Evaluation of Factory Infrastructure for Next-Generation PV Manufacturing

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ABSTRACT

The cost of PV modules has fallen rapidly over the last decade which continues to squeeze the profit margins of PV manufacturers. PV factory owners' value cost effectiveness, execution efficiency, predictability, and safety in factory construction to get their PV product out in the market in a timely manner. The development of a cost and energy efficient PV cell and module manufacturing facility is crucial to manage overall factory CAPEX and OPEX. M+W's approach to PV facilities construction involves a deep collaboration with the manufacturer to define process technology, equipment, and production environment needs. This forms the basis to optimize the arrangement of the various functional areas, the utility distribution network, the facility systems, and the facility's environmental control. M+W has developed a factory design concept for PV technology that delivers production materials into the facility, and ships out finished PV modules with minimal site and utility impact. M+W has also benchmarked the cost and design attributes of several PV factories it has built over the last 15-years that facilitates new projects in a fast and a lean fashion to maintain a low CAPEX.

Keywords: PV, manufacturing facility, thin-film, CdTe, CIGS, c-Si, factory CAPEX

1 INTRODUCTION

PV module prices have dropped dramatically over the last decade, and they continue to do so in 2016. PV module prices, at the end of 2016, were $0.35/W [1]. Next generation module manufacturing requires the overall PV factory CAPEX of <$0.65/W to maintain a healthy debt [2]. Facilities CAPEX, which includes the building shell and the interior works, is typically 20% of the overall factory CAPEX (i.e. $0.13/W). Previous studies [2] indicate that halving CAPEX could reduce minimum sustainable module prices by $0.13/W (15% relative), providing significant progress toward achieving the U.S. Department of Energy's SunShot module price target for the industry. CAPEX is an important metric that helps explain certain industry-wide trends related to scale and innovation such as: a) company's sustainable growth rate, b) the interdependence of ROI (Return on Investment) on margin and CAPEX, and c) barriers faced by companies seeking to scale up innovative technologies into commercial production.

The design and construction of PV facilities need to be tremendously lean to maintain low costs and yet be able to deliver on a schedule that allows the manufacturers to enter the market at the right time. Facilities design also needs to quickly adapt to changing PV technologies, manufacturing tools, automation, and process flows with minimal cost and schedule impact.

M+W proposes a factory design concept for emerging PV technologies that delivers PV production materials into the facility, and ships out finished PV modules with minimal site and utilities impact. M+W is an engineering and construction company in the advanced technology facilities space across sectors such as Semiconductor, PV, Science & Research, and Flat Panel Displays. M+W builds manufacturing facilities, and is also focused on the engineering of complex infrastructure such as cleanrooms, dryrooms, and controlled environments. M+W was established in Germany in 1912, has over $3B in annual sales, and is present in 30+ countries.

2 APPROACH: PV FACILITY DESIGN

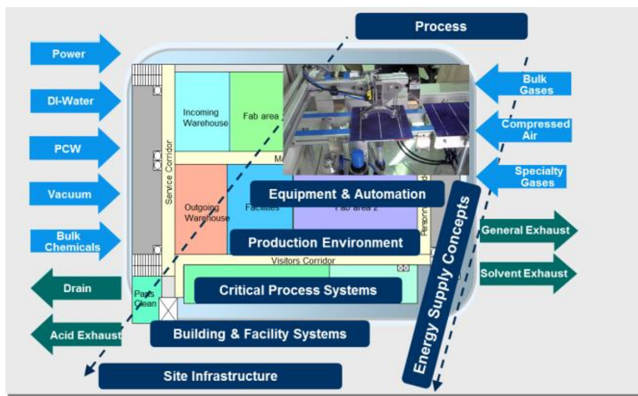

Figure 1: Impact of PV technology on facilities design

The reduction of the overall CAPEX and OPEX of a PV facility is achieved by engineering the manufacturing facility to sufficiently meet the quality and quantity specifications as required by the manufacturing process. The key is not to over-engineer the facility. To that end, M+W has developed an inside-out approach to facilities design (see Fig. 1), which first develops a deep understanding of the manufacturer's process technology and the production specifications and then develops the necessary facilities infrastructure to support the scale-up. M+W specializes in the advanced technology industry and has in-house technology experts that have specific domain expertise in their field of manufacturing. In the case of PV, M+W's in-house PV technologists develop a blueprint of the owners manufacturing process technology, process flows, and the environmental requirements. A process tool-list and tool specifications (dimensions) are developed that assist in the design of layouts for the production floor and other facility areas. The technologists also develop specifications for the production environment (temperature, humidity, contamination requirements) to meet production quality standards of the manufacturer. A utility matrix is established that collects utility consumption data (liquids, power, bulk gases, specialty chemicals, drains, etc.) from the process tools and facilities areas. Typical utilities coming into the process tools and leaving the facility are indicated by blue and green arrows (see Fig. 1). The knowledge of the utility consumptions, tool layouts, and the production environment specifications facilitate the overall sizing of the production and other support areas and the design of critical process, building, and facility systems. The process systems deliver water, bulk gases, and chemicals to the process tools, and treat (and then drain) the utilities flowing out of the tools. The building and facility systems manage exhaust (general, acid, laser, solvent, etc.), make-up air, and facility HVAC. Energy supply concepts that optimize the overall energy use (through energy efficiency, heat recovery, etc.) in the facilities are developed at this stage. These include both design (efficiency of facility system itself) and operational (i.e. optimizing temperature/pressure set-points, redundancies, etc.) aspects. M+W's in-house experts also cover architectural, structural, and permitting disciplines that review facility code compliance, roof and structure integrity, and all the permitting related requirements with the city or the town (e.g. building permits, air permits, etc.). Finally, site infrastructure needs such as bulk-gas generation yards (Eg. N_2, Ar, O_2), electrical sub-station needs, alternative power generation, landscaping, parking, and commercial traffic flows are developed. The function, operation and shape of any PV facility are primarily driven by process and manufacturing requirements. This inside-out approach to factory design balances the manufacturing needs with the level of facilities engineering effort that is required to get a high-quality product shipped out of the facility.

3 PV FACTORY CONCEPT

M+W has developed a factory concept that is applicable to both thin-film as well as Silicon cell and module facilities. The following description assumes a greenfield factory. Manufacturers may also consider brownfield factories (existing buildings) to keep their CAPEX costs low, and improve their time to market. Such factories may require a higher degree of re-engineering of the existing shell, layouts, and facility systems to accommodate manufacturing needs as compared to greenfield projects. As shown in Fig. 2, the facility is proposed at a single-level with the facilities areas located adjacent to the manufacturing space. This allows efficient flow of utilities between the manufacturing and the facilities areas. Also, any future expansion of the manufacturing and the supporting facilities area can occur in the same direction. The facilities area typically contains process and mechanical equipment for water, gases, solvents, and air-handling (e.g. exhaust), abatement etc. It also contains electrical equipment such as switchgears. It is common to locate certain facility areas outside of the walls of the building, but within the project site. These facility areas may contain gas yards, volume storage tanks for consumables, or certain utilities infrastructure that supports the building. The main manufacturing area contains the process tools along with the automation/handling systems. The pieces of equipment are organized in a ballroom fashion. The cluster of manufacturing equipment is referred to as a 'line' with a certain nameplate capacity (e.g. 100 MW/year/line). One or several of such 'lines' are organized in parallel. The support areas consist of failure analysis lab (containing materials composition, microscopy, etc. tools) and a machine shop. It is also common for certain large first-of-a-kind manufacturing facilities to accommodate a pilot (or R&D) line that drives technology development (not shown in Fig. 1) roadmap. Such an R&D line can be located in the vicinity of the main manufacturing area to allow a smooth porting of next-generation materials and process development know-how into production tools. The logistics area consists of storage for incoming glass and other consumables, warehouse for out-going product (palettes of PV modules), tool-staging, and shipping-receiving areas. The administration area contains offices, breakrooms, and gowning areas. The factory layout aims to maximize efficiency of material and personnel flow through the various fab areas to ensure maximum output from the facility with minimum energy consumption. This is achieved through a floor layout that allows direct connection of all supporting fab areas with the main manufacturing area. Unlike semiconductor fabs, PV fabs do not have as large a proportion of process chemicals and gases per square foot of the manufacturing space. Hence, the facilities area is a smaller proportion of the overall fab space. A multi-level building with clear horizontal separation between facilities areas and fab areas, which is typical in a semiconductor fab, is not necessary in PV. All the chemicals, gases, and solvents are handled locally within the facilities area shown in Fig. 2 and dispersed to the manufacturing tools. There are critical safety considerations when handling process chemicals. PV manufacturing technology uses a variety of process chemicals that can be toxic, carcinogenic, corrosive, or flammable. These include materials and gases used in CdTe, CIGS, and Si PV technologies such as Hydrogen Selenide (H_2S), Hydrogen Sulfide (H_2Se), Hydrogen Fluoride (HF), Silanes, Phosphines, Diboranes, Cadium compounds, amongst many others. There are several containment strategies to consider for the prevention of safety hazards related to such chemicals and gases. These can include strategies such as: a) storing as minimum volumes as possible, b) locating scrubbers outdoors, or in a very ventilated area, c) storing cylinders separately from toxic, corrosive, flammable, oxidizing, and water-reactive materials, d) purging storage cabinets continuously with N_2, with highly velocity airflow through several ports, e) explosion resistant cabinets with pads, roof, double fences, and fire protection sprinklers, f) installing gas monitors with automatic shut-off valves at the cylinder, and g) making all exhaust lines of non-combustible materials. These strategies [3] ensure that fab safety is not compromised in any way.

design criterion consider a specification of 66-72 dB (ISO op. theatre to VC-A). Failure analysis labs may contain electron microscopes, X-Ray tools, or certain e-beam optical inspection tools. If this is the case, then a specification as low as 48 dB (VC-D) may be necessary. This is achieved by engineering the walls, floors, or the pedestals on which the tools are mounted to manage the acoustic considerations.

The design and construction of PV facilities needs to be rapid enough to allow manufacturers to meet demand for the product. M+W implements several strategies to reduce manufacturer's time to market. Typical PV projects go

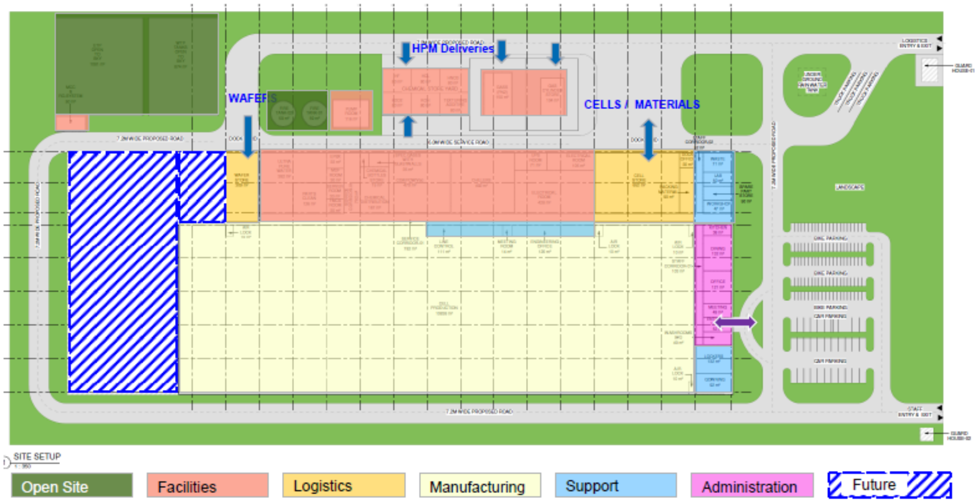

Figure 2: Generic site plan for a PV cell facility

Most PV technologies do not need cleanrooms of any type. Traditional thin-film technologies such as CdTe and CIGS are tolerant to normal atmospheric contamination and require the facility areas and manufacturing personnel to maintain only a general level of cleanliness. Certain Silicon PV cell technologies, particularly those requiring the integration of thin-film manufacturing processes such as lithography, PECVD, etc. require clean manufacturing areas (typically ISO 8). PV technologies are tolerant to a certain degree of temperature and humidity fluctuations in the environment that they are processed. High degree of humidity can be an issue with the stability and life of the PV cell, since warranties require that the PV product last 25-years in the field. A relative humidity specification of 40% to 60% needs to be maintained within the facility, which can be achieved by engineering the air-handling and dehumidification systems in the manufacturing areas. A temperature of 23°C +- 2°C in the fab is sufficient across various PV technologies, and allows HVAC related to costs to be low. The HVAC complexity and costs also depend on the climatic region where the factory is located. There are certain vibration criteria for the fab, in certain isolated areas. Typically, laser and mechanical patterning tools (e.g. in thin-film PV fabs) drive any vibration specifications in the manufacturing areas. Feature sizes in the technologies can be in the range of a 20-150 um, and require that the

through a design process, after which, work packages for construction are developed, and then the project is bid out for construction. M+W involves in-house procurement early-on in the concept design process. This allows pre-qualification of vendors and development of long-lead item work packages well before the detailed facility design process is complete and the project is ready for construction. On a PV project, 3-6 months of savings can be realized through this approach. Another strategy M+W deploys is the use of prefabricated construction modules wherever possible. Examples of these are the use of pre-fab buildings, modular cleanrooms, pre-fab piping racks, and equipment skids that are manufactured in an off-site facility and delivered to the project site. Even process tool installation modules such as high-purity piping can be assembled, welded, and leak checked off-site prior to delivery. This helps reduce project schedule and labor cost, especially in an environment where union labor rates are mandated. The above construction strategies are commonly deployed on PV projects.

4 PV FACTORY BENCHMARKS

M+W's global PV experience covers a spectrum of technologies: CIGS, CdTe, GaAs, crystalline Silicon, amongst others. M+W maintains a database of benchmarks, which contains critical facility design and cost related data from every facility that M+W has built. These benchmark numbers enable M+W to progressively reduce CAPEX on new factories by engineering the facility only to required manufacturing specifications. The benchmark data also serves as an experience and educational tool for PV manufacturers that scale-up for the first time by providing facility specifications that their PV technology is likely to need.

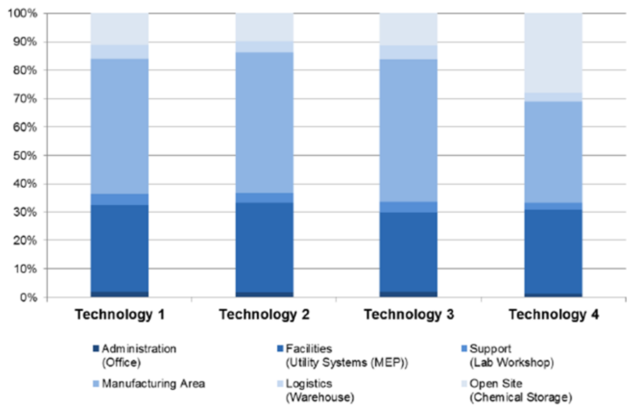

Figure 3: Area breakdown in a PV manufacturing facility

Figure 3 shows area comparisons between facility areas for different PV technologies. Manufacturing area is typically 40-50% of the overall site area, followed by facilities (30%), open site areas for chemical storage (15-30%), warehouse (<5%), support areas (<5%), and administration (<2%). This breakdown is fairly even across different technologies except for technology 4, where the open site area has a larger proportion at the expense of the manufacturing area in that project. The process chemistries and consumptions between different PV technologies tend to be drastically different. The chemical storage area may have certain restrictions to meet codes (due to their hazardous nature) or the quantities may be very large. Hence, the ratio of the open site area (area that houses certain process chemicals or gases) to the overall manufacturing area is different in the case of technology 4.

Figure 4 shows the breakdown in the cost of building the manufacturing facility across different PV technologies. There are three significant cost components for a factory: CSA (Civil, Structural, Building Architecture), MEP (Mechanical, Electrical, Process, and Life Safety systems), and CR (Cleanroom). CSA includes work on the building shell itself while MEP includes all interior works that covers aspects such as the facility systems, process piping, electrical, and all ductwork. For PV, 65-70% of the cost of the facility is for MEP, while 30% is for CSA. Cleanrooms cost <5% of the facility since the specification and the area covered is minimal. The high MEP portion of the costs reflect the level of detail in the interior works that is necessary in an advanced technology manufacturing facility. The MEP to CSA cost ratio in PV is expected to be in the range of other advanced technology industries such as semiconductor and flat panel displays.

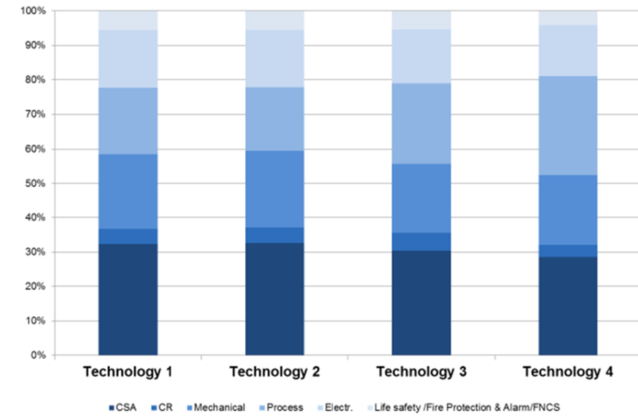

Figure 4: PV facility design and construction costs

5 SUMMARY

PV module costs have been falling dramatically over the last few years and the manufacturer's profit margins are under pressure. The industry is also witnessing unpredictable geographical shifts in global PV demand. The PV industry values attributes such as low CAPEX, time to market, and flexibility in implementing new technologies. It is important for manufacturers to get a quality PV product out of the facility fast enough to meet the wave of incoming demand. M+W proposes an inside-out approach to PV facilities design that develops a deep understanding of the manufacturer's PV technology and the required environmental specifications to drive engineering of the facility at low CAPEX. M+W has developed a low-cost and rapidly adaptable factory concept that deploys prefabricated construction modules for PV facilities to address the needs of the manufacturer. M+W has built several PV facilities globally and has collected statistical benchmark data on fab area characteristics, utility design, and construction cost breakdowns. The benchmark data and the experience of building several PV facilities globally enables M+W to continuously reduce fab construction costs and deliver quality PV fab projects in a timely manner.

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