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How automation can benefit the PV industry

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ABSTRACT

Although the different roadmaps for PV vary somewhat from each other, the bottom line always remains the same: exponential growth is predicted over the next 5–10 years. The latest cell technologies meet the demand for grid parity even in central Europe and PV will therefore continue to be the most popular source of renewable energy. In consequence, the whole PV industry has developed from a niche product towards mass production. Every player along the entire value chain is now faced with the need to stay profitable while meeting the ever-increasing demands of the market. Implementing suitable automation can improve competitiveness and thus pave the way to becoming or remaining successful in this turbulent market.

Introduction

The PV industry currently faces a time of consolidation. All players, without exception, are being asked to rethink their own strategies and make the right decisions. This phase of market adjustment has been observed in other areas ever since the beginning of mass production. If a close look is taken at the issues that cell/module manufacturers are currently experiencing, the well-known triple constraint of time, cost and quality can be observed.

The time factor is ever present in production. The overall output of a factory is directly linked to cycle times and equipment downtimes. An optimal process layout can help to decrease both of these and therefore lead to an increase in throughput.

The definition of costs in PV production is made up of two main components. One major cost driver is the quantity of expensive/rare materials that is required. As this is determined by the technology itself, it cannot be affected by the actual production. The second one is the waste of resources – such as consumables, labour and energy – and is therefore the one mostly related to automation and process control.

The quality of production – the third constraint – is mainly described by the ratio between the number of good units coming out of a process and the overall number of units going into it. Referred to as 'yield', this relationship can be optimized by ensuring low breakage rates and implementing accurate, fine-tuned processes.

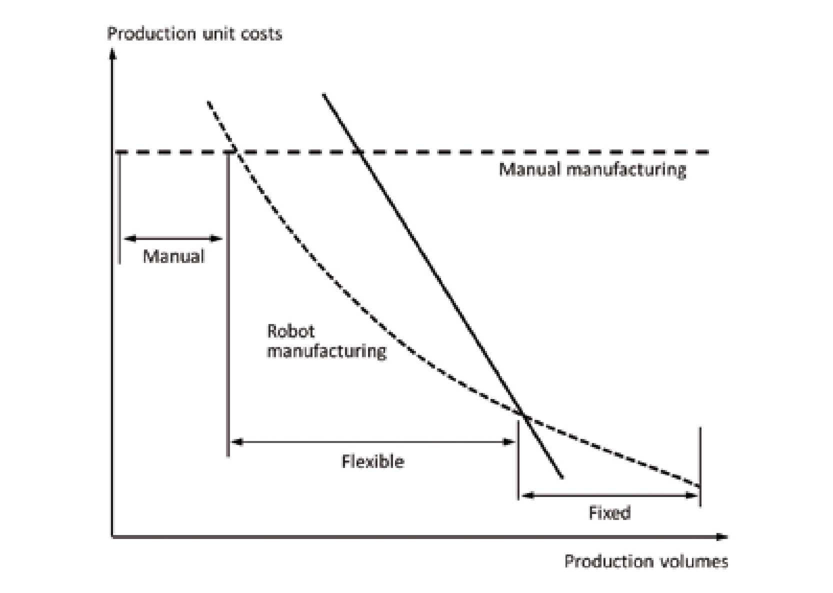

Figure 1. Useful degree of automation as a function of production volumes and production unit costs [1].

Automation in PV

Automation in production has a long history. Edmund Cartwright's weaving loom is mentioned as being the first automated production machine in 1785. The use of steam engines instead of manual labour speeded up the growth of automation, which has continued to the present day.

Because of ongoing improvements to various technologies in the field of sensors and control, automation has become more flexible and capable of more complex tasks. The introduction of computer-controlled equipment gave a further push towards mass production, by reducing the costs while simultaneously increasing quality.

Without significant, ongoing improvements in the field of automation in all branches of industry, manufacturing would be completely different from what it is today. As soon as manufacturing touches one of the DDDs (dangerous, dirty and dull), a suitable automation should be implemented. Although the cost-saving potential is seen to be the major benefit, there are many more advantages of automation. The predictive repeatability of programmed steps, the ability to meet ever-increasing throughput requirements and the capability of handling huge amounts of (sensor) data are also closely related to automation as such.

The basis of a suitable automation concept always lies in understanding the production itself. To optimize the benefits, a knowledge of, and experience in, both the field of automation and PV production are needed. Maximum productivity can only be achieved if the optimum solution for the process step concerned is actually capable of fulfilling requirements.

Factory automation is the versatile interaction of different hardware and software systems – so-called computer-integrated manufacturing (CIM). Determining the optimum degree of automation in manufacturing facilities or process chains is a complex decision for factory planners. To understand the background to this challenge, it may help to take a closer look at history. In the 1970s, the term 'CIM' equated to development efforts to transform shop floors into areas without a human workforce. Because most of the experience possessed by operators could not be implemented into the software of the automation system, the idea of making the shop floor human-free was reconsidered. From then on, CIM began to change. The concept of a fully automated production line turned into the aim of implementing the right amount of automation, i.e. only as much automation as necessary. Calculations to ascertain the optimum degree of automation are based on conflicting targets, relating to labour costs, automation costs, manufacturing quality and production uptimes.

> "For PV producers, the most important argument for an automated production process is the need for high-volume manufacturing."

One of the most difficult questions now facing PV producers is how to determine a manufacturing strategy that includes the optimum degree of automation for the future PV market. As in other industries, the initial motivation for companies to consider (further) automation is the problem of increased production costs and the need for more reliable and reproducible manufacturing processes with appropriate capacities. Many other reasons may also be found, such as the desire to increase productivity, speed up time-to-market and realize flexible made-to-order production. However, for PV producers, the most important argument for an automated production process is the need for high-volume manufacturing.

Fig. 1 shows the general automation trade-off based on production volumes. The graph in this figure strictly considers the economic relationship between manual, flexible and fixed production processes. Technical considerations affecting the decision between robot manufacturing and hard automation may play a more important role in certain cases. Owing to the large number of solar products manufactured daily, hard automation is widespread in the production of silicon wafers and crystalline cells. Hard automation is also advantageous because of the low diversity of workpieces in a PV production line. The manufacturing of today's standard 156mm × 156mm wafers with a thickness between 160 and 220µm is an almost stable process. A certain degree of automation therefore enables producers to optimize the overall production system.

While looking at the benefits and advantages of automated systems in the production of PV goods, the challenges and efforts related to implementation should not be forgotten. As well as the monetary investment, the development of a new automation solution also involves systematic planning and design in order to master the technical complexity. In consequence, to ensure a sustained successful solution, the scope of automation needs to take both current and future requirements into consideration. First, the analysis of a fundamental and systematic evaluation concerning the technical challenges in combination with expected future savings is necessary [2]. Based on this, the possible and feasible solutions for automating a dedicated sequence have to be identified and realized.

If the worldwide distribution of industrial robots is taken as a general indicator of hardware automation, 45% of the automation solutions implemented in industries worldwide perform handling tasks, followed by 27% for welding activities and 10% for assembly work [3].

Automation vs. manual work

In principle, it is necessary to differentiate between fully/partially automated and manual work. Automation is useful in the case of large quantities or if, as mentioned before, at least one of the DDD aspects is a factor.

> The pressure to reduce cost and to increase quality rose tremendously within the last few months. Automation is the key to reduce breakage and to minimize contamination on the wafers. Since Asia is facing a significant rise in labour cost every year the return on investment for automation systems becomes more and more attractive. The mass production environment in the PV industry is the ideal setup for the use of automation systems, it combines high production volume with minimal variations in the product range. *(Florian Nachbauer, Head of Supplier Management, centrotherm cell & module GmbH)*

The motivation to fully automate a production line is not just the reduction of labour costs: automation can also ensure increased production capacities and significantly improve product quality. In combination with an ongoing process of standardizing interfaces, manufacturing efficiency can be enhanced and ramp-up phases shortened at the same time. Since factories are flexible and capacities are on the increase, the effort involved in adapting automation to the needs of growth can be planned and realized more easily than the effort required to organize larger amounts of manual work. In other words, a suitable automation solution makes life easier.

Credit: centrotherm cell & module GmbH.

Figure 2. Handling prior loading of a carrier.

> "An adapted, optimally balanced automation solution can help to minimize problems associated with wafer breakage or quality defects such as micro-cracks, and thus improve yield and quality."

Handling procedures for (un-)loading and transportation can be optimized, and process steps assessed individually. Manual handling is a non-measurable procedure that cannot be repeated exactly and is highly dependent on the person concerned. Regarded as a single task being performed manually, this operation can clearly be categorized as dull and is therefore predestined for automation. Ever-increasing throughput and reliability require a high repetition of simple and complex tasks with constant precision. In theory, simple tasks executed manually should have a low failure rate. But, in practice, doing the same, simple repetitive tasks for eight hours or more is extremely tedious, making it difficult to concentrate throughout the entire period, with the result that failure rates are higher than expected. An adapted, optimally balanced automation solution can help to minimize problems associated with wafer breakage or quality defects such as micro-cracks, and thus improve yield and quality.

When (un-)loading wet-chemistry benches, operators are exposed to the risk of injury from caustic fluids or vapours. The use of automated systems can reduce this risk to a minimum and therefore increase safety at work.

In contrast to the semiconductor industry, PV manufacturing does not require highly sophisticated clean-room conditions. Nevertheless, bilateral studies have shown that the use of mini-environments for dedicated process steps could increase the overall efficiency of the final product, especially in thin-film technologies. Investing in such local clean environments will therefore pay off if implemented in the right place and in the right dimensions.

> “It is much more difficult to assign quality defects or failures to manual handling steps.”

Factory automation is more than just a matter of transporting objects – it is also the excellent interaction between software and hardware. Measurement and control systems have to be integrated to ensure the consistent high quality of the product. Quality-related data and sensor signals are used to control process flows, to adapt individual processes and to track and optimize the influence of single process steps on the quality of the end product. Compared to manual work, automation systems have the advantage that the configuration or state at a specified time can be tracked and reproduced in order to investigate the influence of the system or to detect failures. A compatible software system also facilitates wafer and cell traceability to improve quality checks along the whole production line. It is much more difficult to assign quality defects or failures to manual handling steps, and wafer and cell traceability can only be partly achieved. A broad overview of the capabilities of factory IT systems will be given later.

Suitable instruments of automation

In PV manufacturing, automation is highly dependent on the process step, and therefore on the product being manufactured. Throughout the entire process chain, the various products and consumables have to be forecasted, scheduled, transported and supplied with the required quality at the right time. A closer look at the value chain reveals that the object to be transported changes significantly – from polysilicon to the finished solar panel – and thus the automation requirements also change. In particular, transport and handling during wafer and cell processing is a challenging issue in PV industry automation projects. A thin, fragile substrate – 156mm × 156mm in size and between 160 and 220µm in thickness – has to be handled between the various process steps. Special needs result in dedicated solutions, mainly for pre-separation, feeding, positioning, pick-and-place and assembly.

The challenge in these transport operations is not only the delicacy of the object to be handled but also the high throughput of up to 3600 wafers or cells per hour. For a standard handling operation, this means that the automation system has a time frame of only one second for each wafer. There are different ways of managing this situation using automation systems. One solution is a really fast handling system that is capable of functioning at such speeds with the required sensitivity; another solution is a slower method whereby several automation systems act in parallel. Both methods use grippers to handle the substrate. With today’s manufacturing lines, the standard gripper is invariably integrated by the supplier. Studies at Fraunhofer IPA have shown that, dependent on the different process steps, a dedicated choice of gripper and gripping principle is beneficial to production quality. Because the surface structure of the substrates changes during processing, handling parameters need to be adapted accordingly.

An inflexible automated production line for photovoltaic cells is only useful in high-volume processing if the required quality of the workpiece can be assured. The term ‘quality’ in automated PV production, therefore, has different meanings. In consequence, it is not only process output quality due to certain factor combinations in subordinated processes that needs to be taken into consideration: quality inspection and checks to ensure the reliable operation of automated sequences, such as handling by pick-and-place, are also relevant.

For the PV industry, automated handling is one of the most interesting areas of automation. Since the necessary feasibility analysis for a handling automation solution is a challenging task for solar cell producers, the Fraunhofer IPA offers/carries out dedicated handling tests and automation developments for the PV industry. A professional feasibility study of handling tasks for delicate wafers helps to identify the quality and function of the automation solution as well as minimum cycle times and total costs of ownership. Decreasing wafer thicknesses to reduce silicon consumption and new solar cell technologies require the adaptation and testing of appropriate handling equipment and components. By using the design of experiments (DOE) method to make a comprehensive handling evaluation, the achievable position accuracy of a handling component, such as a Bernoulli gripper, can be determined.

One complete pick-and-place cycle is a combination of a number of single steps to be performed, as shown in Fig. 5 [4]. In total, a pick-and-place cycle is made up of a

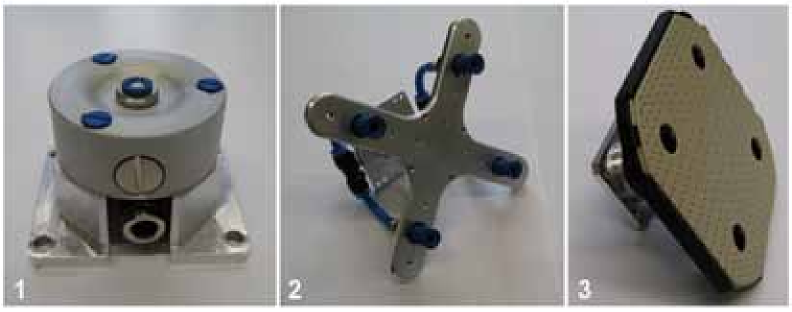

Figure 3. Different grippers for PV handling: 1) Bernoulli gripper, 2) vacuum cups, and 3) area gripper.

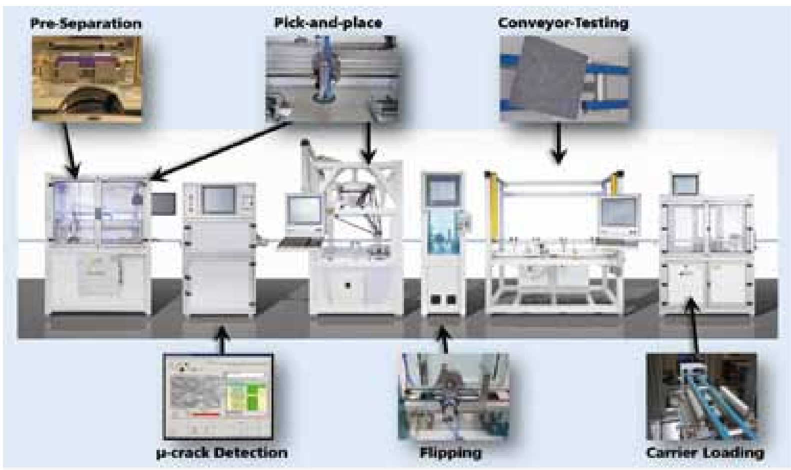

Figure 4. PV test and demonstration centre at Fraunhofer IPA.

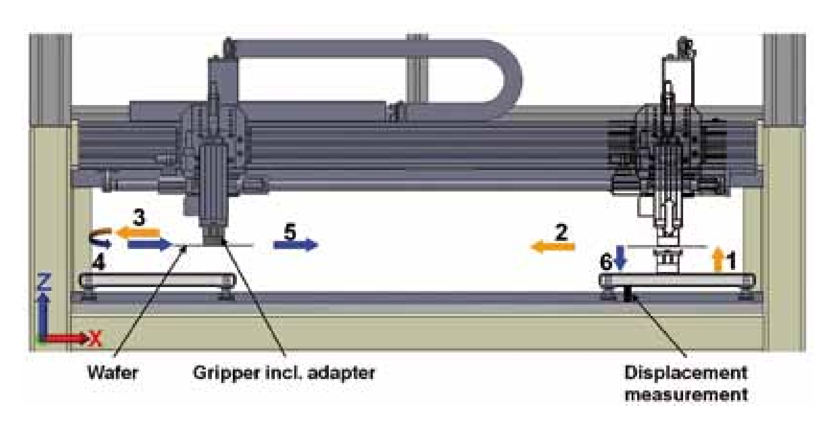

Figure 5. Pick-and-place cycle.

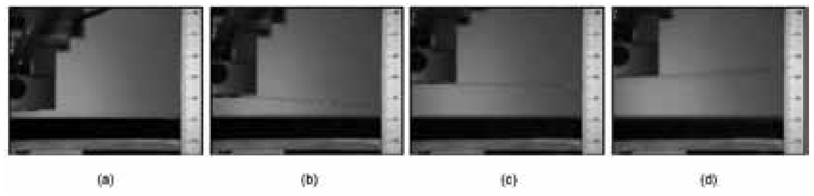

Figure 6. High-speed images (at the points indicated on the graph in Fig. 7) of a wafer being picked up.

sequence of seven movements. To achieve comparable results, test conditions such as lifting height and lateral distance are kept constant for each test batch.

1. The first step is to pick the substrate by utilizing either a positive pressure or a vacuum, depending on the gripping principle.

2. As soon as the substrate is held by the gripper, it is lifted up by a dedicated vertical axis.

3. The lateral movement along one axis simulates the movement from A to B in a production line (i.e. out of the box and along the conveyor belt).

4. To simulate changes in direction and therefore the horizontal forces applied to a substrate due to negative and positive acceleration, a U-turn is performed.

5. The movement performed in step 5 is the same (with the same parameters) as in step 3, but in the opposite direction.

6. The last movement is placement of the substrate in the target position.

7. To complete the cycle, the adhesive forces between the gripper and substrate have to be eliminated, i.e. by turning off the vacuum (depending on the system utilized).

A particular group of data gathered by these experiments relates to the vibrations impacting on the wafer. The high-speed images (Fig. 6) already indicate what the sensor records (Fig. 7) [4].

> "Optimization and cost reduction along the whole value chain are key factors in remaining competitive."

Factory IT

Optimization and cost reduction along the whole value chain are key factors in remaining competitive. While, in the past, companies focused on production processes, new materials and material handling, there is today an increasing awareness of the potential for improving manufacturing systems. Suitable IT systems, having proved their aptitude and gained wide acceptance in many industrial sectors with mass manufacturing systems, are now implemented at all hierarchical levels of a factory organization. On the management (strategic) level, established software – such as Enterprise Resource Planning (ERP), Supply Chain Management (SCM) and Product Lifecycle Management (PLM) – support the long-term planning and supervision of company activities. Below this level, systems can be found that support the operation, monitoring and control of the actual production. They are typically connected

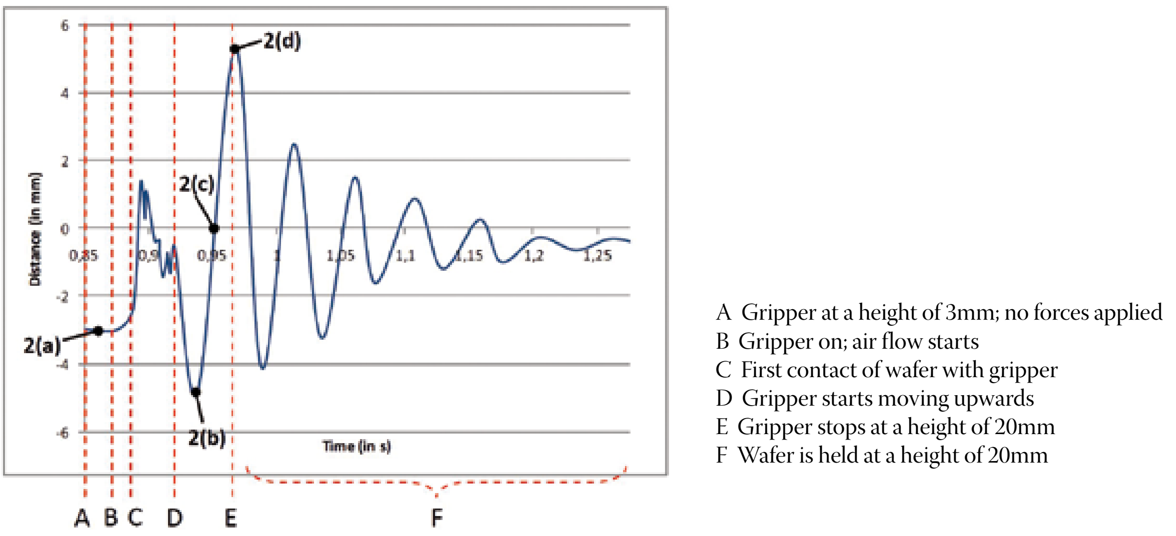

Figure 7. Graphical illustration of substrate vibration during pick-up.

to the lowest (process) level and serve as an intelligent link between the other hierarchical levels (vertical integration within one single production facility). Although not yet widely used in the PV industry, these tools are considered to offer great potential for optimizing production control and are known as manufacturing execution systems (MES). Depending on the software supplier, not all of the features explained below form part of a single system; in some cases, several applications are used to fulfil these MES tasks. The list is not intended to be complete, but aims to highlight the most valuable features for optimizing the degree of automation.

Data capture and analysis

A key benefit of an integrated MES is the automated capture, correlation and aggregation of data. Production data is linked to equipment data, allowing in-depth analysis of certain scenarios, as well as the calculation of the high-level key performance indicators (KPIs) of interest.

Low-level equipment parameter settings (recipes) can be correlated with process results and quality data. These data sets can be used for statistical process control (SPC) software which feeds analysis results back to the MES to enable active process control. Advanced process control (APC) tools extend this approach by considering data from multiple, interconnected pieces of equipment when adjusting recipes. The focus of these automated systems is to keep processes at a stable level to achieve higher yields and improved cell efficiency. Manual intervention is only required when certain critical conditions occur. Despite these advantages, the underlying – partly very complex – rules for process control need to be defined and maintained manually. Moreover, operators may lose some authority for manually adjusting equipment parameters.

An MES allows end users to define KPIs that can be calculated in real time in order to support operative or tactical management decisions. Automated notifications and alerts can be specified to minimize equipment idling or standby times. Additionally, the data analysis can help planners to predict upcoming maintenance actions on the basis of historical data, equipment utilization, recipe parameters and quality-related data.

Material tracking and identification

For full production system control, the software and planning team need to know the location of materials at any point in time. In combination with actual equipment and material-handling states, this allows equipment utilization and throughput to be optimized. Furthermore, a historical database comprising material identification, process recipes applied and quality-related data can be set up. This may be useful in dealing with warranty issues, quality problem identification and inventory management. Nevertheless, material tracking in crystalline PV production can be quite challenging because of the high takt (cycle) times and the changes being made to the material surface during the process flow. Physical systems, such as laser-based cell marking developed by Q-Cells SE, are available, as well as MES-integrated virtual (software-based) material tracking.

Detailed production planning and execution

On the basis of the production demand from a management-level IT system, the MES is able to calculate and execute detailed production orders regarding material, resources (e.g. equipment) and material flow. A schedule is generated utilizing actual shop-floor data, for example on equipment's and other resources' states. Automated execution will result in the distribution of recipes to equipment, wafer starts and material-handling jobs. Some MESs facilitate the local dispatch of material to equipment and may also allow ambitious targets defined by the management to be achieved.

Major drawbacks of IT-based automation

To tap the benefits of a partly software-controlled manufacturing system, a number of conditions and requirements need to be carefully evaluated and fulfilled. Costly software and hardware have to be purchased and maintained. Rules for handling exceptions (software failures, updates, manual interventions, etc.) need to be well defined, and an option to run the production 'offline' must also be considered. Equipment and material-handling systems from different suppliers have to be integrated into the production IT. Despite the increasing acceptance of SEMI PV2 as a unified equipment communication interface standard and the availability of commercial PV2-compliant connectors, a significant amount of heterogeneous software interfaces can still be found on the market. Sometimes no interface exists at all; in this case, customized graphical user interfaces are required at operator terminals, with manual data acquisition.

No neutral, comprehensive analysis of measurable benefits emerging from the use of production IT in automating PV manufacturing appears to be available on the market. Nevertheless, experience from similar industries with related manufacturing systems indicates positive outcomes from the use of such software. The increasing number of software suppliers offering solutions tailored to the needs of the PV industry confirms this. Ultimately, the selection of an appropriate software solution to fulfil manufacturing requirements, combined with an adjusted integration and operation concept, leads to a more efficient factory operation.

Digital image processing

Digital image processing has become indispensable for PV manufacturers and helps to identify weak points in the production line with regard to required cycle times. Inspecting the contours and shapes of wafers, checking for microscopic cracks in the brittle silicon material, and scanning the printed contacts are just a few of the image-processing methods that can be applied to ensure the automated production of high-quality PV goods. To guarantee the quality of a wafer at a certain point in the production process, the substrate needs to be positioned in the correct orientation for processing, such as for screen printing or edge isolation.

By using direct IR lighting, advanced image processing with an absolute precision of less than 12µm is capable of detecting the exact position of handled wafers. The wafers are placed directly in the field of lens coverage and their positions measured immediately in order to correct travel for the next positioning sequence. Through consideration of two regions of interest in assessing an object's position, the object to be handled can thus be aligned more precisely (e.g. by an accurate alignment tool) to compensate for deviations in position during the handling process. The position aspect has become of more interest ever since cell technology development came up with the idea of back-contacted cells, because that particular process requires higher positioning accuracy.

> "The focus of interest – to drive down the costs per unit – will therefore shift from cell efficiency to yield and throughput."

Outlook

The shake-out has already begun. For a manufacturer to remain competitive, it is essential to make mass production more efficient and thus drive down manufacturing costs. A suitable automation solution that takes handling as well as sensors and related IT structures into consideration is vital in order to meet the demands of future mass production. Each fabrication process has individual boundary conditions and requires a tailored automation solution to meet the conflicting demands of time, cost and quality.

Time will show whether the main driver for investments in PV cell and module factories will continue to be the improvement of cell efficiency or become instead the improvement of manufacturing efficiency. The focus of interest – to drive down the costs per unit – will thus shift from cell efficiency to yield and throughput. Investments made today in R&D in the field of production and automation will therefore pay off immediately. Lessons learned by other industries can be adapted to the needs of PV and consequently guarantee further success in the future.

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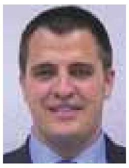
Fabian Böttinger holds a diploma in computer engineering and a master's in logistics business engineering. He joined Fraunhofer IPA in 2005 and is currently a project manager for factory planning and optimization in photovoltaics and related industries. Fabian's main expertise is the analysis, modelling and simulation of logistics and automation processes. He also works in the field of factory IT and equipment integration.



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Tim Giesen graduated in industrial engineering from the University of Applied Sciences Kaiserslautern. After graduation he joined the Fraunhofer IPA, where he works as an international project manager for photovoltaic-related automation. Tim focuses on production engineering, material flow automation and product prototyping in both public-funded and private research projects.

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