Fab & Facilities
Materials
Cell Processing
Thin Film
PV Modules
Power Generation
Market Watch

Overview of automation in the photovoltaic industry

Kevin Reddig, Fraunhofer IPA, Stuttgart, Germany

This paper first appeared in the fourth print edition of *Photovoltaics International* journal.

ABSTRACT

The aim of this paper is to provide an overview of the methods of automation and their application areas. Current technologies and their applications in both crystalline and thin-film technology will be the main focus, with detailing of the value chain, starting from the feedstock to the finished product. For ease of discussion, the focus is on the part of the value chain where discrete manufacturing on the substrates takes place. The paper will show different philosophies of automation and highlight their advantages and disadvantages, and will contribute a commentary on future developments. Throughout this paper, we have given a step-by-step breakdown of the applications of automation in the PV manufacturing industry, from automation for crystalline technology to automation for thin-film manufacturing.

Introduction

The photovoltaic industry has been increasing tremendously in recent years. Global production volume has risen from 1.7GWp in 2005 to 7.1GWp in 2008 (estimated 9-10GWp in 2009), made possible by increased demand and the resulting provision of capital.

Compared to other industries, photovoltaics is just beginning to activate and exploit its full potential. With the currently predominating technology based on rigid substrates, such work paces as are seen in other industries could never be achieved for the photovoltaics industry. Nevertheless, many acceleration methods can and certainly will be introduced to decrease the overall production costs.

In this context, factory automation was and still is a key enabler. Were it not for the introduction of automation, many factories would not have been established and ramped so quickly. However, automation is not the end in itself and therefore this paper will also deal with its limitations.

"Were it not for the introduction of automation, many factories would not have been established and ramped so quickly."

As this paper will only give an overview of automation in the industry, it does not claim to be a complete report. Future contributions to *Photovoltaics International* by Fraunhofer IPA and others will address more specific aspects of automation.

Definition and purpose of automation

The most common approach is to introduce automation into production to reduce costs by enabling a faster and cheaper processing as well as by facilitating 24/7 manufacturing. One result of automation is the reduction of the workforce, often required in regions with comparatively high wages. Automation can also ensure

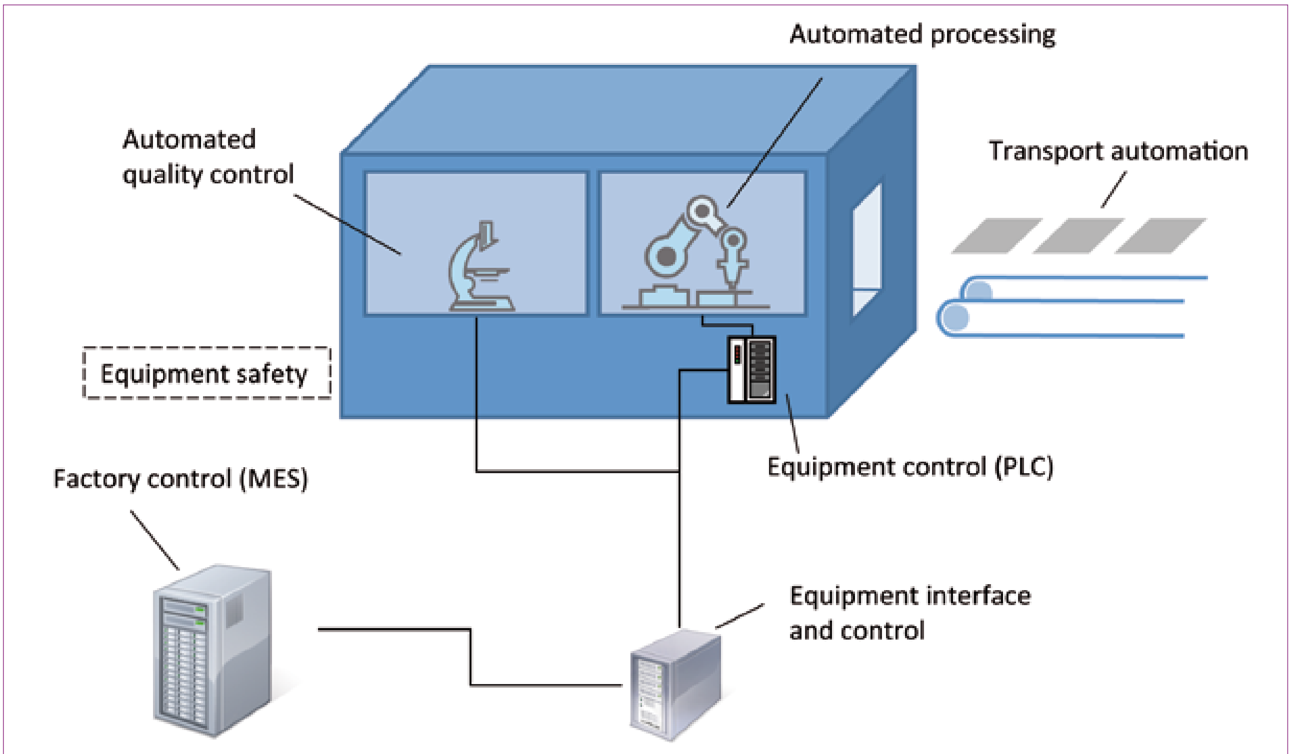

Figure 1. Aspects of automation in photovoltaic manufacturing.

product quality, staff safety and better environmental conditions. Cost reduction is a well-known necessity, and the sheer amount of substrates processed in today's larger factories usually calls for an elevated degree of automation. In terms of quality requirements, wafers and substrates are delicate products that can easily be damaged if not treated properly, while there are further crucial considerations to be taken into account in relation to the safety of operators.

Factory automation is a complex and integrated interaction of different systems, not only in the physical transport of a product from A to B, but must comprise software and hardware that interact perfectly. Such a system contains equipment that has to meet the requirements of the automated process, material flow, consumables, communication and control systems.

Integrated automation systems in a factory typically have to provide the following functions:

- Automated processing: interfacing appropriately with the manufacturing environment to carry out processes in an automated manner.
- Physical availability of the required materials: the automation system typically comprises elements that 'care' for the automated transport and provision.
- Measurement and control: sensor signals and quality data are used to both control the process flow and to control and adapt the individual production units.
- Interfaces: different types of equipment have physical interfaces as well as control interfaces to allow for automated access as well as for human interference.
- Safety: the automation system must also provide safety measures for the protection of humans, the protection and quality assurance of materials and for overall environmental safety.

Different views on automation

A manufacturer is not only interested in more cost-effective production methods, but also has to consider location-specific factors such as labour costs and regulations. The introduction of automation increases capital expenditure, and brings with it the risk that the flexibility of the production line might be reduced. Moreover, there is an increased dependency on the equipment itself.

Automated equipment usually utilises actors, sensors and corresponding equipment control. The more automated a procedure is and the more information is gathered regularly from these procedures, the more complex the equipment is in terms of the components used and the equipment control. Especially in a manufacturing environment, technical components can deteriorate faster than expected, leading to greater equipment supply and training requirements as the technology is updated more regularly. For the maintenance of such equipment, the availability of qualified personnel in a factory must be guaranteed.

Automation unfolds its strength when standardized procedures have to be executed more or less exactly in the same manner. A visual check of wafers or substrates by a human operator can often unveil deviances which otherwise might remain undiscovered. Nevertheless, manufacturers generally wish to have control over their processes by applying automation.

> "Automation unfolds its strength when standardized procedures have to be executed more or less exactly in the same manner. A visual check of wafers or substrates by a human operator can often unveil deviances which otherwise might remain undiscovered."

Labour costs can be comparatively low in some regions, thus permitting the employment of more operators in the manufacturing line and reducing the need for some aspects of automation. Chinese company Suntech is an example of such a strategy in that it endeavours to apply as many manual processes in the cell production as possible. The consequential effects are reduced investment costs and an increased flexibility.

Cost of automation and future factories

The costs of automation usually do not contribute very much to the manufacturing costs. In the thin-film industry, for instance, the costs of automation typically contribute 1-3% to the total investment, which itself has a share of roughly 25-35% of the total production costs; measured according to cost per watt peak, it is well below 1%. The equipment costs in crystalline wafer and cell manufacturing are usually below 25%; for module manufacturing they are below 10%. Depending on the degree of automation, the resulting costs also make up less than 1% of the total costs for cells and modules.

Large factories can also reduce the costs tremendously due to better purchasing conditions of the required materials. For thin-film technology a share of 50% of the total costs is assumed for all required materials; for crystalline technology, usually more than 60% has to be calculated for the material (including silicon). Should the company need to purchase silicon products (polysilicon, wafers or cells) the share will increase further. In the case of module manufacturing, this sums up to more than 75% if cells are bought on the market. (Due to the current economic situation, the cost of cells has decreased.)

Therefore, future factories will definitely increase in size to leverage the benefits of the economy of scale, which will also affect the suppliers. In this situation of increased consumption, it will be beneficial to produce several kinds of material in nearby factories. This applies for substrates (glass or wafer), gasses and media or encapsulation materials. Factories in the gigawatt range might as well operate a dedicated glass production line that will introduce new requirements into the integrated automation solution.

Operation of such a large factory will require further developments, including:

- Compliance with standards
- Capability for interaction with higher control systems
- Ability to perform quick maintenance and repair.

Standardization

Standardization in manufacturing means the creation of a common comprehension of the technical characteristics of work pieces and the means of production. Standards are based on written specifications that describe how the features of the addressed area should be designed and require a large uptake in order for them to be introduced successfully and realized by stakeholders in their companies. Generally speaking, standards should be open and accessible to all stakeholders. Proprietary knowledge (e.g. patents) sometimes also creates a de facto standard, resulting in a monopoly in this area.

Standardization in manufacturing is usually viewed as a way of facilitating the build-up and the operation of factories. Standards are generally introduced to reduce the product costs, facilitate the entry of new market participants and to inspire customer confidence. By its nature, a standard is usually based on the mutual agreement of a large group of stakeholders, and often takes a long time to be adopted due to uncertainty on the part of the market participants, as well as a reluctance on the part of the stakeholders to bear the initial costs generated by the introduction of standards, coupled with concerns of a slowdown of innovation. Technologies that do not comply with a standard can be constrained as a result.

In the photovoltaics industry, standards can be applied with respect to automation in the following areas:

- Substrate dimensions and characteristics
- Carriers and other means of handling and transportation

- Loadports of equipment and interfaces for consumables
- Equipment interfaces for control and data collection.

The latter area has been tackled by a group of stakeholders who created a standard published by the semiconductor association SEMI [1]; the other areas are currently being investigated by different interest groups.

However, many suppliers and manufacturers have developed their own methods of handling and transport, and will undoubtedly be reluctant to alter them without seeing a long-term benefit.

In the long run, several experts nevertheless see the necessity for an agreement of certain automation standards. In order to achieve this, two vital factors have to be considered:

- A standard usually does not succeed if stakeholders wish to introduce proprietary products and methods.
- If different solutions already exist, some stakeholders will need to give up certain proprietary solutions and adapt to a common standard.

Manufacturing control

Due to the demand for an efficient line control, Manufacturing Execution Systems (MES) are being considered more and more often by manufacturers. One of the first functionalities used is the collection and the analysis of the production and process data, and as a result, the Statistical Process Control (SPC) is quickly becoming one of the most used functionalities of the current MES.

From the standpoint of process equipment, the interface to a higher factory control (usually MES) is the main obstacle to full integration. The full functionality of the above mentioned standard will allow the achievement of active control in terms of the process start and stop or the recipe changes. Most of the process and automation equipment are controlled by a PLC (Programmable Logic Control) which, when used in the creation of the equipment interface, is currently regarded as very expensive, but will undoubtedly decrease as the demand for such interfaces increases.

> "Many suppliers and manufacturers have developed their own methods of handling and transport, and will undoubtedly be reluctant to alter them without seeing a long-term benefit."

Material tracking is a necessity for a full factory control scenario, but remains a challenge, with frequent alterations of the shape and surface of crystalline substrates during the processing impeding permanent marking. Technical and economical barriers hamper the introduction of corresponding methods. The tracking of glass substrates (especially in thin-film production) is quite simple as cost-efficient laser marking and readers are available for substrate tracking. Such systems are widely used in thin-film manufacturing solutions.

From an economical point of view, single substrate tracking is critical, as large amounts of data need to be gathered and analyzed. One disadvantage of a batch tracking approach is the difficulty of mixing of lots and batches in production lines which impairs the usage of the production data and a very close coupling with the MES.

Future factory control solutions must take into account the short cycle times in photovoltaics, and that cost reductions and process simplification are the predominant goals of all manufacturers. By achieving the stabilization of manufacturing processes, the quality and the process control in mass manufacturing will only have to be used at certain steps.

Challenges and expected developments in automation

Photovoltaic modules are generally viewed as commodities that must bring with them a guarantee of quality and a warranty, leaving the buyer to consider such crucial factors as price and availability as the main decision-making criteria. In terms of manufacturing and automation, the key to success will be to increase the throughput while maintaining reliability and quality. The manufacturing processes will further accelerate, the factory capacities will increase and the substrate sizes will also finally increase, forcing automation to adapt to meet these requirements.

Suppliers of automated process equipment will have to increase uptime for a higher overall utilization of the production line and increased throughput. Nevertheless, the process equipment will still have to be maintained and altered during its lifecycle. In order to compensate for downtime and other process deviations, substrates have to be stored or rerouted. In interconnected lines the material flow then has to enable the transfer of products to equipment that is capable of carrying out the same process step. Likewise, the control system has to track the material as well as balance the capacities of all manufacturing equipment.

Experienced manufacturers usually plan new production lines on the basis of gained experience and individual requirements. Such manufacturers seldom use turnkey

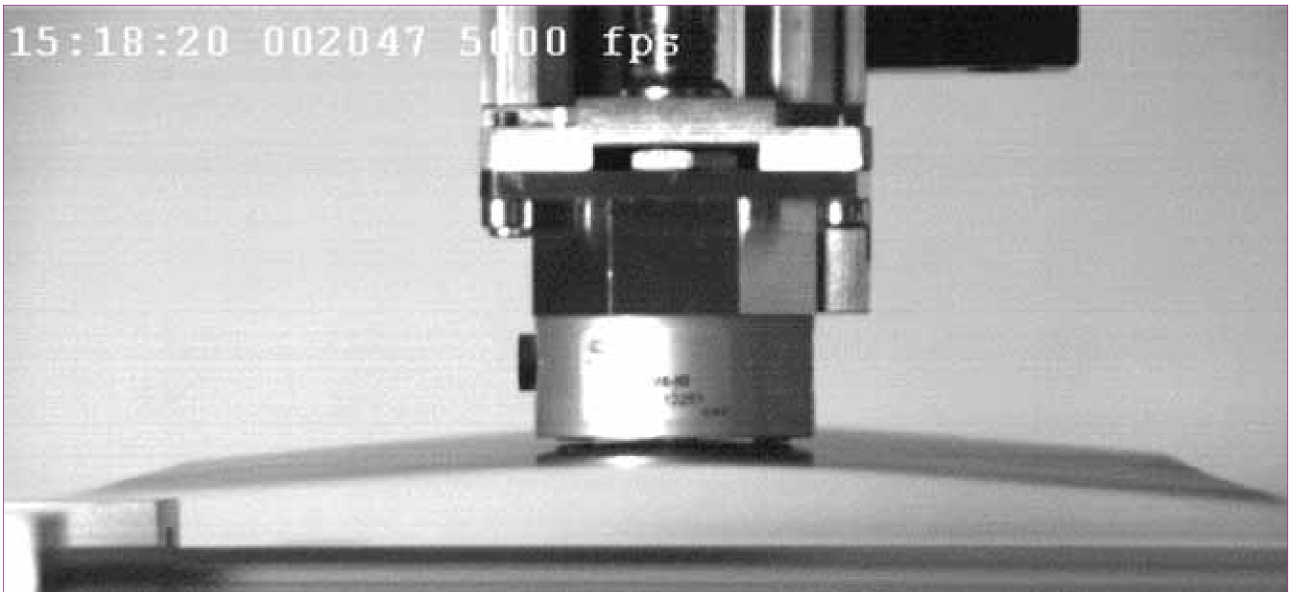

Figure 2. Visualization of gripper performance at Fraunhofer IPA test facilities.

offers from equipment suppliers, choosing instead to select particular components to build up their manufacturing lines. An increase in demand for these equipment types will definitely call for a modularity of such tools, allowing manufacturers to make the best choice concerning their own requirements.

Challenges and developments in crystalline technology

With the throughput of factories set to increase in both size and speed, current crystalline technology processes that usually have a cycle time of more than a second per wafer will use automation to increase the speed of all operations. As a result, the two main objectives will come into conflict with each other: a stress-free and gentle handling of more and more fragile wafers on the one hand and a continuous reduction of the cycle times on the other hand. Some stakeholders try to overcome this challenge by paralleling the handling and the multi-loading of the process equipment; however, the majority are engaged in finding new or optimized gripper and handling solutions.

The thickness of a wafer will be defined by considering silicon's prices and its yield, but thinner wafers will always be desirable in crystalline technology. A closer look at the production and its characteristics might propose a lower limit of about 150µm. This is defined by the current technology of cutting wafers with wire saws and the increased breakage rate of thin wafers during further processing. There appear to be three possible future scenarios for the development of thinner wafers: thickness will be reduced, wafer size will be increased, and wafer/cell design will change.

> "Experienced manufacturers seldom use turnkey offers from equipment suppliers, choosing instead to select particular components to build up their manufacturing lines."

All comparable industries have followed the path of increased wafer size, and the PV industry should follow suit. The shortage of silicon and the struggle for a higher yield and uptime of the current sizes has delayed this development; however, many suppliers have overcome this problem by designing their equipment to be able to process on wafers with an edge length of 210mm. Once a main producer successfully introduces such an increased wafer size, many others will follow suit to tap the full resulting cost-saving potentials.

Inline manufacturing looks set to dominate, as the loading and unloading of carriers is time-consuming and more stressful for the wafers. Furthermore, there is an increased need for automation equipment. "Every avoidable handling step needs to be eliminated. Once a wafer is placed on a manufacturing line it should run all the way through" said Dr. Andreas Reischl from Schiller Automation at the Photon Expo fair in Munich. Nevertheless, many stakeholders prefer batch processes for reliability and cell efficiency reasons.

All encapsulation materials for module manufacturing certainly leave room for the cost reductions of larger quantities and new technologies, but the costs of the encapsulation material most likely cannot be reduced as quickly as those of the cells. An important aspect is that module manufacturers have to issue the guarantee of their products for at least 20 years. Markus Steinkötter from Sunnyside upP adds: "Module manufacturing and automation face two major challenges. On the one hand we have to transform the processes into a continuous flow to reduce the production costs. On the other hand we are in need of equipments which can also be operated in less developed regions in order to open new markets."

Automation for the PV industry – a step-by-step guide

Automation for crystalline technology

In crystalline photovoltaics, the central focus of the manufacturing is on the wafer. One important aim of automation in this sector is to ensure a maximum output of good wafers and cells. (Automation of the ingot manufacturing process is intentionally omitted in the following discussion.)

Crystalline wafer manufacturing

Wafer manufacturing starts with the preparation of the ingots by cutting them into manageable semi-squared (monocrystalline) or squared (multicrystalline) silicon blocks as well as grinding and polishing the edges and surfaces, usually requiring several manual handling operations. Cutting the wafer out of an ingot involves the ingot being glued to a workpiece holder – the first instance of automation in the process – which is then incorporated into the wire saw. Such solutions already exist in some factories.

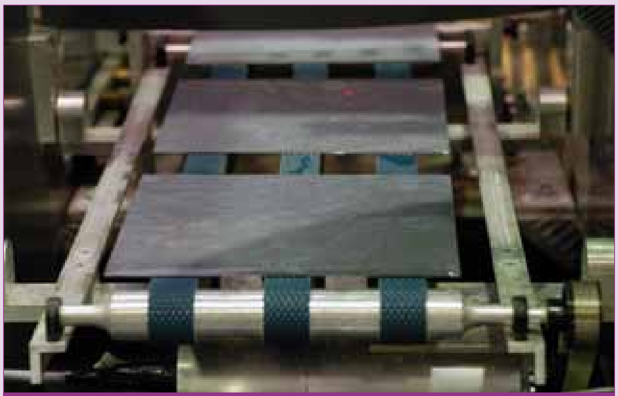

Figure 5. Wafer after separation (Fraunhofer IPA).

Figure 3. Manual placement of a silicon ingot on the adhesive.

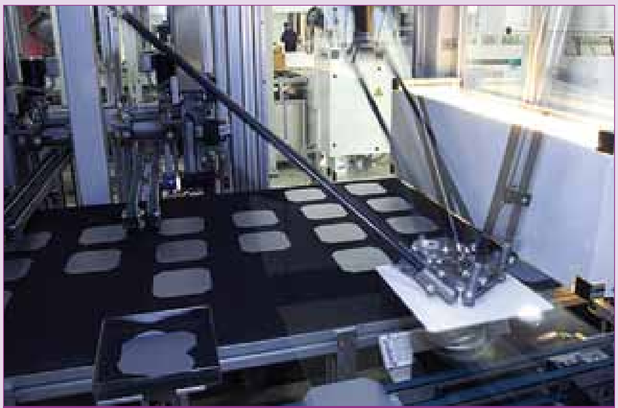

Figure 6. Wafer being transferred and sorted (Solarworld/ OregonDOT).

The transport of the ingot to the wire saw is done manually with the aid of handling devices. An automated solution would have to be heavy-duty as the ingots are quite heavy and the equipment deals with a lot of contaminating fluids. The insertion and the extraction of the workpiece holder into the wire saw also need to be controlled by operators.

Figure 4. Silicon ingot in a wire saw, ready for process start.

The separation of the wafers after the sawing is a tricky process, where the sawn ingot is thickly covered with slurry (typically silicon carbide dissolved in glycol). After pre-cleaning of the entire wafer stack, the wafers are still separated by hand in many factories, while wafer sizes exceeding the average hand-span call for automation. After the wafers are separated, they are cleaned and dried on conveyors through the different cleaning basins.

Although inline cleaning is very common some manufacturers also use a carrier based batch cleaning in which the carriers are dipped and rinsed in different basins. After being cleaned and dried the wafers are tested and sorted into quality bins, packed and delivered to the cell manufacturers – an additional handling step for the wafer manufacturers and the cell manufacturers who have to unpack the wafers.

Cell manufacturing

The biggest difference of automation in cell manufacturing is the type of production processes that means whether they are primarily based on batch or inline manufacturing. Usually manufacturers base their decision on previous experiences and the requested cell quality. In the following we will go into more details about the characteristics of the two alternatives.

Batch manufacturing

Process steps such as etching, diffusion or deposition are executed in batches of (typically) 100 wafers that are moved from process to process using automated handlers, some of which require chemical resistance and temperature resistance. The frequent reloading of wafers involves gripping several wafers at once or else extracting the wafers from a carrier one by one.

Figure 7. Styrofoam box of wafers ready for cell production.

Step-by-step guide continued

Figure 8. A quartz bot being loaded into a diffusion furnace (SEMCO).

The frequent reloading of wafers involves gripping several wafers at once or else extracting the wafers from a carrier one by one.

The transport of carriers can be done manually, supported by PGVs (Person Guides Vehicle), or automatically, often using conveyors where the carriers are placed upright onto the conveyor belt with utmost care to prevent breakage.

The lack of standardized interfaces is a concern, in that several suppliers and manufacturers have developed their own carrier system that ends up being a unique solution customized only for one manufacturer or even a single factory. Although there were some standardization activities in the past, they have yet to be mutually accepted.

Inline manufacturing

The aims of inline manufacturing are speed and the facilitation of the wafer handling. Equipment is available for all process steps except the antireflex coating (ARC) with silicon nitride in the PECVD process, which is carried out in a kind of batch process. For batch building, the picking and placing of single wafers can be either carried out by scara robots or by special solutions such as delta kinematic robots.

Figure 9. Manufacturing of cells (Solar World AG).

The first step is the separation of dry wafers from a stack, typically carried out by grippers and pressurized air, which supports the separation of the wafers. Transport is then left to the o-rings and conveyor belts.

Buffers are usually used between the process steps to increase the overall utilization of the production line and can double as stacker solutions, allowing wafers to pass through if the succeeding process is in operation. The stacker will gradually store the wafers if the following process step cannot be carried out. One disadvantage of such a solution is the uncertainty of when the stacker can be emptied and the resulting risk of a long-run storage of individual wafers.

Module manufacturing

From the perspective of automation, module manufacturing is quite diverse as it involves handling of several different material types. The material costs of a module, excluding the wafer, have an average share of more than 80% of the total module costs. For this reason, a high yield of all materials used is required for a profitable operation.

Figure 10. Wafers being dispersed onto several conveyors (AMB).

Figure 11. Wafer in stacker buffer (AMB).

The core process steps in module manufacturing are the tabbing and stringing of the cells as well as the lamination with a substrate (typically glass). Interconnection of cells is usually done automatically, for fragility reasons, by a stringer that can connect up to 12 cells. Feeding can be performed either manually or using automation.

The cutting and the lay-up of the various foils used can be done manually or with the aid of semi- or fully-automated equipment. After substrate assembly, the structure is transported to the lamination equipment, usually roller and belt conveyors.

Figure 12. Inside view of a stringer (Somont GmbH).

Process steps following lamination can also be automated. However, many manufacturers prefer manual operations for tasks like edge trimming and the setting of the junction box. The finished modules are often framed and handled by means of 6-axis robots both for uniformity and human safety reasons.

Challenges and developments in thin-film technology

Compared to crystalline technology, the mass manufacturing of thin-film products is still in its development phase (with the exception of First Solar). Manufacturers started to use technology developments in this sector with the help of pilot lines to further enhance efficiency, yield and throughput. Several equipment suppliers developed their own solutions, mainly based on silane, and now offer turnkey solutions. Other thin-film technologies such as CI(G)S and CdTe are now developing in a similar way.

Process stabilization will remain with higher module efficiencies and yield improvement as a main goal for manufacturers as equipment can have long down times and modules are subject to considerable fluctuations in terms of their efficiency. Once process engineers have accessed process and quality data, the close monitoring and adaption of the equipment processes and recipes is crucial, perhaps even for each individual process run. Equipment interfaces and methods gathering and correlating process and quality data are therefore highly desirable, as are interfaces that can control the production processes automatically.

Automation for current factories mainly comprises solutions accumulated from the glass industry. Single lines are often rigidly coupled, with buffers in between. Future factories will have to incorporate more flexible solutions to maximize the utilization and reliability, with a clear need for equipment productivity to be on a high level and avoidance of idle time of a piece of equipment. Automation suppliers therefore have to work on reliability, user-friendliness and the repair capabilities of their equipment, which should only require specialist interference in the most exceptional cases.

> "Future factories will have to incorporate more flexible solutions to maximize the utilization and reliability."

In terms of factory layout and configuration, future factories and production lines will need a higher interoperability and more opportunities for the exchange of substrates, thereby enabling the establishment of larger factories that benefit from a better balance of production capacities. Stefan Huttelmaier from Schiller Automation says: "…future factories will have to adapt automation to the requirements of the manufacturing processes. Mixed variants of equipment cluster as well as fixed linked processes will be developed to achieve the maximum throughput in a factory." Such equipment clusters can be advantageous for the facilitation of operation and maintenance.

A major step will also be the scaling up of substrate formats, as already introduced at Applied Materials. When equipment suppliers and manufacturers successfully establish the processes to homogeneously deposit on larger substrates, automation suppliers will have to provide solutions for an efficient transport and handling.

The advantage of the roll-to-roll production concept is the continuous feeding of the substrate material as well as the reduced footprint of the equipment. For this concept, automation must be designed for lightweight materials such as metal or polymer foil. With the long-run stability of the modules a major issue to be tackled, production methods for the potential scenario of flexible solar cells becoming a niche market still need to be decided.

Visions for the future

Regardless of their individual technologies, future factories and their automation will have to meet certain requirements, some of which are outlined below:

Production costs

The production costs of one module have to be well below €1

Step-by-step guide continued

Automation for thin-film manufacturing

Thin film automation usually deals with the transport and the processing of glass substrates, the sizes of which *typically* can vary from 0.6m to 1.1m in width and from 1m to 1.4m in length (and larger), with *some* of the methodology originating from the glass industry. Current thin-film manufacturing lines are quite small: compared to a typical float glass line, which produces 500-700 tons of glass per day, a typical thin film factory with a capacity of 60MWp/a processes 28-35 tons of glass per day.

In most thin film factories the material handling and the transport are based on conveyors. These conveyors connect the process equipments (deposition, scribe, cleaning, etc.) – often based on a single substrate processing – with each other. The entire line is therefore typically coupled in a rigid manner with the possibility of using buffers, bifurcations and access points in between. Some equipment suppliers also offer batch-processing equipment, which provide the opportunity of transporting and storing the substrates in cassettes. Both solutions have advantages as well as disadvantages (see Table 1). For the present, the conveyor and the cassette based manufacturing will continue to exist in parallel as well as in mixed applications.

The buffering of substrates in thin-film production lines is not a trivial task. The sheer size of the substrates requires large facilities that have to be able to lift heavy substrates. Buffers based on a LIFO (last-in-first-out) principle need a smaller footprint, but in this case, the substrates can end up remaining in the buffer for a considerable time. FIFO-buffers (first-in-first-out) typically require a larger footprint; in this case, the storage time of substrates can be controlled more easily. Generally, thin-film manufacturing demands the monitoring of the waiting times. If the defined time interval is exceeded between certain process steps, some layers might be influenced negatively by the climatic conditions existing in the manufacturing building. For this reason, other high-temperature process steps call for a subsequent cooling time before the next one can be carried out. Automation has to consider all these requirements. Therefore, it must provide fast transport, a sufficient amount of buffers, and capabilities to control the material flow.

Figure 14. Glass handling with a 6-axis robot (Schiller Automation).

Compared with silicon wafers, the identification of glass substrates is quite easy. Usually a dot matrix code is applied to the substrate with a laser, allowing the tracing and the tracking of each single product. As a result, special routes for substrates can be realized to use the individual substrates for engineering or as a measurement reference. If such a seamless traceability is demanded by the manufacturer, the automation solution also has to provide ID-readers at specific points as well as control systems that can modify the process plan or the recipes of the individual substrates.

Figure 13. Special transfer solution for unloading and loading of process equipment and cassettes (Schiller Automation).

	Single substrate	Batch
Transport	Proven, state-of-the-art	Cassettes, special solutions
Handling	Feed-in with conveyors	Substrate needs to be extracted from the cassette
Storage	Buffer solution	Transport carrier can be used as buffer
Line concept	Fixed coupled lines are most popular	Flexible concepts with clusters possible

Table 1. Advantages and disadvantages of manufacturing types.

per watt peak. Generally, this is already possible for all technologies. Today, thin-film modules could be produced on a large scale between €0.5 to €0.6 per watt peak.

Supplier capabilities

The supplier capabilities need to be enhanced to provide adequate equipment and services for the installation of large factories. With the support of standardization, the available quantity of equipment on the market will have to increase to meet future demand.

Reliability and uptime

Future automation solutions have to be comparable to other mature industry solutions that have an availability of 99.5% or more.

Thomas Schmidt, former COO of Q-Cells, whose role is now to support the implementation of production lines within his company TST-C, also sees many practical aspects: "The suppliers of automation solutions do not only have to improve the quality of the equipment and the services. Rather, the sufficient support at the manufacturer's site is a key factor for a successful implementation. This also includes the maintenance and the upgrading of the existing equipment in use."

Conclusion

The future of the photovoltaic industry has not been predictable from an automation requirements point of view. Unlike the semiconductor industry, the photovoltaics industry does not only compete with itself – it is up against technologies like solar thermal or wind energy, and in the future will also have to compete with traditional energy sources. As a result, the ultimate goal of photovoltaics is cost reduction.

> "The photovoltaics industry does not only compete with itself – it is up against technologies like solar thermal or wind energy."

Also, population in developing regions will need access to clean energy, otherwise global efforts for reducing CO_2 emissions will not be sufficient. This implies the increase in size – not only with respect to factories but also to companies. At the moment, manufacturers often lack the financial power to grow fast enough to reduce costs. Therefore, large manufacturers of other commodities might take the lead in mass manufacturing. In terms of long-term development, photovoltaic manufacturing is comparatively young and therefore there is enough potential to develop further.

Acknowledgments

The author wants to thank all contributors to this paper who brought their expertise and were partners of some very interesting discussions. Apart from individuals and companies mentioned in this paper, thanks goes to Christian Fischmann and Tina Kabus from Fraunhofer IPA.

Reference

[1] SEMI, Document 4557: SEMI Guide for PV Equipment Communication Interface.

About the Author

Kevin Reddig is a team leader at Fraunhofer IPA, which he joined in 2002. He received an M.S. degree in industrial engineering from the University of Karlsruhe (TH) and now works in the field of factory planning and automation including equipment automation, material flow solutions and data modeling and processing. He has experience in both hardware and software automation projects, mainly from the photovoltaics and semiconductor industries.

Enquiries

Fraunhofer IPA
Nobelstrasse 12, 70569 Stuttgart
Germany

Email: reddig@ipa.fraunhofer.de
Tel: +49 711 970 1232