited by asset protection considerations, the insurer's requirement and local safety and environmental codes and regulations. As an example of the latter, the consumption of some hazardous process materials has also resulted in comprehensive evaluation of recycling technologies.

Due to the higher initial investment for large-scale manufacturing facilities, a sustainable design of the complex is a critical factor in order to cope with future process and manufacturing technology development and avoid premature obsolescence of the factory. Appropriate design strategies and solutions can be transferred from other industries such as semiconductor or flat panel displays where a high level of volatility of process, product and technology development can be observed.

Conclusions

Despite current market conditions, the PV industry is maturing at a rapid pace in terms of large-scale manufacturing of its mainstream technologies that will drive the reduction in manufactured cost per Watt peak in order to attain grid parity in many regions and countries.

It has been demonstrated what level of economies of scale can be achieved through implementation of cell production buildings with a manufacturing capacity of 600MWp. The major contributors to these savings are the reduced investment in process equipment through higher utilization, as well as a reduction in all building areas and facility system capacities.

Improvements in economies of scale calculated during the benchmarking evaluation of the selected fabs in this paper are summarized in Table 4. The Basebuild Investment KPI quantifies the overall reduction in normalized investment for the building and facilities from a CAPEX perspective by over 21%. The larger saving in the number of process equipment, generated by the improvement in their overall productivity, would further improve the overall CAPEX productivity KPI.

Additional benefits of a large-scale facility include its ability to facilitate further reductions in manufacturing cost per Watt, and to improve environmental compliance. Additionally, alternative facility system and building design approaches, including low CO_2 discharge energy supply concepts and enhanced waste collection and recycling technologies are possible.

When evaluating the business case for a large-scale facility, certain considerations should also be discussed and clarified.

The key criteria for the successful design and execution of a large-scale cell manufacturing facility on a fast track schedule include:

- Production space flexibility.
- Centralized plant with modular design/expansion.
- Accurate determination of current utility consumption data of the process equipment and allowance for future process development requirements.
- Standardized construction methods.
- Increasing production environment requirements for future technology nodes with higher efficiencies.
- Commercial procurement strategy for large-scale multiple fab sites.

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Hartmut Schneider is deputy manager of M+W Zander's Global Technology Services Group and is responsible for industrial engineering activities. This includes a range of services to define the fab concept, the process equipment layout of the cleanroom, support areas, utility requirements and the automation concept as well as to consult on operational and process-related design issues. He joined the company in 1991 and has a degree in physics from the University of Stuttgart, Germany.

Martin Beigl is Managing Director of M+W Zander's European Division. He has an extensive background in the design of all types of mechanical and utility systems for advanced technology facilities, as well as specialized experience in the design and construction management of cleanroom systems, including HVAC systems, environmental control, cleanroom layouts, air management and particle control. He joined the company in 1985 and received his engineering degree in mechanical engineering from the Fachhochschule Esslingen, Germany.

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