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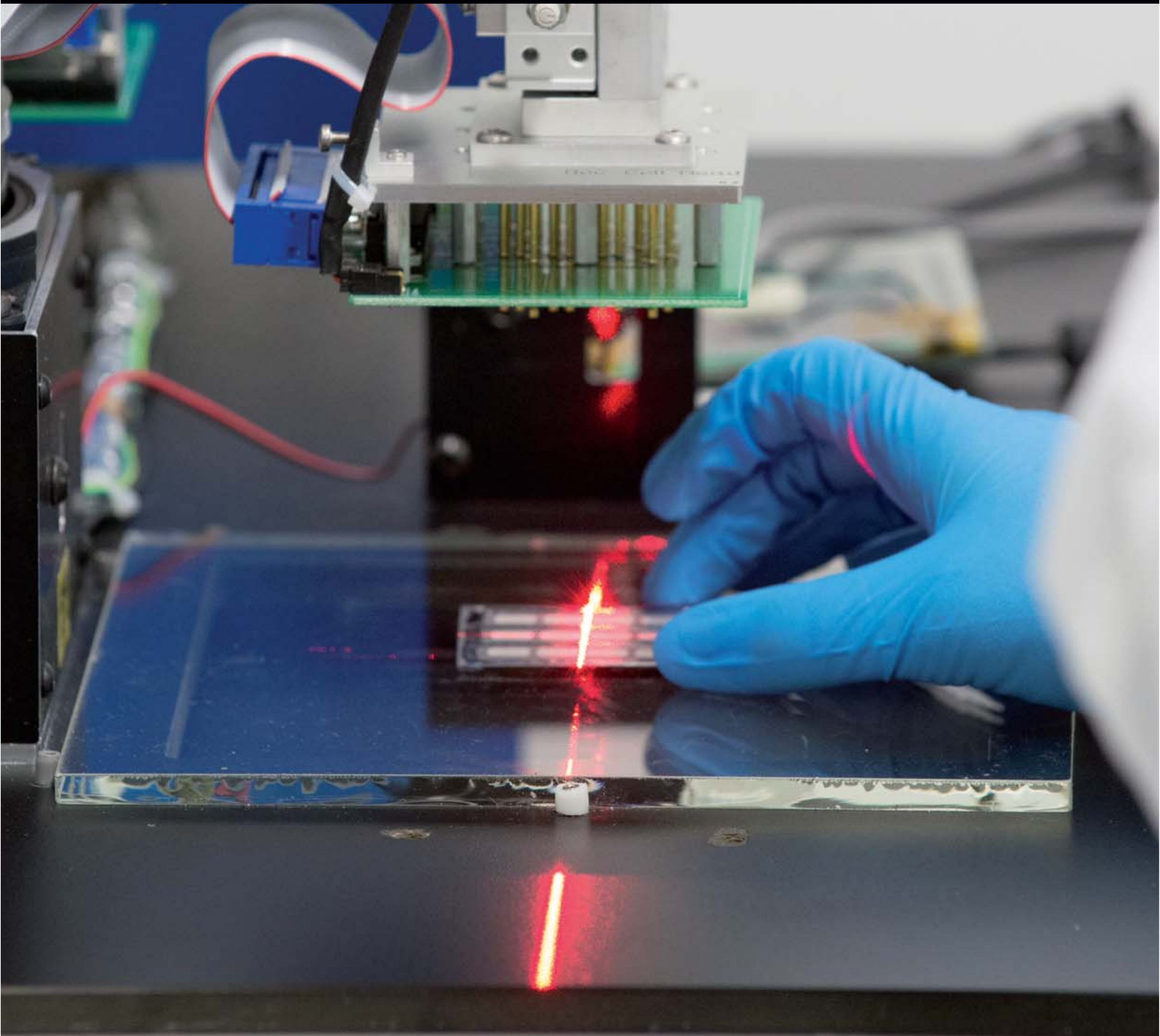

M+W Group Changing global market and technology trends – new challenges for PV manufacturing strategies and facility concepts

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Changing global market and technology trends – new challenges for PV manufacturing strategies and facility concepts

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ABSTRACT
The PV manufacturing and technology hubs established over the past decade will change at an accelerated pace through the globalization of solar power installations. This development will be most pronounced in regions with high solar radiation, where grid parity can be achieved without subsidies. It can therefore be expected that parts of manufacturing within the PV added-value chain will also be established in new markets, such as South America, Africa, the Middle East and Asia. This trend will also stimulate these economies by the generation of new employment opportunities in the advanced technology sector. During the development of a new business plan, the key factors to resolve include the optimum manufacturing size and the extent to which upstream integration, from module manufacturing to poly Si, will be competitive. This paper addresses technology trends and strategic considerations for optimally selecting a PV manufacturer's strategy for each region, the determinants for centralized versus decentralized manufacturing, and the impact of these on fab and facilities concepts. Furthermore, the dependence of manufacturing capacity on fab and facility cost, as well as on the energy demand for individual manufacturing steps along the value chain, is discussed and compared.

Introduction

Since 2011 the PV industry has been plagued by an oversupply, with worldwide manufacturing capacity in 2013 totalling approximately 60GWp versus a significantly lower demand of approximately 38GWp. This has fuelled rapid price erosion for PV panels/modules and has resulted in strong market consolidation, since many manufacturers have had to sell their products at or below cost. As a consequence, investment in new equipment and manufacturing facilities has generally been low, and, even today, some idle manufacturing capacity is still available. Wherever possible, such capacity will first be upgraded and ramped up before new manufacturing plants are constructed.

The low prices have fuelled demand in new markets and countries looking to implement PV energy at competitive costs, even without the dependence on subsidies. From 2015 onwards it is expected that the gap between production capacity and PV installations will narrow considerably as demand accelerates. Low spot market prices cause older manufacturing lines to become obsolete with respect to technology and equipment, with the result that they are unable to remain competitive. Furthermore, emerging new geographical markets and regions are developing policy-

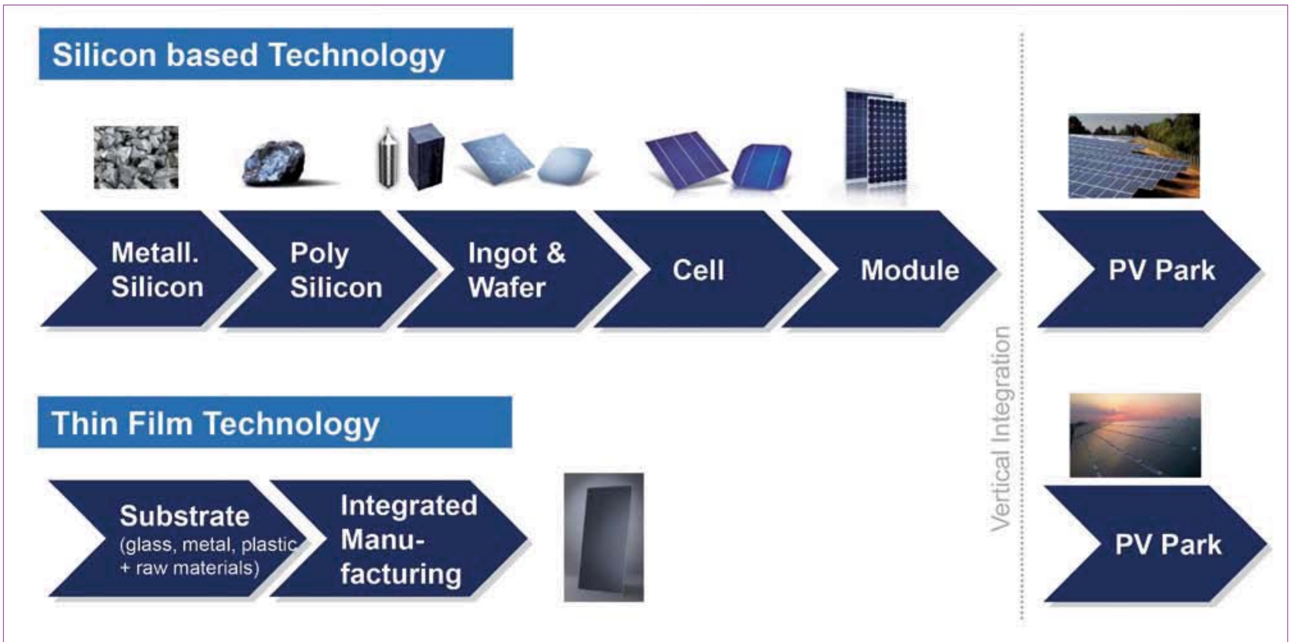

Figure 1. PV added-value chain for c-Si and thin-film technologies.

driven strategic roadmaps to start up domestic manufacturing facilities and the necessary infrastructure to support local employment.

It is therefore only a matter of time until new manufacturing facilities will start to develop globally. Total PV industry spending is expected to increase from $2.3bn in 2013 to $4.34bn by 2015 [1]. This forecast corresponds with market reports [2] as well as internal information at M+W Group. Because of massive competition, only cost-efficient facilities with leading-edge technologies will be economically viable, in line with the constant downward drift for PV panel/module prices, and also paving the way for a reduction in the overall balance of system (BOS) investment costs.

“Because of massive competition, only cost-efficient facilities with leading-edge technologies will be economically viable.”

This paper addresses the challenges and key criteria for cost-effective PV fab design resulting from these predicted developments. The key questions from a fab and facility point of view are the most economic size, the choice of the location, the clustering of particular parts of the PV added-value chain in a certain location, and how to facilitate cost-effective manufacturing. The authors have investigated the value chain based on crystalline silicon (c-Si) with respect to specific investment for fabs and facilities between 100 and 600MWp/annum. Furthermore, the specific energy demand for each manufacturing step is highlighted, since significant differences exist, with a corresponding impact on the operating costs. The advantages of local manufacturing are also evaluated from a macroeconomic point of view by estimating the workforce necessary to operate a PV manufacturing facility, as well as the positive effect on job creation within the support and supply industries. Finally, a set of recommendations for the location and state-of-the-art design for future, cost-effective PV fabs and facilities is provided.

The PV added-value chain

PV modules based on c-Si currently dominate the market. These technologies are characterized by well-defined manufacturing steps as shown in Fig. 1.

Traditionally, most manufacturers commence operations with module manufacturing and continue upstream integration to cell, and even wafer and ingot, manufacturing. Even when co-located on one site, this approach results in independent, decentralized facilities with relatively high maintenance and operational costs, since potential synergies cannot be optimally utilized. Poly Si manufacturing is dominated by companies active in the chemical industry, and, up to now, only a few PV manufacturers operate their own poly Si plants.

PV thin-film technologies are based on CdTe, CIGS or amorphous/micromorphous silicon. All three thin-film technologies share the following features:

- Manufacturing is based on glass substrates.
- Production lines are fully integrated.
- Finished modules exit the line as end products.

Thin-film technologies address specific applications and will grow with the market if the panel efficiency exceeds 14–15% at a specific cost level. For the remainder of this paper, the focus will be on c-Si-based technology since it represents approximately 90% of the entire market.

Technology trends

In order to track the PV price learning curve to and below 0.5€/Wp [3], it is essential to implement new technologies with the aim of reducing costs. The trend is the introduction of high-efficiency solar modules with conversion efficiencies exceeding 20%: high-efficiency modules have the additional benefit that the BOS costs

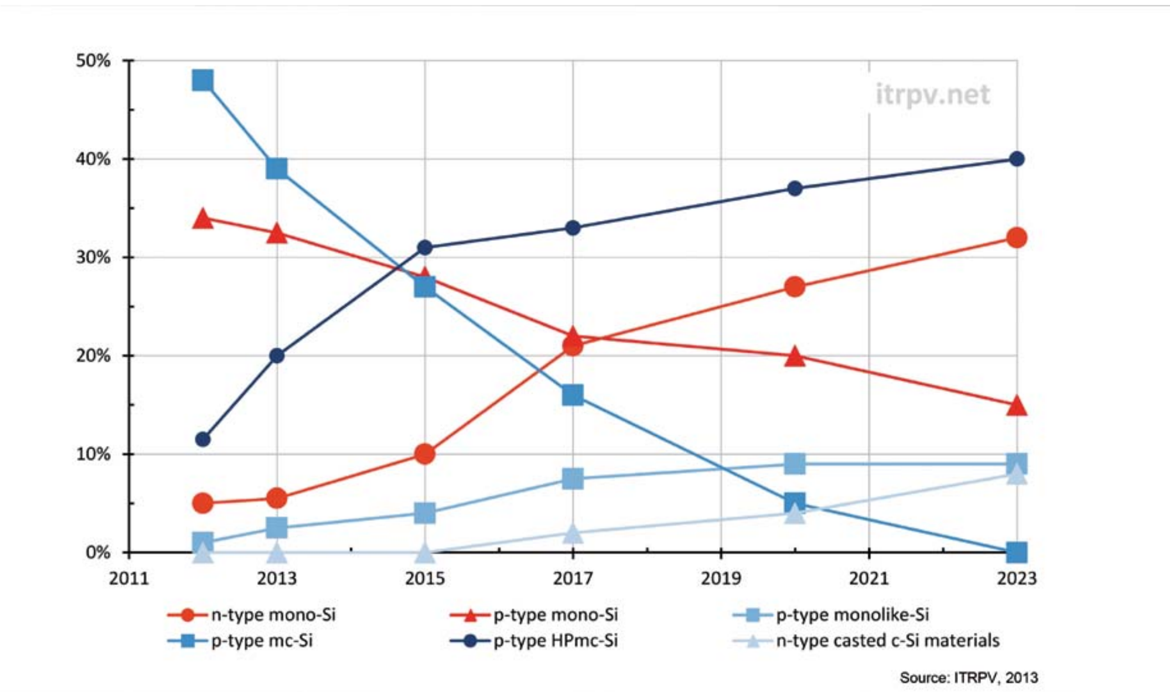

Figure 2. Expected relative market share for cast and mono-Si materials [4].

per Wp also decrease, since less module area is required per Wp. Various new and/or additional process steps have been developed in order to reach or exceed the 20% efficiency level. To date, this has been an incremental evolution rather than a paradigm shift to new and revolutionary technologies. The challenge is that both the investment and the operational costs for any new technology should be minimized, with a target cost level for a finished module at or below 0.5€/Wp.

The International Technology Roadmap for Photovoltaic (ITRPV) forecasts that n-type monocrystalline silicon will increase its market share to 30% in 2023 [4], whereas today's predominant technology, p-type multicrystalline silicon (mc-Si), will sharply decrease, as outlined in Fig. 2.

SunEdison has commercialized a continuous Czochralski (CZ) crystal pulling process [5]; furthermore, diamond sawing (versus traditional wire sawing) will increase its market share. Various cell technologies based on n-type Si are available, including heterojunction with intrinsic thin layer (HIT), commercialized by Panasonic [6], and interdigitated back contact (IBC), commercialized by SunPower [7]. The status and future of industrial n-type silicon solar cells is addressed by Kopecek et al. [8]. Various companies have started pilot manufacturing of passivated emitter and rear cell (PERC) solar cells based on p-type wafers. A recent technology overview of process flows is described by Dullweber et. al [9].

A frequent question is whether the upcoming new technologies will have a significant impact on the design of the building and facilities. Current investigations have shown that such new technologies will have little effect on ingot manufacturing, but more pronounced impacts on the wafer and cell lines, since different manufacturing steps with various new process gases and chemicals will be required.

As a first example, diamond sawing will result in a reduction in slurry handling and disposal systems. Second, HIT technology does not require a high temperature diffusion process step; in addition, this technology also requires a reduced number of process operations. Therefore, both the overall electrical power demand as well as the total manufacturing area could decrease, resulting in a reduction in both investment and operating costs. Moreover, new types of screen-printing metal pastes are necessary, which influence the supply and disposal of the respective chemicals. Some process steps will also require a higher level of cleanliness: the specifications for deionized water, chemicals and gases, as well as the need for local cleanrooms, must therefore be reviewed.

All of these factors need to be taken into consideration when designing new and cost-effective manufacturing facilities, in order to ensure adequate space allocation, appropriate supply and disposal of process-related utilities, optimized logistics and the 'just clean enough' approach.

Scaling effects and integration

The last intensive investment cycle in the PV manufacturing industry (2006 to 2008) resulted in the current global overcapacity. During that period, some manufacturers planned to develop new greenfield sites with manufacturing capacities approaching the GWp/annum scale. So far, very few GWp facilities have been built on a single site. Since the PV industry is rapidly maturing, and new capacities are being planned right now, the question is whether an integrated facility on a GWp scale remains an economically feasible approach.

Several possibilities exist for driving down investment as well as running costs for PV manufacturing facilities, as highlighted in Fig. 3.

The PV manufacturer, as well as its equipment and technology suppliers, has the strongest influence with regard to technology and process tool selection. The PV manufacturer, in conjunction with the design/build contractor (EPC) of the building and facilities, can control scaling effects and the degree of integration. Value engineering (VE) steps evaluated during the early design phases can potentially produce the largest decrease in overall investment cost. The authors compared scaling factors for the manufacturing and gross building areas of a 100MWp/annum with a 600MWp/annum cell manufacturing line [10]. From a cost point of view, and if adequate land is available, it is generally recommended to select a single-level building concept, since multi-level

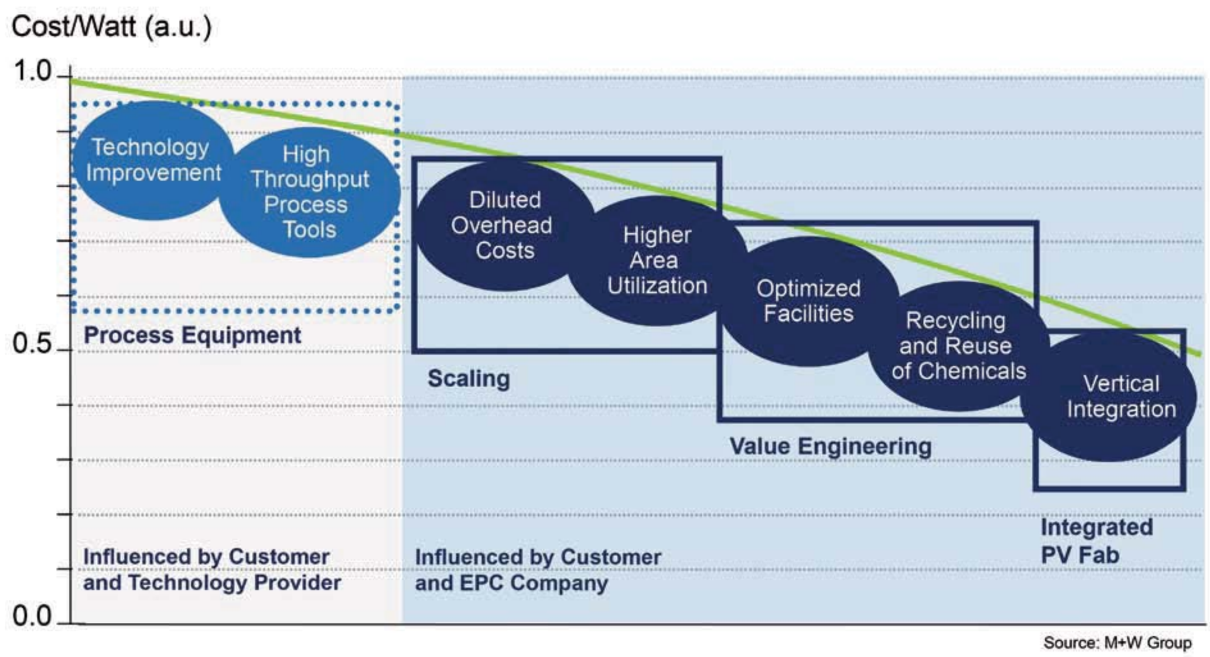

Figure 3. Elements for driving down costs within the PV added manufacturing chain.

buildings take longer to construct, and the complexity of internal logistics and automation requirements become increasingly challenging.

> "It is generally recommended to select a single-level building concept."

The impact of the integration of different added-value steps (ingot to module) by various manufacturing capacities is shown in Fig. 4, consisting of benchmark investments for the building and the facilities for co-located ingot-to-module manufacturing complexes with annual manufacturing capacities ranging from 100 to 600MWp.

The most pronounced decline in specific investment occurs between an annual manufacturing capacity of 100 and 200MWp. From 200 to 600MWp/annum the trend continues, but starts to flatten. Above an annual capacity of 600MWp, the authors conclude that a further significant decrease in the specific costs for the building and facilities will not occur for a number of reasons, primarily driven by the increase in overall footprint of the single manufacturing building, where special measures for fire protection in accordance with local codes and regulations may have to be considered. In addition, the volume for make-up and exhaust air increases, thereby increasing the length and diameters of ducts; the specific power consumption of the larger fans also increases as a result of higher pressure drops. These additional measures can completely cancel the potential savings to be gained in manufacturing through further scaling.

Another key question is whether the entire manufacturing process along the PV added-value chain should be integrated and in close vicinity to the end market, or if the decentralized approach could be more cost-effective.

If the proximity to a market and the shipping times become important factors, module manufacturing should be close to the market and the capacity should not be larger than what the local or regional markets can absorb. Other factors – such as the availability of skilled labour, supply chain and cost of utilities – should also be taken into account. The predominant operational cost for the utilities is electrical power. The energy demand for a 600MWp/annum reference PV manufacturing facility was investigated: the results for the specific energy demand (MWh/annum) for poly Si, (mono-) ingot/wafer, cell and module manufacturing are illustrated in Fig. 5.

A poly Si manufacturing plant was included for completeness, the figures being based on an assumed conversion ratio of 5g of silicon per Wp of capacity. Since different technologies are utilized for the various steps, the specific energy demand can vary slightly from the depicted values. It is evident that poly Si and ingot/wafer plants require the highest energy supply on a per MWp basis, primarily driven by the hydrochlorination, CVD deposition and ingot-growing steps, all of which are energy-intensive operations. Consequently, it will be challenging for such manufacturing steps to competitively produce poly Si in regions with relatively high energy costs. The impact of energy costs is less pronounced for cell manufacturing and even less critical for module manufacturing, which suggests locating cell and module manufacturing facilities with small- to medium-size capacities (200 to 600MWp/annum) close to the end-user market. Poly Si and ingots can only be manufactured in a cost-effective manner in countries with relatively low energy costs; in these operations, capacities can be higher (10.000t/annum or above 1GWp/annum, respectively) in order to benefit from potential scaling effects.

Localization of PV manufacturing

To date, the largest markets for module installation have been in Europe, and most manufacturing capacity has been built in Asia. PV installations are expected to shift from Europe to the Americas, Asia and the Middle East/North Africa in the near future. In parallel, the overall market is predicted to grow to 56GWp in 2016 (Fig. 6).

To maintain sustainable growth in the long term, solar power cannot depend on local subsidies or feed-in tariffs to achieve grid parity. Consequently, new cost-effective manufacturing facilities will be required as the supply and demand

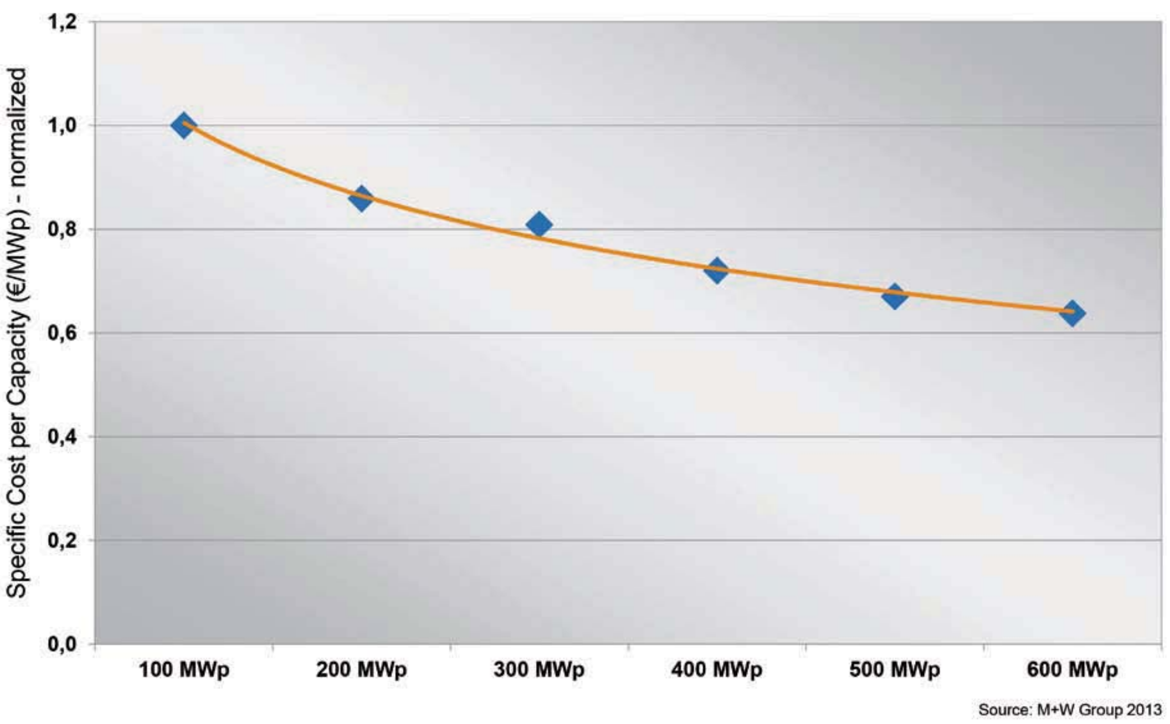

Figure 4. Specific fab and facility investment for ingot/wafer, cell and module manufacturing by capacities.

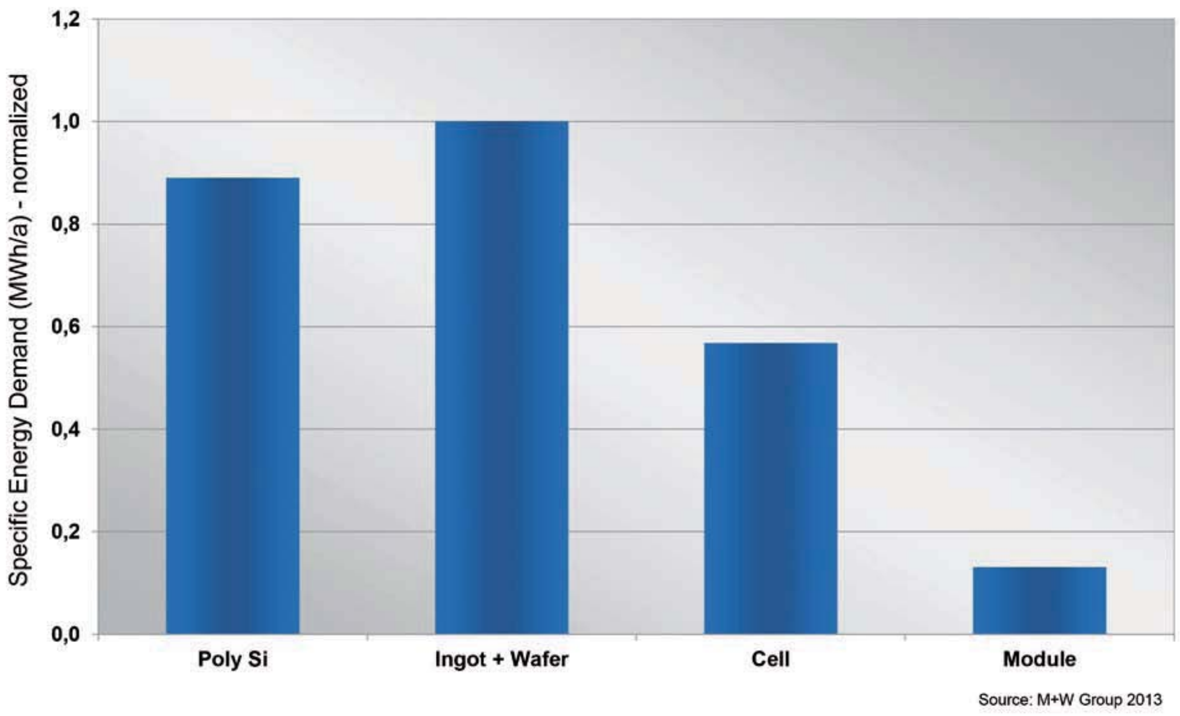

Figure 5. Normalized specific energy demand in MWh/annum for poly Si to module manufacturing.

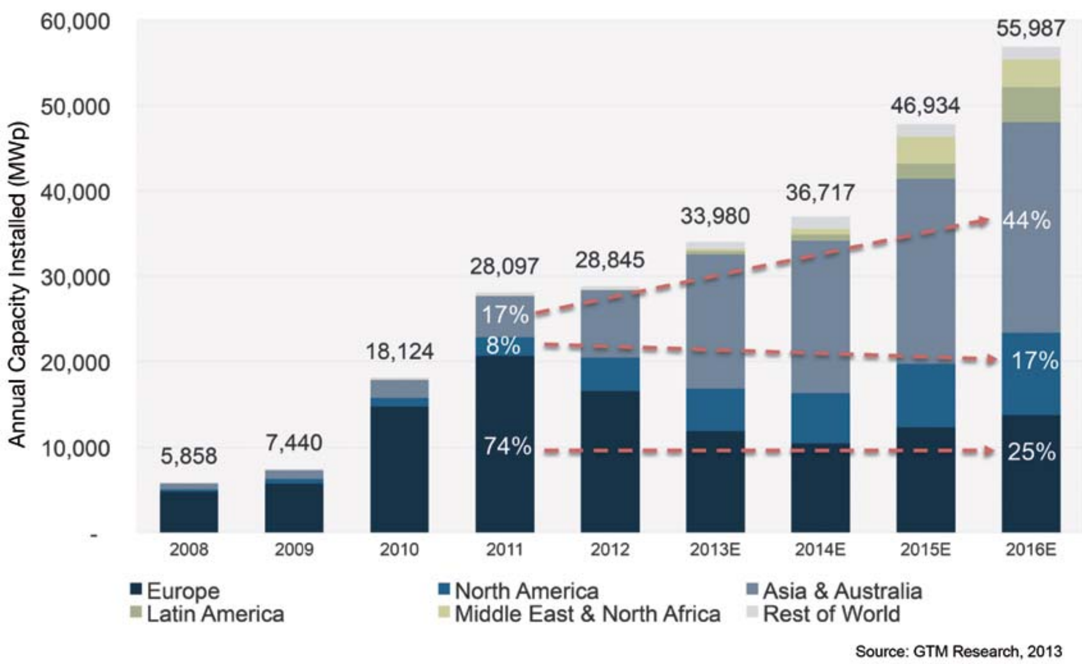

Figure 6. Global PV installations: 2008–2016E [11].

curves converge, and PV manufacturers will need to evaluate new site locations. As previously discussed, energy costs are a key decision-making criterion, particularly for poly Si and ingot/wafer manufacturing, but another important site selection consideration exists that relates to macroeconomic requirements at national level.

Through local PV manufacturing, countries will become less dependent on fossil energy and generate numerous employment opportunities for a broad range of skill sets. The job creation aspect is not limited to the manufacturing site itself, but also applies to the related service and supply industries. As a rule of thumb, 15 new jobs per MWp annual capacity are required for an integrated poly Si to module manufacturing facility: 9000 people must therefore be hired to operate a 600MWp/annum plant around the clock. In addition, there is a leverage factor of approximately two to three for job creation in the service and supply industries, as well as in the downstream sector for PV power plants. The diverse types of support function required for a PV production plant in terms of R&D, education centres and the service and supply industries are shown in Fig. 7.

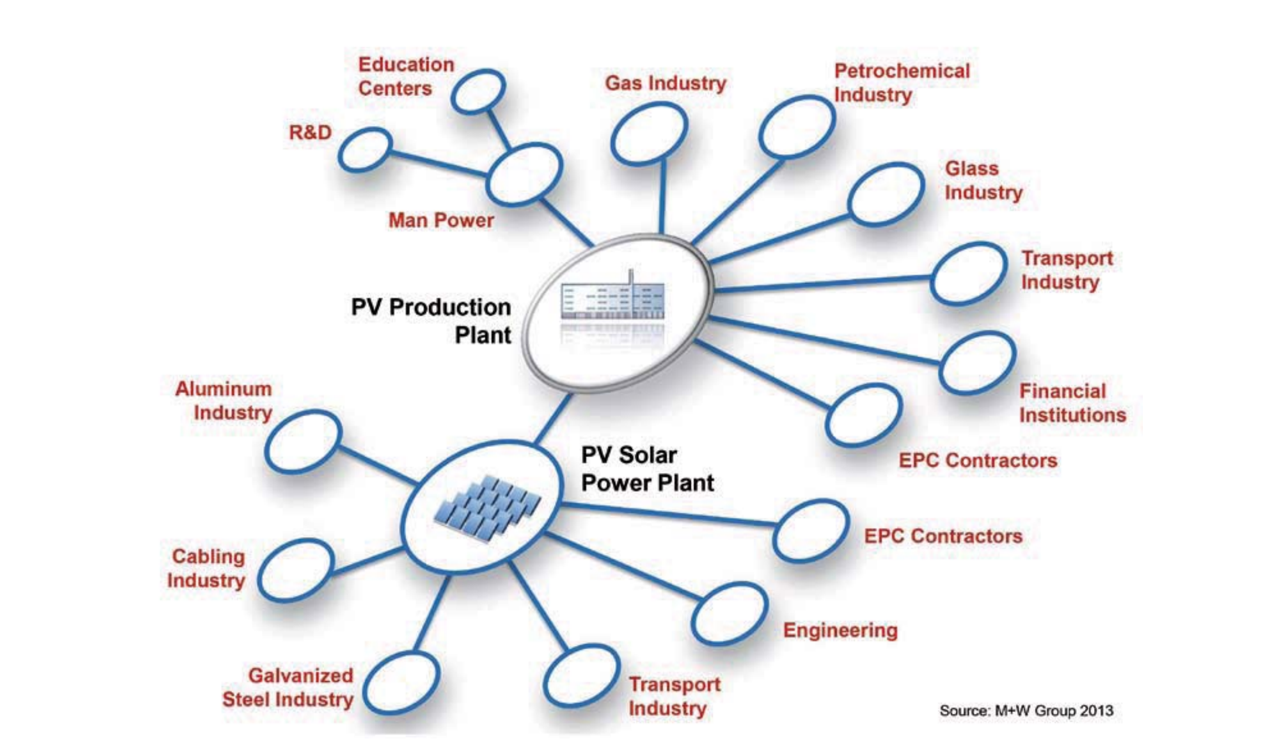

Figure 7. Job creation opportunities for PV manufacturing and solar installations including the entire supply chain.

This also explains why a number of countries with high growth rates in solar installations are eager to set up local manufacturing for single parts, or even for the entire added-value chain. An important consideration in the case of closed markets is that the price of modules and related BOS costs could increase. To establish a new industry in conjunction with the creation of employment opportunities, a national incentive plan acts as a useful catalyst, but only for a limited period in order to allow the local industry to become competitive during the ramp-up of production.

Future trends

Process technology advancements will remain one of the most important factors in driving down manufacturing costs of PV modules. Because of the expansion of the global PV markets in different climatic conditions, the optimal selection of cell and module process technologies should be considered on a case-by-case basis. For this reason, the authors do not anticipate the dominance of one mainstream technology, but rather the co-existence of a suite of different technologies. Incremental steps will occur to increase module efficiency and drive down cost. From an EPC company's perspective, it will be important, during the engineering of such a fab, to design the facilities to precisely match the requirements of the process and manufacturing technology. Seamless integration of process and facility technologies is key to achieving these targets without oversizing the facility systems for each individual production technology.

> "Reducing the investment and running costs will be of utmost importance to fully utilize potential synergies."

Reducing the investment and running costs, particularly for integrated facilities co-located on one site, will be of utmost importance to fully utilize potential synergies. M+W Group has experienced requests for either centralized and integrated or decentralized manufacturing complexes, depending on an inquiry's origin. The recycling of water and certain process gases and chemicals will become cost-effective for GWp/annum-scale facilities: as previously discussed, the cost of electrical energy and the potential market's size are key drivers for such decisions. A state-of-the-art concept for a fully integrated PV manufacturing facility from poly Si to module on a GWp/annum scale has been recently developed by M+W Group and its partners, and is illustrated in Fig. 8.

As depicted, a central facility plant serves the individual process steps with main utilities, with specific utilities located within the respective manufacturing buildings. The poly Si manufacturing plant is adjacent to the ingot/wafer building. Wafers are transferred to the cell deposition building, followed by module assembly and final storage/shipping. By utilizing synergies for the utility supply and disposal systems, investment as well as running costs can be significantly reduced. Such facilities will most likely be implemented in countries with low energy costs and sufficient market demand.

Countries with relatively high energy costs or limited markets (below 400MWp/annum) will primarily follow the trend towards the construction of local cell and module manufacturing plants. Scenario planning should focus on potential future needs in order to be flexible for expansion in case of short-term market growth. Specific factory planning employed at an early stage during site assessment/selection and site master planning can mitigate potential surprises later on.

Conclusions

The PV manufacturing industry will resume its growth after the recent downturn and intensive consolidation. From a fab and facility perspective, the key questions are:

- What should be the optimum manufacturing capacity?
- How much process integration should be implemented?
- Where will the new facility be built?

Figure 8. Concept for a fully integrated PV manufacturing line.

- How should the facility be designed to ensure cost-effective operation?

The authors have addressed the specific cost per manufacturing capacity within the PV added-value chain, as well as the specific energy demand for each of the production steps. A minimum production capacity of 200MWp/annum is recommended for cost-effective manufacturing. Increasing the production capacity from 200 to 600MWp/annum will further result in specific operational reductions, but to a lesser degree. From a fab and facility perspective, for production capacities above 600MWp/annum, the effect on specific production cost reduction decreases further.

> "A minimum production capacity of 200MWp/annum is recommended for cost-effective manufacturing."

The degree of integration will be influenced by the local cost of electrical energy. In regions with high energy costs, it will be challenging to operate poly Si and ingot/wafer plants in a cost-effective manner because of their high energy demand. It can therefore be concluded that central poly Si and ingot/wafer plants with capacities exceeding 1GWp/annum will be situated in locations with competitively low energy costs. The location of future cell and module facilities near to the end-user market should be considered, since this approach offers numerous benefits, not only from a cost perspective, but also from a macroeconomic point of view, with direct employment creation and the development of the associated service and supply industries.

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