Scaling up: aiding solar manufacturers using lessons learned from past high-tech industry scale-ups

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ABSTRACT

As demand for solar products prompts producers to scale up their manufacturing operations, CH2M HILL's advanced technology manufacturing experts consider some of the most significant issues related to factory expansion. This article consists of the direct experiences these experts have gained from the scale-up activity in other industries with technological similarity to solar – most notably from the semiconductor and flat panel realms.

Introduction

Solar PV manufacturers have pressing needs to build new or expand existing operating facilities to gain market share and meet business objectives. The drivers for the owner are familiar ones of schedule, cost and quality. However, most of these companies have limited resources and their expertise is often focused on technology, finance, and operations – not on building factories. Dealing with all the details (e.g. permitting, contracting, site selection, equipment selection and utility needs) presents a daunting logistical challenge. Missteps during this process can cost money, cause schedule slippage and adversely affect the resulting quality of facility and product, ultimately impacting a company's bottom line.

Like owners in industries that preceded them, solar manufacturers need all the insight they can find to correctly calculate their individual risk/reward profiles. Many of those insights can be gained by looking to the lessons learned in manufacturing industries whose processing technologies have much in common with solar: semiconductors and flat panel displays. The authors' extensive experience in both of these more mature industries has given us many insights to solar PV manufacturing. In this article we focus on a few of the most important considerations owners need to ponder before deciding where, how, and when they should consider scaling up their operations.

Because solar processing technologies are diverse, there is no one-size-fits-all roadmap to solar scale-up decision-making. Each solar processing technology (c-Si, a-Si, CdTe, CIGS, etc.) has its own unique wrinkles. Neither the smaller producers nor the industry leaders are immune to the challenges and risk of learning painful lessons through growth. The history of growth in related industries has repeatedly reminded us that there are many opportunities to go down the wrong path, particularly for producers coming out of a pure research background or buying turnkey solutions.

Semiconductor manufacturing experienced many challenges related to growing pains during the late 1980s and early 1990s. The benefits of scaling up were supported by solid metrics; the conversion to 300mm wafers and the 'geometry shrink' driven by Moore's Law around the turn of the century provided a combined output advantage equal to 4x per wafer and a 30% cost reduction. But despite the benefits, the whole process of scaling up sites, structures, and the quantities of chemicals, gasses, materials and throughput was a rough learning experience for many in the business.

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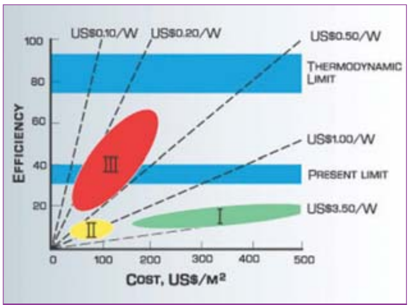
Flat panel display manufacturing also endured a steep learning curve, especially because the industry's facilities are inherently large to begin with. In a period of just four years, the flat panel industry sprinted from Generation 3 glass panels (measuring roughly 550mm x 650mm) to Generation 10 panels (2,880 x 3,130mm). Generation 11 dimensions of more than 3,000mm per side are not far behind.

The solar industry today is at a crossroads of its own, as owners contemplate production capacities of a gigawatt and beyond. As shown in Fig. 1, solar product efficiencies are expected to steadily increase, with a corresponding steep drop in cost ($/watt).



Source: University of New South Wales.

Figure 1. Efficiency and cost projections for first-, second- and third-generation photovoltaic technology.

Putting building and facility costs into perspective

Rather than focusing only on the straightforward aspects of scaling up manufacturing capacity, such as increasing the size of a facility and the number of tools a facility houses, it is informative to look at increasing a facility's productivity and output in terms of 'cost per megawatt,' just as the semiconductor industry used the metrics of 'cost per computation' or 'cost per memory.'

Using 'cost per megawatt,' we arrive at four strategies for scaling up solar facilities:

1. Provide the flexibility to integrate novel manufacturing technology improvements into a facility. This strategy does not have to involve higher facility costs, but rather attention to the details that allow an owner to anticipate and incorporate future improvements.
2. Increase the throughput of a plant's processing equipment using manufacturing integration and Lean manufacturing principles, automation, optimization of line balancing and cycle times, etc.
3. Increase the size of substrates produced where technically feasible.
4. Take the conventional approach of increasing factory output by increasing

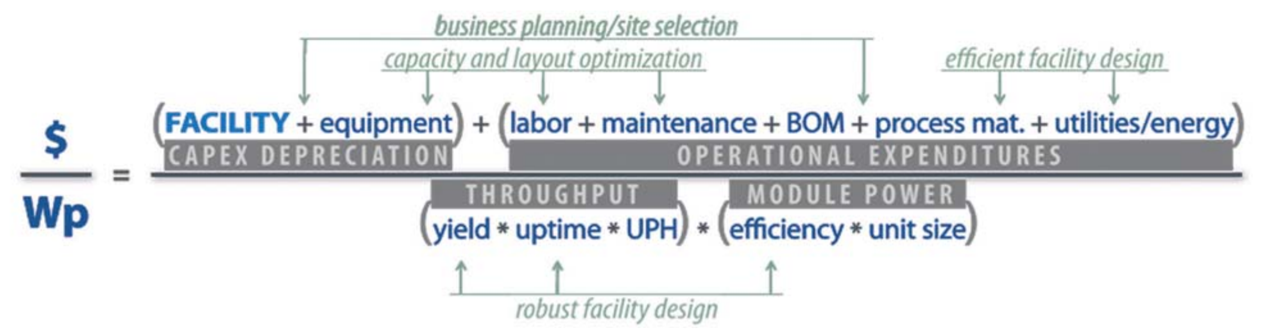


Figure 2. Cost per Wp: simplified calculation.

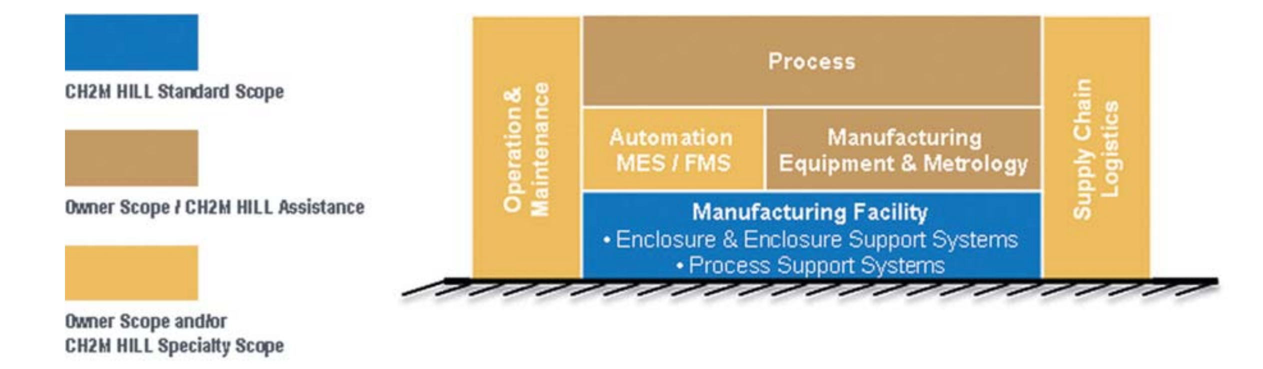


Figure 3. The manufacturing facility as the base building block of a robust, efficient and safe operation.

the size of the facility and the scale and/or quantities of processing equipment in the facility.

Simply increasing the size of the facility and amount of processing equipment is a straightforward means of achieving scale-up, but this approach can consume more capital than necessary. Missteps during the factory scale-up process can cost money and cause schedule slippage, adversely affecting the resulting quality of facility and product, thus impacting an owner's bottom line. Managing information from the owner's side is imperative for facilitating a smooth and reliable path to bring a very large factory to an operating state.

> "When prioritizing the elements that comprise a scale-up strategy, it is important to put into perspective the relative importance of each element."

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In the case of thin-film solar processing, for example, building and facility-related costs constitute 1-5% of overall cost of ownership, calculated in $/Wp (depending on technology and depreciation method – see the simplified formula in Fig. 2). As a first conclusion, one could rightfully state that facility costs are thus not very significant in the overall cost of manufacturing. This is a dangerous conclusion, however: the facility is the backbone of the manufacturing activity, and non-optimized facility designs can dramatically impact productivity and output.

The planning of the site and the design and construction of the facility have a great impact on various elements of the cost and performance factors – an impact which can overwhelm the initial capital cost of the facility.

1. **High uptime and yield, and best module/cell efficiency through robust facility design**. When scaling up manufacturing capacity, it is critical to have stable conditions for the equipment, material handling and – most importantly – the process, in order to achieve the best overall factory performance. The goal is to achieve a narrow distribution of average module/cell efficiency close to the champion efficiencies achieved in mass production, while ensuring high uptime and world-class line yields (>>90%). Assuming facility depreciation is 3% of overall production costs, a 1% increase in either yield or uptime would more than compensate for a 30% higher building cost. In other words, if your yield, uptime and average efficiency were to suffer more than 1% each (more than 3% total), then one should not accept the building even if it is free.
2. **Efficient facility design**. Here again, the cost for process materials (e.g. industrial gases for vacuum deposition, chemicals for etching), general utilities and electricity are usually higher than the facility depreciation cost; i.e., in order to plan for the lowest lifecycle costs when scaling up, a greater focus needs to be given to operational expenses vs. facility capex expenses.
3. **Reduction of equipment, labour and maintenance costs by capacity and layout optimization**. With intelligent facility design through capacity and layout simulations, one can save on equipment capex on the initial set-up, and also when the manufacturing lines are being upgraded and/or scaled up in the future. Many factors play into optimizing a factory floor layout – whether adopting in-line or batch processing approaches, applying Lean manufacturing techniques, or implementing a Manufacturing Execution System (MES) and new QA strategies (inline/offline). Advanced industrial engineering using modern dynamic simulation tools optimize tool count, material handling flow and labour requirements to operate and maintain the equipment.
4. **Reduction of capital and operational costs through business planning and site selection**. A key element when scaling up manufacturing capacity is the choice of the site. Not only must the site fulfil all technical and space requirements, it also significantly drives capital and operational costs. Some

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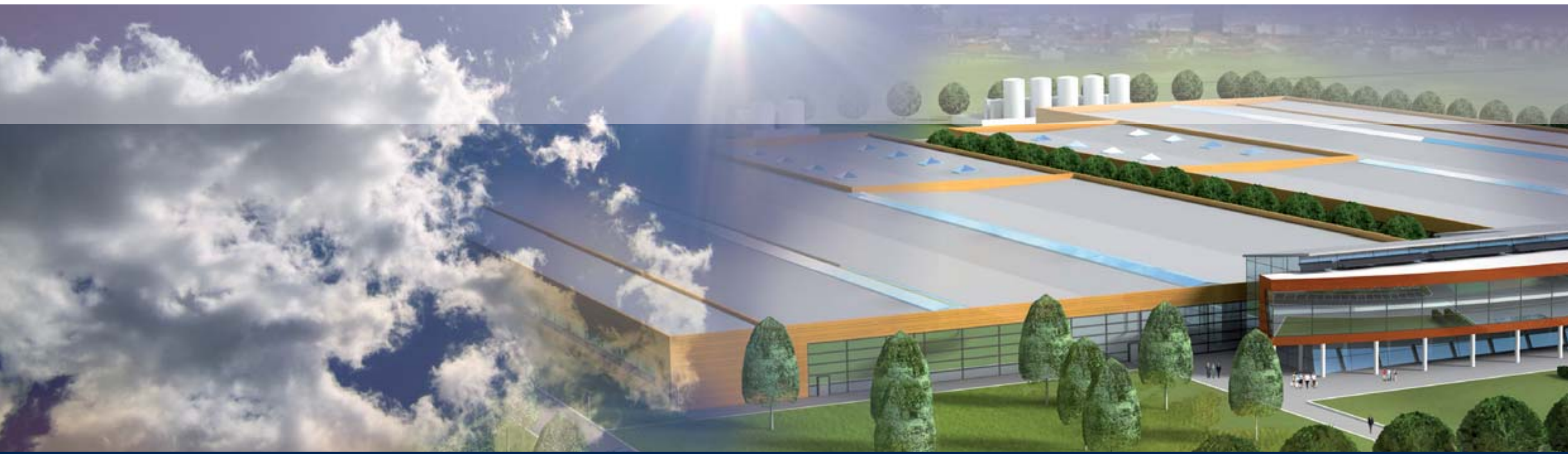

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regions are ready to offer attractive incentive packages that help an owner offset the 'first costs' of capital investment into facility and equipment. However, the majority of the costs over the lifecycle of the factory are operational costs, and it is critical to consider the influence of the site selection on parameters such as local labour costs and education levels, access to inexpensive utilities and electricity, ability to generate some process gases onsite, distance to major BOM suppliers, etc.

Advanced planning issues

There are many advanced planning issues to consider when contemplating scale-up. Many of these – such as strategic analysis of competitors, or the potential for economic development incentives to offset scale-up costs – are not site-related. For this article, however, we are focusing only on a few key site-related priorities related to advanced planning.

One priority for scaling up manufacturing in existing facilities is to improve the long-term energy efficiency of the facility using technologies that may not have been applied when the original manufacturing facility was built. For example, advanced approaches can be used to reduce the long-term costs of controlling heating and cooling loads. This can be done by integrating more passive heating and cooling approaches that exploit local climate conditions, and introducing intelligent environmental control systems. This is an advanced planning issue, because an important contributor to achieving such advantages is the orientation of buildings on a site to optimize the harnessing of solar energy, or to reduce the potential for a building's airborne emissions to contaminate the building's makeup air. Airflow modelling applied inside as well as outside a planned building environment is a valuable tool to precisely define the kinds of energy-saving advantages that can be realized on a specific scaled-up site. These techniques can also be applied during 'greenfield' facility design to optimize energy efficiency of the new construction.

Another important topic for any scale-up effort (greenfield or expansion) is permitting and other regulatory issues. These can be insidious impediments, especially when the planning process assumes that past regulatory standards will apply to the new facility. It is wise to challenge this assumption in the earliest stages of any scale-up program, and to validate whether a facility's existing permits provide adequate flexibility to accommodate the degree of desired expansion. Critical aspects of this analysis include water consumption, air and wastewater discharge, hazardous materials storage, and transportation requirements. In the U.S., for example, owners must be aware of the latest 'threshold quantities' requirements for the storage and handling of certain chemicals that were an outgrowth of Homeland Security provisions in the last few years. Another forward-looking consideration to plan for is the ability to comply with anticipated future requirements to reduce a facility's carbon footprint, such as 'carbon tariffs.' Bringing older buildings into compliance with these and other potentially more restrictive codes can be cost prohibitive.

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A common pitfall of upscale project teams is the tendency to be overly optimistic about the amount of time required to resolve regulatory issues. Overlooking this important step during the advanced planning phase increases the potential for misunderstandings and a change of the rules mid-project, resulting in rework and delay. A 'Plan B' should be available which would engage a strategy to expedite permitting approvals. Such a strategy best relies on personal intervention of code experts representing the owner. Particularly in international regions, where regulatory officials may not be familiar with a facility's planned processes and the hazards associated with the chemicals supporting those processes, it can be very effective to engage regulatory officials in direct dialogue to explain the particulars of the planned manufacturing processes.

Form factor scaling

Form factor scaling is a productivity approach that CH2M HILL has observed in both the semiconductor and flat panel display industries. This approach typically generates equipment productivity improvements, since the rate of increase in product output exceeds the rate of required increase in manufacturing floor space. In the semiconductor and flat panel industries, for instance, 2x output increases associated with diameter or generation changes respectively have historically been associated with roughly a 30% increase in capital investment. The net result is significant cost reduction (output/capex).

A related scaling phenomenon is also occurring in the PV manufacturing industry. In silicon wafer-based manufacturing processes, scaling is currently occurring through the thinning of the silicon substrates. Since silicon costs are one of the highest direct manufacturing costs for a wafer-based PV line, thinning the substrate provides a direct reduction in cost-per-watt metrics. Thinner wafers, however, can cause other issues with the manufacturing process, such as increased yield loss due to the handling and processing of thinner wafers. Facilities and automation systems must anticipate these trends in wafer thinning and deliver equipment and systems that can grow with these trends.

The thin film industry is already benefitting from form factor scaling. Applied Materials has successfully deployed manufacturing processes at Generation 8.5 form factor that scaled up from 30cm by 30cm 'minimodules.' Other manufacturers, such as Oerlikon, have successfully deployed processes using Generation 5 substrates, and we expect this trend to continue among other thin-film equipment manufacturers. One issue currently hindering scale-up in the thin-film industry is the lack of form factor standardization. This lack of

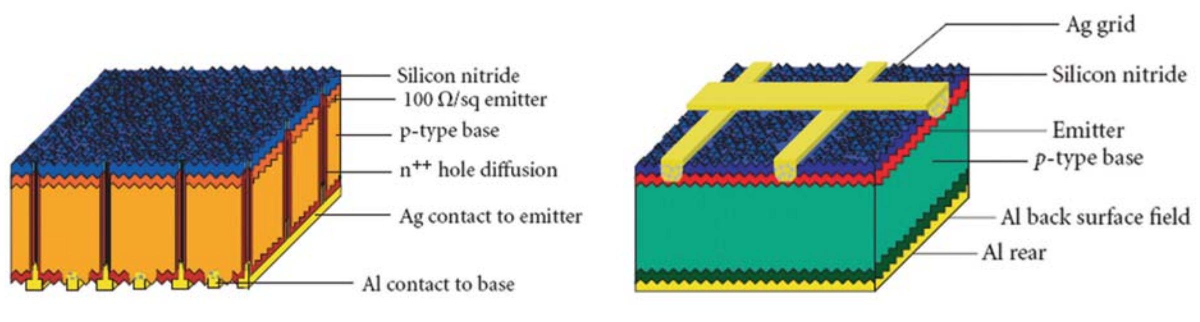

Figure 4. Example of emitter wrap-through process.

Source: Hindawi Publishing Corporation.

standardization makes it more difficult for factory owners to pick and choose specific equipment from various suppliers, instead forcing owners to take delivery of an entire turnkey equipment line from one supplier. This is typical of an industry in the early stages of growth, and this issue is especially noticeable in the amorphous silicon market.

However, again based on trends observed in the semiconductor and FPD industries, we expect that eventually the various segments of the thin-film market will standardize on specific form factors, allowing increased competition in the equipment market. What this means for the facility owner is more uncertainty in the long-term manufacturing equipment set, line configuration, and facility infrastructure requirements over time. However, experience on related projects verifies that a solid facility design approach can address this uncertainty without adding significant cost. For instance, a facility owner may reconsider decisions about column spacing, crane capacities, utility sizing, and clear heights when anticipating form factor scaling changes over the lifecycle of the factory.

Process issues

Critical to optimizing performance of a PV manufacturing facility is the ability to continuously adopt processes and technology breakthroughs that improve cost-per-watt metrics. These improvements are anticipated to come in the form of improved power conversion efficiency, improved yields and better reliability of both manufacturing equipment and products. To this end, both thin-film and silicon wafer high-volume manufacturing facilities must be constructed with the ability to adapt to emerging technologies, manufacturing equipment and process chemicals.

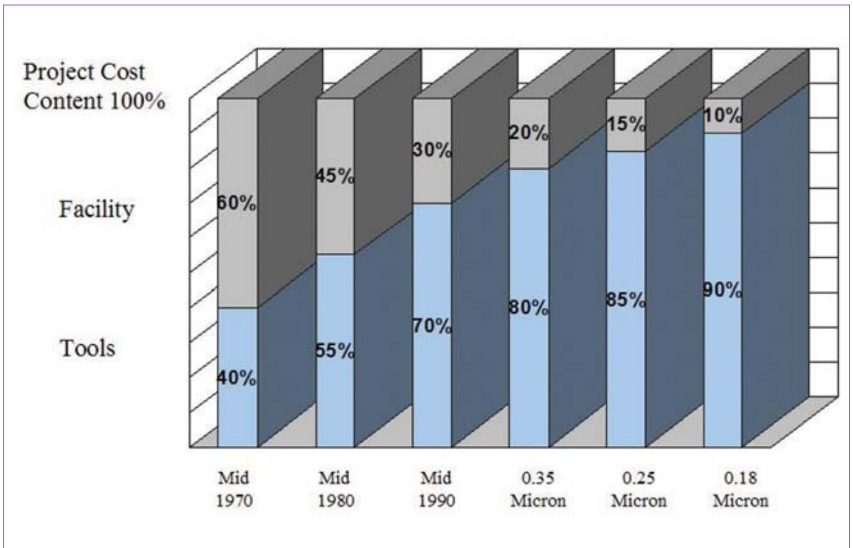

Figure 5. In the semiconductor industry, the ratio of tool to facility costs steadily skewed in favour of tools as the industry matured and manufacturing processes became more complex.

In the crystalline silicon PV market, for example, many process improvements are currently under consideration or are being adopted to improve power generation efficiency. While some incremental improvements can be expected through the optimization of existing processes and manufacturing equipment, major improvements will be required to reach grid parity. Metal and emitter wrap-through processes, for

example, are just two of many methods in the early phases of deployment in high-volume manufacturing that are expected to increase power conversion efficiency. However, these processes require new tooling (lasers) and improved lithography alignment techniques.

Longer-term efficiency improvements, such as photon up- or down-conversion, may include the deployment of advanced quantum dot materials and solution processing equipment such as inkjet-based equipment, neither of which is in widespread use in manufacturing today. As was the case in previous semiconductor and flat panel industry scale-ups, solar processing improvements require additional factory floor space, place increased burdens on process chemical supply and waste treatment systems, and may introduce new regulatory restrictions on the facility. These issues can be mitigated through careful upfront planning of the facility with the owner.

The situation is similar in the thin-film PV market, where technologies must also significantly improve cost-per-watt metrics. In the amorphous silicon market, many companies are focusing technology development on improving the performance of interfaces and the incorporation of new materials to increase efficiency through improved absorption by light scattering and improved reflection. These approaches are likely to result in either new equipment or the modification of existing equipment. Either approach can have an impact on the manufacturing line, either by requiring additional equipment or by altering the line balance by changing equipment throughput. In CIGS and CdTe, where the focus is on optimizing existing processes and improving the productivity of manufacturing equipment, improvements over time may also result in line imbalances and potential lost output. In order to maximize the capital investment, large thin-film factories must be designed with the flexibility to adapt to these dynamic scenarios in order to maximize output.

CH2M HILL has demonstrated that, through careful scenario planning and modelling, inexpensive or cost-neutral decisions regarding infrastructure and utilities can be incorporated during facility design to address evolving technology. These changes are expensive, impractical, or impossible to implement later on in an operating manufacturing facility. We have used this approach with great success in both the semiconductor and flat panel display markets to design affordable flexibility into manufacturing facilities. For instance, by understanding the evolution of the photolithography roadmap in the semiconductor industry, CH2M HILL was able to help a client minimize lifecycle facility costs while ensuring adequate floorspace for vibration-sensitive equipment over the expected lifetime of the facility (several process generations).

Chemical issues

On the small scale, manufacturers only need small containers of chemicals to function effectively. In high-volume manufacturing, everything changes. It is critical to plan for:

- Significant space needs and cost of bringing chemicals in by the tank truckload. This requires space for a tank farm, truck unloading, and effective traffic patterns.
- Sources of supply: is the supply chain in a given location adequate to supply the chemical types and quantities you need?

For example, manufacturers whose process uses large amounts of argon would be constrained in locations where this gas is difficult to access. Argon is incrementally more expensive to produce than many other gases, and cannot be produced on site. When manufacturers transition to larger argon quantity demands, it can become necessary to take delivery of argon in liquefied, cryogenically transported form. Argon is just one example of how owners' chemical and gas supply chains can become very tenuous when they locate far from where their needed materials are produced; these issues can have a profound impact on a facility's overall cost structure.

In general, thin-film processes use a lot of nitrogen. For some of these processes, scaling up will require the on-site production of nitrogen. In order to do this, the owner must plan for the necessary real estate, coordinate with the gas company, and provide for the additional power required at the site. Coordination with the gas company is especially critical; the lead time for a 2000 CFM nitrogen plant is currently 18 months, and plant components alone have a nine-month lead time. There are other scale-up issues related to chemicals,

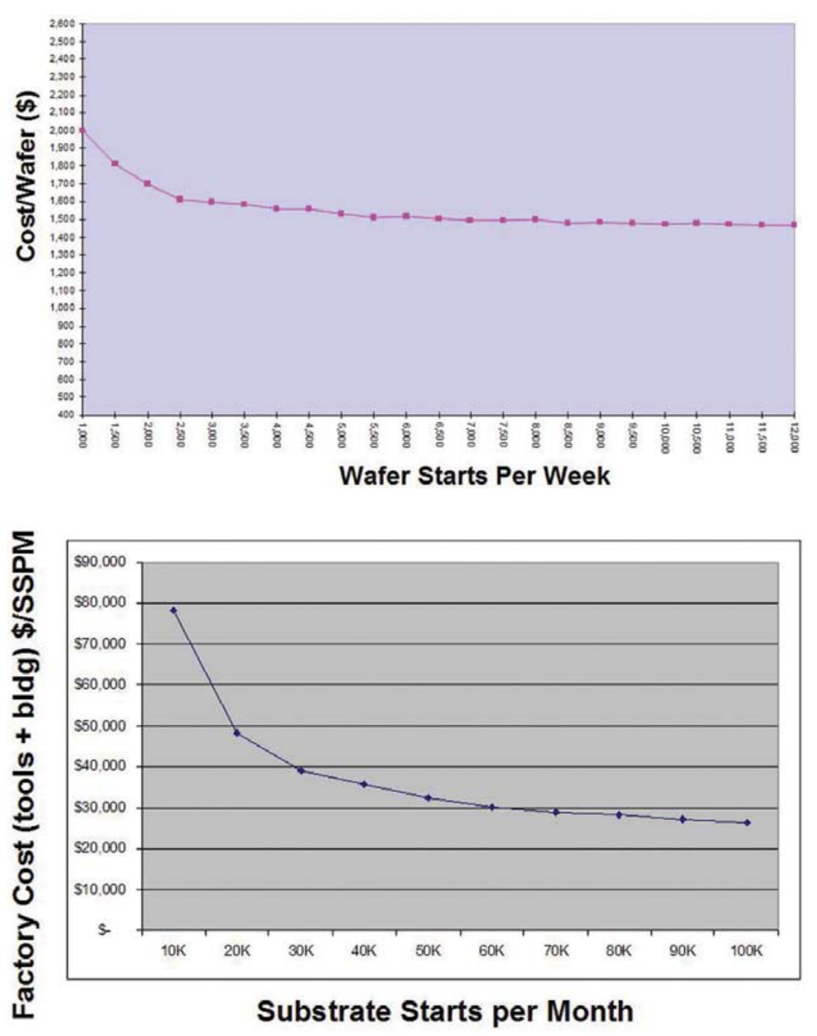

Figure 6. These graphs for the semiconductor (top) and flat panel industries (bottom) reflect how capital costs per unit of capacity fall rapidly, then level asymptotically as capacity increases. We see a family of such curves for PV solar, one curve for each technology. Critical to economic competitiveness is proper selection of factory capacity.

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such as how to decide when it may be most feasible to produce hydrogen on-site instead of trucking it in for certain thin-film processes.

Managing the challenges of dealing with larger silane quantities is also a critical consideration for some thin-film manufacturers. Silane is currently manufactured only in Japan, Korea, the U.S. and Germany, and it is challenging to ship. A 1GW amorphous silicon thin-film facility will consume roughly two trailers of silane every three to four days, or 100 trailers per year. It is easy to see that a hiccup in the supply chain can have a significant negative impact on production.

Facility needs

One of the fundamental considerations in scale-up planning is the physical distance between buildings and discrete processing tools, utilities, and support systems on a site. In a scaled up facility it is more efficient to combine and centralize the chilled water plant and the heated water plant. The downside of this approach is the resulting long utility runs from the central system to a tool or user. The pressure loss eventually gets sizeable enough to move centralization into a grey area of advisability. For that reason, owners need to carefully calculate the relative advantages and detriments and then consider their options. It is more expensive to implement two systems, of course, but in the long run such an approach might be advantageous.

Some due diligence design work is required to pinpoint where the break point is in this balance, which is bound to be different in every situation site depending on the distances involved on a specific site. The systems need to be laid out ahead of time to see which approach is most practical. In the case of an exhaust system, for example, what is the cost of running a 5-foot duct 500 feet? Would it be cheaper to have two systems?

One of our solar clients originally planned to construct a new greenfield 450MW facility as one phase, but eventually decided to split the building in half to be constructed in two phases. In hindsight this was a good move, because if the entire operation had been centralized, there would have been problems further down the road because the distances on their site were so large.

Other scale-up issues that need to be considered related to facility needs include optimizing space adjacencies (consolidating hazardous materials to minimize a scale-up's impact on code issues), consolidating equipment and centralizing support rooms to reduce a facility's distributed HVAC loads and reduce utility runs, and shifting to bulk chemical storage vs. distributed chemical management. Scaling up capacity also calls for a careful review of an upgraded facility's sustainability goals. This is a topic deserving of a separate article, but generally speaking, every owner must carefully weigh the benefits against the liabilities of seeking sustainability only for sustainability's sake. With the right technologies, sustainability should always be expected to deliver long-term enhanced economic value to a manufacturer as well as ethical gratification.

Manufacturing integration

Strong industrial engineering expertise is at the heart of successful scale-up strategies. Refining factory floor configurations during scale-up is a task best begun with process line simulation modelling to virtually test process line variations in the search for the best blend of tool selection and positioning. It has been the authors' experience that factory line simulation modelling can lead to significant savings to owners in the form of reduced floor space requirements, reduced number of required processing tools, and improved overall equipment effectiveness (OEE, equal to the availability x performance x quality). Relating this back to our previous discussion of capex, optimization of OEE can improve a facility's overall bottom line significantly, depending on the degree of complexity associated with a particular process.

Consolidation of functions is an approach that is integral to leveraging the value of the scale-up investment. Consolidating processing equipment, for instance, reduces HVAC loads that would otherwise be widely dispersed in a factory, and enables improved building occupancy and simplification of fire separation. It also enables greater processing flexibility, improved equipment OEE, and cost efficiencies related to work in process. Consolidation is more conducive to integration of automated WIP buffering to hold WIP in place to help downstream operations moving at an optimal pace. Enhancing the adjacency of processing tools allows one or more tools to be taken off line without impeding overall output. Centralized support rooms reduce the length of utility runs, and allow greater utility cost efficiencies, such as shifting from distributed chemical systems to a bulk chemical storage approach.

Wastewater

While water consumption is not as critical in solar PV manufacturing as it is in the semiconductor industry, wastewater is more insidious. Because the solar industry is not a big water user, there is a tendency to reduce wastewater to 'out of sight, out of mind' status when in fact there are nuanced specialty wastewater issues that become vitally important.

The approaches used to resolve wastewater issues at low production levels may not be adequate for scaled-up production. Owners must understand the 'wastewater profile' of the scaled-up facility, in terms of both quantity and quality. There are no industry standards that enable owners to anticipate the next level of issues, and scaled-up facilities face external factors that are not explicitly driven by regulations. Rather, they are infrastructure- or location-driven, and can have serious repercussions if not considered well in advance. When ramping up the volume of wastewater a facility discharges, sustainability headroom issues arise in the form of the ability of the local receiving plant to deal with the wastewater. It is critical to start early communication with the receiving entity to understand the design and cost implications of wastewater infrastructure, capacities, permits, etc.

All too often, the site selection process drives owners toward 'light industrial' candidate sites, often located in smaller communities offering all sorts of incentives, without recognizing the potential impacts of the wastewater side. For instance, with a 60MW line, a facility may comfortably fall within certain wastewater thresholds, but when scaling up they enter a different category. One example: many solar facilities use large amounts of ammonia, which is variably regulated. In some places ammonia does not matter, and in some places it matters a lot. If the facility in question is in a location where it matters a lot, it can cost a lot: the wastewater cost estimate can double in a location that does not 'want' any ammonia.

Conclusion

On the road to very high-volume manufacturing capacity facilities, every industry struggles with the many variables and uncertainties that complicate calculation of the risk/reward ratio. The solar industry will be no different. The antidote to trepidation is preparation; the best way to minimize the inevitable concerns associated with any new capital investment is to review every aspect of a scale-up's requirements by adhering to a structured and rigorous 'checklist' approach.

> "The scale-up strategy should have the flexibility to smoothly integrate new processing technologies as they develop."

The scale-up checklist should begin with an unvarnished analysis of building characteristics, facility infrastructure capacities, the process technology roadmap, process methodology, and automation strategy. Examine how these costs stack up against anticipated


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return on the owner's capex investment. The checklist should assess a range of advanced planning concerns, with particular focus on those issues that can provide the desired short- and long-term value to the owner such as improving energy efficiency and avoiding regulatory delays. The scale-up strategy should have the flexibility to smoothly integrate new processing technologies as they develop into the facility and its utilities and tool sets. There should be no skimping in the area of manufacturing integration, considering the repeatedly demonstrated ability of this field of expertise to return bottom-line value – improved equipment productivity – that far outweighs its cost.

When considering all of these factors, the authors' experience has repeatedly demonstrated that the most successful scale-ups in related industries such as semiconductor and flat panel have tended to be those that made owners active participants in all aspects of the scale-up process. Building an efficient factory and reducing product life-cycle costs requires information and decisions from owners on key issues related to facility needs and site. If the development of critical information such as this can be well managed from the owner's side, a smooth and reliable path can be followed to bring a factory into operation.

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David Krick, Principal Technologist, primarily assists clients with the commercialization of emerging advanced technologies in the field of renewable energy, focusing on solar photovoltaic production and other semiconductor-related industries. He also leverages his extensive expertise in semiconductor research, development, and manufacturing to evaluate high-technology manufacturing and technology roadmaps. He has authored multiple papers and has been an invited speaker at conferences, both domestically and abroad.

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