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Lightweight Robotic Material Handling in Photovoltaic Module Manufacturing-Silicon Wafer and Thin Film Technologies

N. Asadi, M. Jackson

***Abstract*—**Today, the central role of industrial robots in automation in general and in material handling in particular is crystal clear. Based on the current status of Photovoltaics and by focusing on lightweight material handling, PV industry has turned into a potential candidate for introducing a fresh "pick and place" robot technology. Thus, to examine the industry needs in this regard, firstly the best suited applications for such robotic automation,and then the essential prerequisites in PV industry should be identified. The objective of this paper is to present holistic views on the industry trends, general automation status and existing challenges facing lightweight robotic material handling in PV Silicon Wafer and Thin Film technologies. The results of this study show that currently no uniform pick and place solution prevails among PV Silicon Wafer manufacturers and the industry calls for a new robot solution to satisfy its needs in new directions.

***Keywords*—**Automation, Material handling, Photovoltaic, Robot.

I. Introduction

WITH the world population constantly growing, the shortage of fossil fuels has forced experts in the field to explore ways of providing new and clean energies. Clearly, solar energy [1] has proved its advantages over all other forms of renewable energies found to date to answer the world's ever-increasing energy needs. Despite the fact that solar energy industry has experienced a significant growth in the past 20 years [2], there still exist some limitations on the way to its further development; high production prices and its inaccessibility in some parts of the world are among the most important obstacles to that end.

In recent years, photovoltaic industry has been experiencing an enormous growth at the global level. The increasing costs of conventional fuels as well as the growing demand for Renewable Energy Sources (RES) are known to be the main drivers behind this rapidly expanding industry [2]. World's PV industry had an average growth rate of 49.5% from 2002 to 2007 [3]. In 2008, global solar PV production recorded a robust growth rate of 84% from 4GW in 2007 to 7.3GW, with China as the largest solar PV producer globally [4]. The total globally installed solar PV power generation capacity grew by 47% from 15,599MW in 2008 to 22,929MW in 2009, primarily driven by large scale solar PV installations in Europe which recorded a 54% growth in capacity installations of solar PV in 2009 compared to 2008 [4].

The industry's production capacity is expected to grow with a CAGR (Compound Annual Growth Rate) of around 20-30% for the period 2010-2014, depending on the segment within the value chain [5]. Despite PV's rapid growth, the industry is stillincapable of competing with conventional electricity price due to high manufacturing costs.

Employment of automation solutions in photovoltaic industry has proved its efficiency and capabilities in contributing to an increase in the production of PV manufacturing plants while reducing the costs and prices significantly. However, while technologies used in photovoltaic industry develop very fast, the search for finding the most suitable automation solutions aimed at pushing costs further down, continues. Automation in a manufacturing plant is not just limited to the manufacturing processes but it also covers the material handling systems. Nevertheless, an automated material handling system facilitates manufacturing and grant privileges to the whole system.

Obviously, material handling is not viewed as a part of the production system and it doesn't add any value to the product [6, 7&8].Nevertheless, it is considered to be a significant part of production facilities expenses, since handling activities generally account for 30%-40% of production costs [9]. Material handling is one the pivotal applications of industrial robots which involves the movement of materials or parts from one location and orientation to another [10, 11]. Amongst all automation equipment used in material handling systems, due to their performance, industrial robots have proved to be the prominent solutions.

In fact, the ultimate goal of this paper is to identify and take into account the general requirements and existing challenges facing robotic solutions for lightweight material handling in PV Silicon Wafer and Thin Film module manufacturing. By studying a number of key Silicon Wafer and Thin Film PV module manufacturing plants and their respective robot providers, it was possible to primarily understand where within these two PV technologies lightweight material handling is required and how utilizing industrial robots has met the needs of industry so far. In addition, major trends and the status of robots currently used for light weight material handling in PV industry arealso identified. The two leading PV technologies in solar cells discussed here are wafer-based Crystalline (Mono-Crystalline or Multi-Crystalline) and Thin Film (Amorphous Silicon, Cadmium Tellurideand CopperIndium Gallium Diselenide).

Narges Asadi is with Mälardalen University, Sweden e-mail:Narges.asadi@mdh.se

II. Trends in PV technologies

Crystalline Silicon (cSi) is the most common material used in PV cells and is the dominant technology by owning 93% [2] of the total PV market. Although Thin Film technology is a cheaper technology compared to Silicon Wafer technology, the conversion efficiency of different Thin Film solar cells (Amorphous Silicon, Cadmium Telluride and Copper Indium Gallium Diselenide) ranging 6-12% [12], is generally lower than cSi Wafer (Mono-Crystalline or Multi-Crystalline) modules;13-20% [12].

When choosing between one of these manufacturing technologies (cSi Wafer and Thin Film), in addition to manufacturer's preference, the market trends and demands obviously play significant roles.

TABLE I
Advantages and disadvantages of Silicon Wafer and Thin Film technologies

PV Technology	Advantage	Disadvantage
cSi-Wafer	Abundant Silicon sources.	Cost driven-Large amount of first material (Silicon) is needed. Energy driven-Manufacturing process are highly energy consuming. Separate and different production steps. Handling of individual cells and wafers during production processes-cells are connected together in strings. Possible global shortage of solar grade Si.
Thin Film	Low amount of raw material required. Interconnected cell structure in modules - no handling of individual cells during production processes. Integrated manufacturing processes. Flexible and wide range of substrates.	Handling of individual large modules during production processes. Lower efficiency compared to Silicon solar panels.
Thin Film-CIGS	High conversion efficiency -superior to (a-Si) and (CdTe). Free from adverse environmental impact.	Scarce supply of Indium.
Thin Film-CdTe	Abundant supply of cadmium.	Cadmium toxicity- Cd has the tendency to accumulate in the food chain. Scarce supply of tellurium.
Thin Film-aSi	Relatively simple and inexpensive technology.	Degradation after light absorption-the electrical structure of hydrogenated amorphous Silicon is meta-stable, the material degenerates when exposed to sunlight (Staebler–Wronski effect).

The popularity of the technology however, depends on its efficiency andcharacteristics as well as thematerial used in the manufacturing process. Some of the reasons for and against each of the mentioned technologies are summarized (Table I).In the search for a suitable material handling robotic solution, a closer look into physical attributes and trends of the work pieces (wafer, cell and modules) is highly important. The diversity of the technologies and attributes of the products manufactured in the market often makes it difficult to summarize the physical specifications. Nevertheless, to give an overall picture, some physical specifications of different product phases within cSi Wafer and Thin Film technologies are reviewed (Table II).In addition to the mentioned specifications, the standard Silicon cell size is expected to increase (up to 210x210 mm) while cell thickness will be decreasing to about 100 μm in near future.

TABLE II
Typical specifications of PV cells and modules in wafer based Silicon and Thin Film technologies

PV work-piece		Typical Specifications	
Wafer based Silicon	Ingot	Weight (kg)	450 to 650
	Cell	Dimension (mm)	125x125, 156x156
		Weight (g)	~5 (6-10 grams per watt)
		Geometry	Square, Pseudo Square, Rectangular
		Thickness (μm)	~150 to 300
	Module	Number of cells	36, 72 or depending on the size of module
		Cell string length (mm)	~<2400
		Cell distance in string (mm)	~2 to 40
		Final Module size	cSi Modules come in different sizes, thickness may also depend on the size of junction box.
		Module weight (kg)	Typically 8 to 30 (Large modules: up to ~40)
Thin Film	Module	Number of cells	-
		Thickness (mm)	3-8
		Final Module size	TF Modules come in different sizes, thickness may also depend on the size of junction box.
		Module weight (kg)	8 to 30
Cover		Front & rear cover	Low iron tempered glass
		Thickness (mm)	3±0.2, 4±0.2
		Weight per mm (kg/m^2)	2.5
		Surface patterns	Prismatic / Matt, Matt / Matt
		Dimensions (mm)	100 250 to 2500 x 1500

III. Automation in PV manufacturing

Encyclopedia Britannica Online defines automation as “the application of machines to tasks once performed by human beings or, increasingly, to tasks that otherwise would be impossible” [13]. This simply indicates the automation concept; however there are numerous other definitions for the term. [14] described that the original use of the term implies an automatic control which can be open loop as well as closed loop, and can refer to electronic as well as mechanical action. In this definition, automation refers to the full or partial replacement of a function previously carried out by human operator (as discussed in [14]). Automation or -machine execution- of such functions also includes the tasks that human doesn’t not wish to perform, or cannot perform as accurately or reliably as machines [14].

Due to the characteristics of the raw materials and the nature of the manufacturing processes, the fast changing photovoltaic industry can enjoy a highly automated manufacturing line. These specific characteristics and above all the required high precision in most production phases, to some extent limit the intervention of manual labor both in Thin Film and cSi Wafer technologies. Moreover, competition among manufacturers and the market demands seemingly have forced the industry to move toward the mass production aiming cost reduction.

Today, almost all processes in different PV manufacturing technologies; cSi wafer (Mono-Crystalline and Multi-Crystalline Silicon) and Thin Film (CdTe, CIGS and a-Si) can use automation tools and equipment. However, still some of those automated processes (such as loading/unloading, junction box assembly etc.) can also be carried out manually.

The already existing integrated automation possibilities, turnkey solutions and production equipment not only have met some of industry’s basic requirements in different manufacturing processes but also have brought along some other benefits (such as speed, higher quality, reliability and flexibility). Manufacturers can choose to either automate their entire module line or to start with the most labor intensive or highest scrap producing processes first. Nevertheless, the design of plant layout and the use of these resolutions highly depend on the manufacturers’ facilities and choice.

IV. Material Handling in PV

Material handling systems in PV highly depend on the type of technology and the automation solutions. In cSi Wafer technology, cells should be handled gently in a clean room environment with least possible vibration in order to keep their fragile structure and efficiency. Likewise, in Thin Film (TF) technology, modules are preferred to be processed in rather a still position with least possible number of transfers between production steps. In addition, PV manufacturing automation must provide continuous and high speed transport and processing, while maintaining low breakage rates. Generally in cSi Wafer technology, the product is transferred on the industry specific conveyor belts in order to minimize cell damage. Also, cassettes and magazines are used for buffer storage in between the processes. It is worth mentioning that the loading and unloading of materials and products can be carried out both manually and automatically. In automatic material handling, the manufacturing machines are equipped with especially developed conveyors and automatic loading and unloading systems. Furthermore, robots can be employed for different handling, loading and unloading tasks depending on the level of automation and the type of automation facilities (equipment and conveyor system in use).

V. Industrial robots in PV industry

Utilization of robots in the mentioned PV sectors is not limited to loading/unloading or material handling; they can also be used as the main equipment in manufacturing processes (e.g. applying laser, soldering, quality inspection, etc.). Moreover, flexibility to integrate with an already automated line, high throughput and special environmental considerations (clean room options) are among some of general expectations from robotic solutions in PV industry today.Different types of industrial robots including Cartesian, Scara, Delta and Articulated arm robots are currently employed in different manufacturing processes.A look into common PV module manufacturing processes show that a number of different routine tasks can be performed by various robot type.

A. Cartesian Robots

Can be employed in numerous steps of PV production that need in place process and handling such as;

- General Pick and place in cSi Wafer technology.
- Eva foil loading (in encapsulation process) in TF and cSi Wafer technology.
- String lay up (includes flipping cell string 180 degrees for encapsulation process that is possible by applying different automation solutions) in cSi Wafer technology.
- Loading/unloading of production process equipment, stack boxes/ carriers in cSi Wafer technology.

B. Scara Robots

Typically can provide fast and precise processes when applied in pick and place of lightweight items (up to 10 kg). In PV manufacturing processes, Scara robots can be employed in;

- Wafer separation in cSi Wafer technology.
- Sorting cells (for cleaning, classification & inspection of cells) in cSi Wafer technology.
- Cell pick and place (Cell stringing process) in cSi Wafer technology.
- Loading/unloading of production process equipment, stack boxes/ carriers in cSi Wafer technology.

C. Delta Robots

Due to their overhead mounting structure Delta robots can work on the work piece from an overhead position. Like Scara robots, they are mainly employed in PV industry for fast handling of light payloads in pick and place tasks;

- Wafer separation in cSi Wafer technology.
- Sorting cells (for cleaning, classification & inspection of cells) in cSi Wafer technology
- Cell pick and place (Cell stringing process) in cSi Wafer technology.
- Loading/unloading of production process equipment, stack boxes/ carriers in cSi Wafer technology.

D. Articulated arm robot

The articulated robots can be employed in the processes that mainly require higher payload capabilities in comparison to Delta and Scara robots. In addition, due to their structure, these robots are for the tasks in which rotation in different angles and larger workspace is required;

- Module Packaging in TF and cSi Wafer technology.
- Glass loading (glass washing and encapsulation process) in TF and cSi Wafer technology.
- String lay up (includes flipping cell string 180 degrees for encapsulation process that is possible by applying different automation solutions) in cSi Wafer technology.
- Eva foil loading (in encapsulation process) in TF and cSi Wafer technology.
- Module testing/Inspection in TF and cSi Wafer technology.
- Module taping/Edge trimming in TF and cSi Wafer technology.
- Module framing in TF and cSi Wafer technology.
- Junction box assembly in TF and cSi Wafer technology.
- Packaging in TF and cSi Wafer technology.

In Thin Film material handling where the large modules need to be handled, Delta and Scara robots are not utilized, however these two types of robots are widely utilized in cSi wafer material handling where thin and light wafers or cells need to be handled. Additionally, equipping both Scara and Delta robots with vision system enables them to be involved in inspection and quality control tasks when handling work-piece simultaneously.

VI. Lightweight Robotic Material Handling

Analysis of light weight material handling solutions among the selected PV robot manufacturers shows that low cost, high speed (handling up to 5000 wafers per hour in some applications), high throughput (~0.98), low breakage rate (down to 0.1%), small footprint and easy integration with the rest of automation system are the most important factors in choosing pick and place solutions in PV industry.Although custom-built solutions appeared to fulfill the above requirements, seemingly there is a concurrence among the robot manufactures that the industry is still in need of a new solution possessing all these factors and even offering more.

In addition, some common trends have been identified within the studied entities:

-There is an increasing tendency towards building or purchasing task specific manipulators to achieve higher flexibility.

-The number of repetitive quality control steps, within the PV module production processes is on the rise which demands robots handling and intervention. For this purpose vision and image processing is a necessity in most applications.

-Since automotive industry robotics is the origin of robotic solutions in PV industry, huge robots are still the prominent players for handling some applications especially in Thin Film module manufacturing (handling and transferring large substrate measuring up to 2500x1500 mm).

- No uniform pick and place solution prevails in chosen PV sectors. This probably has led to the development and use of various pick and place solutions (different Scara, Delta, 6 axis robots and custom-built solutions). Scara, Delta and custom-built solutions are widely used in handling cSi wafers and cells, while 6 axis articulated arm robots are mostly used to handle large cSi and TF modules.

The two most common robotic concepts for lightweight material handling in PV Silicon wafer appear to be Delta and Scara concepts, however each of these solutions has not yet fully met PV industry's needs. Delta robots don't seem to be the main light weight pick and place robotic solution in the industry due to:

-Problems with vibration and acceleration that lead to damage in cell structure and increase cell/wafer breakage rate, especially in high speed applications. For this reason, it seems that Delta robots cannot be properly utilized in some high speed PV applications.

-Delta robots are considered to be expensive, considering the possibility that two Scara robots can replace a Delta robot offering high speed at the same price.

-The large foot print and limited mounting options still remain an issue in some applications.

on the other hand,Scara robots have been standardized for some applications as they are assumed to be fast enough to handle certain tasks. However the dead zone under robot may still be a problem while performing certain tasks.

Although both Scara and Delta robots are capable of meeting required positioning accuracy in cSi Wafer technology, it should be mentioned that not all applications need the same level of positioning accuracy (e.g. higher positioning accuracy is needed in cell stringing rather than unloading on the belt). The highest required positioning accuracy in the observed processes could be around ±0.1 mm.Moreover, regarding the environmental considerations for Delta and Scara robots, for pick and place applications in PV cSi Wafer manufacturing, no strict clean-room standard is required and normally clean room standard ISO 8 suffices. However, some PV manufacturers may prefer to use higher clean room standards.

VII. Conclusion

This paper summarized the present status of robots used for material handling (focused on lightweight work-pieces) in PV Silicon Wafer and Thin Film technologies.

Reviewing PV overall market status and the industrial trends in both technologies clarified the direction of the industry and future products. In addition to the current status of robots within cSi Wafer and Thin Film technologies, key requirements of such solutions have also been identified.

Based on the observations in the study, PV cSi Wafer manufacturing is experiencing some challenges with the existing Delta and Scara robotic solutions for lightweight material handling, whereas similar robotic concepts cannot be used in Thin Film technology since the work-pieces are rather big and heavy modules. While high speed pick and place is one of the main tools for gaining a competitive edge in cSi Wafer manufacturing and further cost reduction, today's Delta robots do not seem to be the proper equipment for such a performance. At a high speed pick and place, the vibrations from the top mounted structure of Delta robots can lead to damage in PV cells' structure.

The results of this study show that there is a clear need for further development of the existing robots in PV material handling today; a fresh robotic solution that offers all the required technical factors in one package. From a business standpoint, this work can be beneficial in development of future pick and place robots which PV cSi Wafer industry calls for.

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