NREL/SR-520-24823

Photovoltaic Industry Manufacturing Technology Assessment

Final Report

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A national laboratory of
the U.S. Department of Energy
Managed by Midwest Research Institute
for the U.S. Department of Energy
under Contract No. DE-AC36-83CH10093

Prepared under Subcontract No. AAX-7-17655-01
August 1998

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Executive Summary

This report contains the results of the Photovoltaic (PV) Industry Manufacturing Technology Assessment performed by the Automation & Robotics Research Institute (ARRI) of the University of Texas at Arlington for the National Renewable Energy Laboratory. ARRI surveyed eleven companies to determine their state-of-manufacturing in the areas of; Engineering Design, Operations Management, Manufacturing Technology, Equipment Maintenance, Quality Management and Plant Conditions. Interviews with company personnel and plant tours at each of the facilities were conducted and the information compiled.

The report is divided into two main segments. The first part of the report presents how the industry as a whole conforms to "World Class" manufacturing practices. Conclusions are drawn from the results of a survey as to the areas that the PV industry can improve on to become more competitive in the industry and "World Class." Appendix A contains the questions asked in the survey, a brief description of the benefits to performing this task and the aggregate response to the questions. Each company participating in the assessment process received the results of their own facility to compare against the industry as a whole. The second part of the report outlines opportunities that exist on the shop floor for improving Process Equipment and Automation Strategies. Appendix B contains the survey that was used to assess each of the manufacturing processes.

1.0 Introduction

The Automation & Robotics Research Institute (ARRI) of the University of Texas at Arlington (UTA) has completed the manufacturing technology assessment of eleven (11) Photovoltaic (PV) companies for the National Renewable Energy Laboratory (NREL). The companies that participated in this assessment are listed below:

- Siemens Solar Industries, Camarillo, CA
- Photovoltaic International, Sunnyvale, CA
- Utility Power Group, Sacramento, CA
- Solarex of Frederick, Frederick, MA
- Solarex (thin film), Toano, VA
- AstroPower, Newark, DE
- ASE Americas, Billerica, MA
- ENTECH, Inc., Keller, TX
- Golden Photon, Golden, CO
- Iowa Thin Film Technologies, Ames, IA
- Solar Cells, Inc., Toledo, OH

The objective of this survey is to provide a background for defining a roadmap to be used by NREL and the U.S. PV industry for increasing the maturity of its manufacturing technology. The assessment process was performed by ARRI personnel through interviews with company employees and plant tours to observe the manufacturing processes on the shop floor. The results of this survey are summarized in two sections of this report; 1) a General Survey report and 2) a Manufacturing Automation Assessment report.

1.1 General Survey

The General Survey (see General Survey Results Appendix A) was developed by examining a variety of existing survey instruments. A single existing survey was not selected because the desire was to focus solely on manufacturing and related issues. Existing technology assessment tools are most often used to examine an enterprise or company from many viewpoints. The contractual focus of this effort was manufacturing, thus a customized tool was developed. The topic areas covered in this survey are;

- Engineering Design
- Operations Management
- Manufacturing Technology
- Equipment Maintenance
- Quality Management
- Plant Conditions

Other areas such as Management Practices, Human Resources, Market Management, Bidding/Quoting and Purchasing were not included in the survey, although they are just as important to the success of a company. The results of the assessment process provides a sense of how the PV industry measures up to "World Class Manufacturing" principles. Professor Richard Schonberger's in his 1986 book, suggests that the term "World Class Manufacturing" captures the breadth and the essence of the fundamental changes taking place in industrial enterprises. ARRI defines World Class Manufacturing as the ability to build products "Better, Cheaper and Faster". Table 1 below is how some companies measure world class performance.

Performance Measure	World Class
Quality Rejects per Million Parts	<500
Pure Work to Throughput Cycle Time	50%
Setup Time	<10 min
Utilized Capacity	90%
Breakdown Losses	1%
Lot Size	<24 hrs
On-schedule Production	100%
WIP Turns	+/-100
Mean Time Between Layoffs	0
Design Producibility	100%
Design Meets Cost Target	95%
Engineering Changes 1st year/product	1%
Engineering Change Process Response Time	1 day
Annual Training Days per Employee	20
Delivery Lead Time Index	20
Invention to Market Introduction Index	<50

Table 1

Are companies achieving this? The answer is YES! For example, the Kipp Group plant in Ontario, Calif., a manufacturer of injection molds and plastic molded medical products, has impressive credentials, including 103% productivity improvement, customer reject rates of 0.05 parts per million, 95% on-time delivery to customer-requested dates, and zero lost workdays over a 12-month period. But while plant management keeps one eye focused on manufacturing success, the other recognizes civic responsibilities. Approximately 20% of plant openings are filled from the ranks of underprivileged youths in conjunction with the Los Angeles-based Partnership With Industry.

How useful are the results of the General Survey? If you take the results of the survey and try to benchmark the companies to see how they stack up against each other the results would not be very useful. This is because the companies reviewed vary in product types, company size, manufacturing states and anything else you can think of. If you look at the results of the survey in a larger sense, such as what does the solar industry need to look at as a whole then the results are useful. The survey results point to several areas in which the industry as a whole can improve; Work-in-Process Controls and Planning, Statistical Process Control and the use of Design of Experiments, Management of Quality and Material Flow and Plant Organization. It is important to keep in mind that the questions asked in this survey are not based on cutting edge ideas are concepts, they are proven and well established manufacturing best practices. A company should try and achieve a 100% YES to all of the questions in the survey. A summary of the industry responses is provided in section 2.0.

Companies that participated in this survey have received company specific reports and can review their responses to the industries response as a whole.

1.2 Manufacturing Automation Assessment

A technology assessment survey was developed to evaluate the state-of-the industry in terms of manufacturing technology and outline potential solutions to the problems the PV industry is facing. The survey used to perform the assessment is located in Appendix B. As with the general survey the technologies, process and equipment needs vary widely. This simple fact points to one of the main issues facing a lot of the companies today, off-the-shelf automation solutions are not readily available. If I wanted to start an electronics circuit card assembly factory today I would have a long list of equipment suppliers to choose from. There are obvious differences between the electronics manufacturing and PV industry, mainly the market share $$, but how does the PV industry get to a position where there are many equipment choices? Although there are many differences in the products being produced by the PV industry our assessment has identified Equipment and Automation Strategy Opportunities that if addressed can improve the state-of-the industry. The opportunities identified are as follows:

- Wiresaw demounting
- Boat/Conveyor/Coinstack Transfer
- Screen Printing
- Inter-machine Glass Module Handling
- Module Lamination Trim
- Back-end Assembly
- Thin Cell/Breakage Detection
- Cassette Standardization
- Flexible Automation
- SCADA and Inter-machine Communications and Control

The PV companies need to work more closely together to solve common industry problems. There are process technologies that companies will always keep to themselves and hold as there competitive advantage and most of these technologies are already held legally through patents. I would say the rest is fair game for companies to work together to develop industry solutions. Industry collaboration is a key element in developing the manufacturing technologies that are needed to improve the manufacturing process to ultimately reduce the cost per kilowatt of solar electricity. A complete discussion of the results and summary of the Manufacturing Automation Assessment is included in section 3.0.

2.0 General Survey Results

Upon completion of the General Survey at the eleven (11) PV manufacturing companies, the results were "clustered" into reporting elements. Affirmative responses to questions on the manufacturing surveys are desirable and counted as (1). Negative responses to questions are counted as (0). For a given cluster, the total number of affirmative answers for a company is divided by the total number of questions in the cluster. These responses are then averaged to obtain the Average Industry Responses by Cluster shown in figure 1 below.

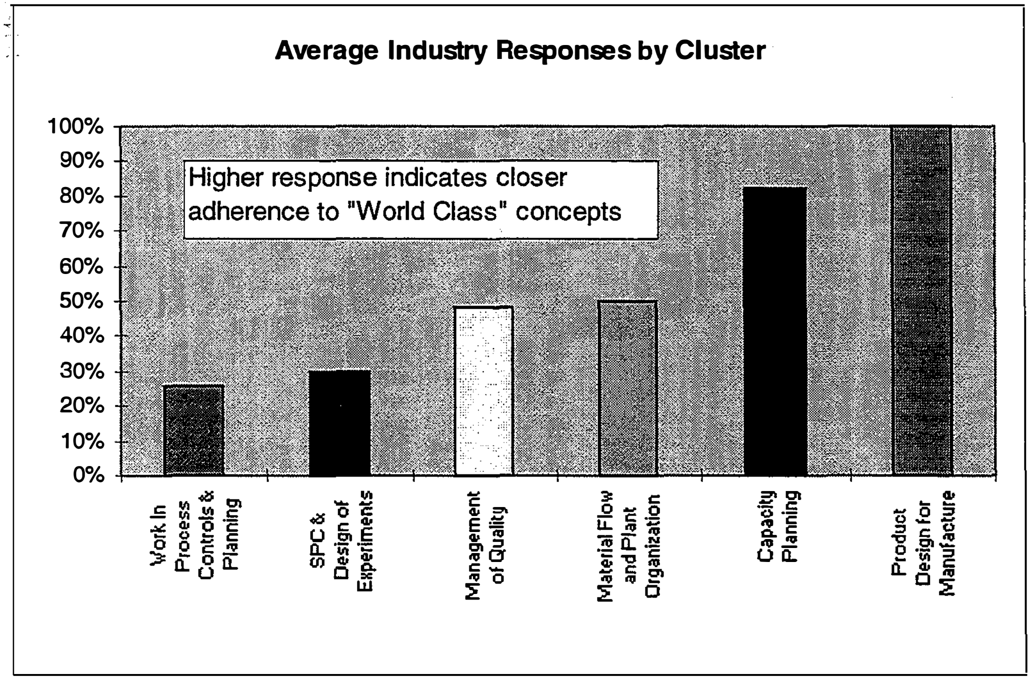

Figure 1 - Average Industry Response by Category

The clusters indicate areas that the industry is doing well in and other clusters point to areas that need to be improved in the PV industry. Improvement of a single cluster response in a plant may not have a dramatic effect on productivity or profitability. Great gains in productivity and profitability are generated by the synergistic effect of improving in all cluster response areas. However, interactions between the clusters and other areas which may or may not be identified in figure 1 should be expected. Further description of the clusters is provided in the Industry Trends section 2.1 of this report and aggregate responses to all survey questions are provided in Appendix A.

As illustrated in figure 1, the PV industry as a whole does a good job of designing products which are manufacturable. This requires efforts on the part of design and manufacturing personnel and is indicative of companies which communicate well between these departments. Areas which should be targeted for improvement include control of work in process, proper implementation of statistical controls on manufacturing processes and to some degree quality and plant layout. These results also provide some indication of the maturity of the industry in terms of manufacturing. For example, all of the companies visited have at a minimum at one time or another concentrated fully on designing their products, thus the high marks in this area. From this point on the differences in each company start to occur mainly in the amount of product they have produced. As the less mature manufacturing companies focus more on manufacturing and make the transition into full production the more manufacturing related issues should be addressed. This is not to say though that the mature manufacturing companies do not need to improve in the areas listed above.

2.1 Industry Trends

As previously mentioned, the general survey was segmented into "clusters" which can be considered to be an area of manufacturing expertise or control. Each cluster contains several questions from the general survey. In this way the impact of a single question is minimized, thus general areas for improvement can be identified. To form the clusters the average responses per question for all companies surveyed were sorted. The extremes of this sortation were examined to select apparent "clusters" which are components of general manufacturing categories. By this method not all questions applicable to a general manufacturing category are included in a given cluster. This process provided a view of industry wide areas for improvement and areas of achievement. The clusters identified were:

- Work In Process - Controls and Planning
- Statistical Process Control and Experimentation
- Management of Quality
- Material Flow and Plant Organization
- Capacity Planning
- Product Design for Manufacture

Examination of the clusters listed above and the Appendix A, of the actual survey, will show that a large number of questions are not represented in the clusters. This is not to say that excluded questions are of lesser value. The questions in the clusters represent an industry wide extreme. The PV industry as a whole responded well or responded poorly to questions in the clusters. Specific company reports have more detailed information and specific benefits to improving their company on a question by question basis.

2.2 Work In Process - Controls and Planning

Work in process (WIP) is that product which is not a raw material and not yet a product. The amount of WIP on a manufacturing floor at any time is an issue because materials in WIP;

- do not have market value and cost money
- can hide quality problems for days or weeks
- provide a buffering capability to stabilize overall production

Thus the control of WIP is an area of which can save a company considerable capital and have dramatic impact on rework and scrap issues within the organization. In an ideal, theoretical factory, all WIP except for that immediately being processed would be eliminated. Clearly this is not an achievable goal for most manufacturing organizations. WIP stores are necessary between some processes. The question to be answered is how much WIP and where should it be located. Survey responses to WIP related questions are shown in figure 2.

In order to effectively design and control WIP, the manufacturing process must be examined as a grouping of interconnected processes. Characteristics of each process must be identified (i.e. processing rate, up-time, processing lot quantities, etc.). A variety of tools can be used to supplement this decision process. A simple rule of thumb is that a process bottleneck should always have WIP stores available at its input. More complex interactions of manufacturing can be examined using discrete event simulation. With the aid of qualified analysts and appropriate data, these tools can be used to set minimum and maximum buffer sizes through-out the entire manufacturing process.

	Work In Process Controls & Planning	Percentage Implemented or Utilized
2.1.1.	Is this data electronically collected on a by job basis?	9%
2.3.1.	Is this data electronically collected on a by job & by process basis?	9%
2.3.1.1.	Are pre-determined levels of WIP established?	9%
2.3.1.2.	Does a system monitor WIP levels?	36%
2.3.2.	Can anyone at any point in the factory readily determine the current order status at any process?	27%
2.3.4.	Are process bottlenecks identified as they arise?	36%
2.11.1.	Is WIP only stored in planned locations?	27%
2.11.2.	Do WIP levels appear appropriate?	36%
2.11.3.	Are aisles free of WIP?	45%
	Cluster Average	**26%**

Figure 2 - Work In Process Cluster

2.3 Statistical Process Control and Experimentation

As indicated by the Statistical Process Control and Experimentation cluster of questions in figure 3, limited effective use of these techniques are found in the PV industry. Developed by Dr. Walter Shewhart in the 1920's, Shewhart charts or statistical process control (SPC) charts provide operators with a means of controlling a processes output by appropriately adjusting process controls. SPC has been widely applied and accepted through-out all types of manufacturing industries. The underlying principles are:

- Everything varies
- Individual observations are unpredictable
- Groups of observations tend to follow patterns or provide evidence that no pattern exists

The difficulty encountered by an operator when examining the output of a process is found in the first two bullets. If everything varies and an individual observation or measurement is unpredictable, how can one tell if the process is operating appropriately. A single observation only provides information about that point. Examining observations by groups allow one to statistically test for trends in the data.

The best possible long term output of a process is the noise level or random variation within the process itself. SPC gives operators a technique which is capable of determining when measurements are outside of what has been shown to be the inherit noise in the process.

Application of control charts to manufacturing processes is a simple and effective means of gaining better control over processes and thus gaining control over product quality. It is extremely important to note that SPC is an operator's technique. Control charts are not window dressing, they must be actively used in order to be of any use. Sampling rates must be sufficient to detect shifts in the process. Examination of a process output on a daily basis is of little use if the process is by some mean adjusted (by intent or not) on an hourly basis. However, the long term goal of an SPC measurement tool is to become obsolete or nearly so. The desire is to inspect as little as possible while remaining in control of the process. SPC techniques when properly applied will provide just that.

	Statistical Process Control and Experimentation	Percentage Implemented or Utilized
2.3.1.3.	Does a system monitor yield by process?	27%
3.4.	Is equipment idle-time periodically analyzed to improve production process?	27%
3.4.1.	Is SPC used to establish control over equipment downtime?	0%
5.9.	Is a formal education/training on quality concepts provided to all employees?	45%
5.15.	Is design of experiments used to develop manufacturing processes?	64%
5.10.	Are Statistical quality control techniques understood and used?	18%
	Cluster Average	**30%**

Figure 3 SPC and Experimentation

2.4 Management of Quality

The Management of Quality cluster provides a view into the underlying philosophies of PV companies with respect to product quality. Fostering an atmosphere of worker built quality is considered to be the "world class" approach to manufacturing.

Building quality into the process is more than the latest manufacturing craze. Documented quality programs, preventative maintenance and involving employees have definite impacts on cost and profitability. The PV industry is heading in appropriate directions with regards to overall manufacturing quality issues. Programs which seem to need more attention are preventative maintenance and effective use of existing quality tools to support the developed quality manuals.

	Management of Quality	Percentage Implemented or Utilized
4.1.	Are documented preventive maintenance programs for shop equipment in place?	36%
5.1.	Is a quality manual compiled?	64%
5.2.	Is a quality manual kept up to date?	55%
5.3.	Is a quality manual given or available to all employees?	45%
5.6.	Does the quality system rely on problem prevention as opposed to problem correction?	27%
5.7.	Do quality objectives support the quality policy?	45%
5.14.	Are rework and/or scrap reasons investigated and resolved?	64%
	Cluster Average	**48%**

Figure 4 Management of Quality

2.5 Material Flow and Plant Organization

This cluster addresses basic plant layout and operational issues centered around the collective term of plant layout. In a well planned facility, product flows are near straight line from input as raw materials to output of final products. The benefit of a streamlined flow is faster through-put and easier management of operations. Of greater importance than a perfectly straight flow line is the relative locations of departments. Simple logic dictates that departments, processes, or areas which interact on a regular basis should be close to one another. Equally clear is that material flow aisles should be sufficient, and always clear for the progression of WIP and general traffic through the factory.

In a high growth industry such as PV, facility layouts are often less than optimal. New equipment or increase numbers of work stations to keep pace with increased production requirements are often "fitted" into an existing layout. If left unchecked, high growth industry plants become mazes of ineffective aisles and resemble a garage (or basement) more than a manufacturing plant.

	Material Flow and Plant Organization	Percentage Implemented or Utilized
2.10.2.	Is inventory stored in designated areas only?	55%
2.11.	Are WIP material locations planned ?	55%
6.6.1.	Are aisles free of inventory?	55%
6.2.	Is facility allocation planned and adequate?	55%
6.3.	Is the plant free of crowded working conditions?	36%
6.4.	Is the plant free of poor material flow patterns?	27%
6.5.	Are aisles marked?	36%
6.6.	Are aisles clear?	45%
6.6.2	Are aisles free of WIP?	55%
6.7.	Are aisles appropriate for operations?	64%
6.7.1.	Are aisles straight?	55%
6.8.1.	Is the manufacturing flow free of long material movement	64%
6.8.3.	Is material movement minimized?	45%
6.8.4.	Are material movements efficient (load, method...)	55%
	Cluster Average	**50%**

Figure 5 - Material Flow and Plant Organization

Clear simple flow patterns are important. Few tools other than an engineers expertise are available to assist in the layout process. Facility layout is a process which must account for long term changes in a company. The expense associated with moving equipment for "today's" requirements is prohibitive, thus facility planners must adopt a longer view. As is shown in the figure 5, the PV companies surveyed have achieved some level of organization in plant layouts. It is of concern however, that the growth trends in the industry are not incorporated into many of the layouts observed.

2.6 Capacity Planning

The issue of near and long term capacity planning appears to be well addressed in the PV industry. While complex models of machine up-time are not generally present, the scheduling functions required in PV companies do not appear to warrant such efforts.

	Capacity Planning	Percentage Implemented or Utilized
2.4.	Current shop capacity is known and used to forecast daily loading?	73%
2.4.2.	Does capacity consider inventory on hand?	73%
2.1.	Are the number of hours, cost of materials. and services recorded for each job?	82%
2.3.3.	Is any part on the floor easily associated with its work order?	82%
2.4.4.	Is raw material delivery time considered in shop capacity?	82%
2.10.	Is an inventory tracking system in place?	100%
	Cluster Average	**82%**

Figure 6 - Capacity Planning

2.7 Product Design

The design of a product such that it can be manufactured by the most economical means is of clear benefit. Less money spent on manufacturing means lower overall product costs, and one would expect better sales as a result. The PV industry appears to do a very good job at designing products it can effectively build. This is not to say that products being built are free from processes which are difficult to perform or control, as that is not often the case with high technology products. In the favor of the PV industry, the product life cycles are long and most new products are simply reconfigurations of existing product streams. This allows for optimization of designs and equipment.

	Product Design for Manufacture	Percentage Implemented or Utilized
1.1.	Is a formal Design for Assembly/Manufacturing Process implemented?	100%
1.5.	Are integrated design and manufacturing teams present?	100%
1.7.	Is prototyping and testing performed prior to production?	100%
	Cluster Average	**100%**

Figure 7 - Product Design

3.0 Manufacturing Technology Assessment

Among the objectives of the ARRI visits was to perform a general and brief evaluation of the state-of-the PV manufacturing process technology. This information would ideally suggest to both NREL and the PV community some of the common equipment needs or trends which are not being currently satisfied by off-the-shelf solutions, either in a cost-desirable manner or at all, as well as general automation strategies that would benefit the PV industry as a whole.

We emphasize that this component of the ARRI assessment is not directed towards proprietary PV process technologies or related issues which differentiate a particular company's offerings, but rather focused on generic and recurring PV material handling and process control needs. It must also be stated that, while the "bird's eye view" of the factory floor operations across the PV industry offers grounds for a number of general suggestions, the assessment lacks the necessary resolution -- and does not pretend -- to make definitive diagnoses on any one individual process.

The PV Manufacturing Automation Survey in Appendix B was used by ARRI during the plant visits to gather information. A worksheet was filled out for each major manufacturing process, including manual, semi-automated, and fully automated. A description and rationale for each of the questions follows.

I Process Information

Name: common identifier used by the company.
Purpose: short statement of purpose.
Description: brief explanation of major components & work flow.
Production rate: approximate rates, current or forecasted.
Major automation equipment: actuation and control technologies chosen for the task.
Input/output material: major items, including scrap and rejects, to be added and removed by the equipment.

II Suitability to task

(a,b) Process quality, Speed/Throughput: identify common failure modes inflicted by equipment or operator, segregated according to whether they affect product quality or process throughput.

(c) Technology/Process match: assess whether the solution implemented is appropriate both functionally and from a cost perspective.

(d) Design for assembly: assess whether process solution resembles the response to an "over-the-wall" design. Oftentimes, minor design changes which do not functionally impact the product can have a significant impact on manufacturability.

III Maintenance

(a) Preventive maintenance: establish degree of problem prevention to rule out as a potential problem source.

(b) Downtime & repairs: establish whether highly outdated or worn out equipment might be a potential problem source.

IV Automation Strategy

(a) Hardware proliferation: identify manufacturer/technology of equipment to compare with other like units in the factory. A high degree of commonality is desirable for training and maintenance purposes, though not always possible for equipment supplied by system integrators. Non-standard hardware and software can pose support and upgrade difficulties as equipment ages.

(b) Networking: identify potential for equipment integration into a plant-wide information system. Even if control is always done at the local machine, accessibility of process data from a centralized location for data logging, reporting, troubleshooting etc. is desirable. Integration with Supervisory Control and Data Acquisition (SCADA) packages oftentimes facilitates this function.

(c) Flexible assembly: most manufacturing automation solutions tend to be highly specialized to meet the needs of the product, and thus inflexible when it comes to changing throughput requirements or part family designs. Flexible assembly technologies which highly differentiate infrastructure and process-related equipment layers address this problem and are gaining acceptance in industry.

3.1 Manufacturing & Automation Technology Issues

The factories visited by ARRI span a very wide spectrum of manufacturing operations, ranging from single-digit employee outfits carrying out simple manual assembly to multi-million dollar automated lines performing highly precise and sophisticated processes. The different PV technologies being themselves quite unique makes it doubly difficult to speak of industry-wide automation solutions.

This said, the bulk of the current production is borne by the crystalline wafer flat plate manufacturers -- Siemens and Solarex -- and there some common patterns did surface which also have applicability to other PV technology providers (e.g., coinstack demounting). Potential for process improvements were also found in the final or "back-end" module assembly, which spans crystalline and thin film suppliers alike. Again, no one solution truly applies across the board.

The information collected is broadly categorized into equipment needs and automation strategies.

Equipment opportunities

- Wiresaw demounting
- Boat-to-boat transfer
- Boat-to-coinstack transfer and vice-versa
- Boat-to-conveyor transfer and vice-versa
- Coinstack-to-conveyor transfer and vice-versa
- Screen printing
- Inter-machine glass module handling
- Module lamination trim
- Back-end assembly
- Thin cell/breakage detection

Note: the words "boat" and "cassette" are used interchangeably

Automation strategy opportunities

- Cassette standardization
- Flexible automation
- SCADA and inter-machine communications & control standards

A discussion of each of these categories follows.

3.2 Equipment opportunities

3.2.1 Wiresaw Demounting

This operation takes wafers from the wiresaw process and places them into individual cassette slots, some 20 to 30 wafers per cassette. This process is currently performed manually and there is no equipment available from manufacturers or systems integrators of which ARRI is aware (except, perhaps, for the prototype developed by ARRI for Solarex under PVMaT Phase 2B). This is a necessary, difficult, time-consuming, highly repetitive, and all-manual operation, with high potential for wafer breakage, particularly as wafer thickness' continue to decrease. Companies which require this process are in agreement that a suitable automated solution is highly desirable. This is a non-trivial and risky automation problem; solution avenues are for a systems integrator willing to assume the risks to step in, or for research-grade prototyping to continue using ARRI's current design or even alternative ones.

Suggested minimum specifications for this equipment are as follows:

- Wafer queue: 500 wafers (20-30 cassettes)
- Cycle time: 2-4 seconds per wafer
- Wafer thickness: 150 microns or less
- MTBF: 4 sigma or better which equals about 1 failure per 5,000 wafers

3.2.2 Boat/Conveyor/Coinstack Transfer

Most of the implementations found to handle wafers into and out of cassettes, conveyor belts, and coinstacks are manual, though companies are exploring or have partially implemented automated methods with varying degrees of success. This again is a labor intensive and breakage prone operation needed at various stages throughout manufacture. Coinstack demounting seems to be the farthest along, with conveyor placement somewhere in the middle and boat loading/unloading the farthest behind. The already difficult handling problems are compounded in some instances due to clean-room operation requirements. As with wiresaw demounting, fully automated solutions are very much desired by the companies affected, and again either system integrators can fill the void or further research in alternative handling methods can be performed. Note that the success of this automation depends very strongly, as in the case of cassetting, upon standardization of cassette interfaces, and ideally (though hard to imagine) upon standardization of the wafer sizes; please read below for a continued discussion. Note also, with regard to coinstacking, that companies who directly purchase finished solar cells from suppliers stand to benefit from an off-the-shelf automated de-stacking solution.

3.2.3 Screen Printing

This operation is performed on every single flat-plate solar cell and on several thin film processes, and is currently implemented by different manufacturers at various levels ranging from manual assist to fully-automated. It was found that some of the screen printer machine designs were not optimized for quick changeover of multiple wafer or film sizes, and that they were not integrated into the production line in a flexible fashion. A potential benefit exists, therefore, for developing improved screen printer designs, more generic and usable throughout the industry, based on flexible assembly technology.

3.2.4 Inter-machine Glass Module Handling

Both flat-plate and thin film manufacturing requires the manipulation of relatively large glass panes at multiple steps throughout the line, handled both in batch as well as continuous flow configurations. These needs ought to be satisfied industry-wide through the use of generic equipment solutions such as vertical & horizontal cassettes and carts for WIP or batch processing, horizontal conveyance between machines, large-reach articulated robot arms, and special glass handling end-effectors with both suction and edge grip options. The availability of these standard handling tools would allow the seamless integration core processing equipment, leading to overall cycle time reduction and increased capacity.

3.2.5 Module Lamination Trim

Module manufacturers rely on sheets of EVA and Tedlar to provide environmental protection for the cells under the glass. Following lamination, excess material must often be removed -- a process done manually by means of a razor-blade knife. Although a successful automated process would yield safety and throughput gains, solving this problem in a cost-effective way is not trivial, plus some companies do not appear to perceive any significant gains from it. This perception could quickly change, however, with production rates jumping to significantly higher levels than they are today.

3.2.6 Back-end Assembly

Back-end assembly refers in general to the final assembly steps that turn a working solar cell into an actual salable module, which include:

- bus bar attachment
- leadwire or j-box attachment
- framing

These steps present additional opportunities for automation improvement in crystalline and thin film operations alike. Bus bar and leadwire/j-box attachment involve manipulation of flexible tape, soldering, and dispensing (glue and two-part polymers) processes. Framing involves the application of sealing tape or dispensing of a butyl bead, the placement of aluminum frames around the module sides, and the driving of fasteners. The few automated methods explored to date have been rather unsuccessful because of the large floorspace requirements, lack of flexibility and unacceptably high cycle time; manual methods, meanwhile, remain subject to common problems of worker fatigue and repetitive motion disorders. Comments similar to lamination trim apply here, however: some companies do not appear to place a very high value in the automation on the final module assembly, at least at current production levels.

3.2.7 Thin Cell/Breakage Detection

This is a widespread concern in flat-plate cell manufacturers because of the ever decreasing wafer thickness' expected throughout the coming years, from the current 200-250 microns down to 150 microns and below. Thinner cells intrinsically carry higher breakage risks, which justifies investment into fracture detection equipment. Effective in-line fracture detection in particular will justify its investment by improving process control and by avoiding further processing of cells which are broken and that will eventually be found to be unusable in final output tests.

3.3 Automation Strategy Opportunities

3.3.1 Cassette Standardization

This is perhaps the single most important step PV companies in the crystalline silicone business could take to facilitate the design of wafer handling equipment. A large benefit would already be derived from standardizing just on the mechanical interface to hold the cassette, irrespective (within reason) of wafer size or shape. On a more advanced level, standardizing on a few wafer sizes, the fewer the better, might truly make high-speed wafer handing a reality. The semiconductor industry has addressed issues of standardization in their industry to resolve issues of wafer handling. Other challenges related to cassetting include the fact that boats must endure repeated, harsh chemical baths and even high-temperature furnaces, requiring the use of expensive and specialized materials. Nevertheless, bringing manufacturers together on this issue will pay off handsome dividends.

3.3.2 Flexible Automation

This term refers to an emerging practice throughout the worldwide manufacturing industry to design assembly systems based on a chain of highly modular workcells. These cells typically consist of a base robotic manipulator mounted on a structure which is then surrounded by "pluggable" modules which perform process-specific tasks (such as wafer-to-cassette handling, breakage inspection, cell output sorting, screen printing, tabbing, dispensing, soldering, screw driving, parts feeding, etc.) The mechanical, electrical and software interfaces between the process module and the material handling robot are well defined, allowing quick reconfiguration to meet changes in product design and production schedules. This separation of infrastructure (utilities, base manipulator and part conveyance) and process-specific tooling yields high gains in flexibility and productivity, particularly since standardized solutions to many of the generic assembly processes can be acquired from third parties; it also lowers costs since reinvestment in the base infrastructure for a workcell is not needed as it is dedicated to a new process. Flexible assembly practices have been long implemented at leading Japanese and US manufacturers, and use throughout the US and abroad is spreading through the support of industry-wide consortia such as the National Center for Manufacturing Sciences' Light Flexible Mechanical Assembly group (NCMS-LFMA).

3.3.3 SCADA and Inter-machine Communication & Control Standards

Many opportunities exist in PV manufacturing for improvements in process control. A category of software known as SCADA packages exists to address this need. This software, available from a range of established and proven suppliers, can be used for such tasks as machine or line supervisory control, man-machine interfacing, event and data logging, and statistical process control; it runs on all major computer platforms and minimizes costly custom-development efforts. One of several examples where it should be considered is in thin-film deposition chambers, where temperature control and logging critically affects the quality of the process, and yields. The sizable list of SCADA suppliers include Wonderware (InTouch), Intellution (FIX) and USData (FactoryLink).

A related long-term strategy for the automation of solar manufacturing would be to adopt the semiconductor industry standards for inter-machine communications and control (SECS/GEM). Equipment compliant with these standards assures quick integration with plant-wide control and information systems. Most semiconductor manufacturers enforce the purchase of GEM-capable process equipment from direct suppliers, and third-party automation suppliers provide compliant equipment as well.

3.4 Summary Chart

The matrix below summarizes the equipment opportunities and automation strategies identified and discussed in the preceding section, along with their applicability relative to the three broad PV industry categories (crystalline, thin film, and concentrator/other).

	Polycrystalline	**Thin Film**	**Concentrator/Other**
Equipment Opportunities			
Wiresaw demounting	√	n/a	n/a
Boat/conveyor/coinstack transfer	√	n/a	√
Screen printing	√	√	n/a
Inter-machine glass module handling	√	√	n/a
Module lamination trim	√	√	n/a
Back-end assembly	√	√	√
Thin cell/breakage detection	√	n/a	√
Automation Strategy Opportunities			
Cassette standardization	√	n/a	√
Flexible automation	√	√	√
SCADA/comm standards	√	√	√

Appendix A - General Survey Results

The following is a complete listing of all survey questions and the average industry response over the eleven (11) companies surveyed. Questions are all formatted such that a positive response is desirable from a "world class" manufacturing perspective. The questions were initially organized into six (6) sections:

As previously indicated in the Industry Trends section of this report, a post survey clustering of the questions was performed. Overall the response to the survey was approximately 60% positive. The meaning of this is somewhat dubious as questions cannot be rated equivalently and a negative response to a given question may automatically illicit negative responses to several related questions.

Topic:1. Engineering Design	Benefit	Industry Average
1.1. Is a formal Design for Assembly/Manufacturing Process implemented?	A formalized design for assembly or design for manufacturing approach to design helps to ensure the lowest possible cost and highest quality products are manufactured.	100%
1.2. Are Design related problems are seldom discovered during mfg.	Discovery of problems in a design at the point of manufacturing results in higher product cost and often negatively impacts product quality.	73%
1.2.1. Are engineering Change Orders (ECO) issued?	Engineering change orders are a method of tracking changes to a product. A rigorous implementation of an ECO system helps to ensure that the entire company is on "the same page" and that the product being built incorporates the latest design requirements.	64%
1.2.1.1. Is data is collected on ECO frequency by product?	Collection of ECO data by a product provides a measure of design quality. A product which has a long history of ECOs represents a design which was inadequately defined, did not consider the manufacturing process, or in some other way did not achieve expected results	18%
1.2.1.2. Is a cost applied to the ECO?	Application of cost to an ECO provides the entire company with an updated view of product cost.	18%
1.3. Are drawings generated and checked according to standard drawing procedures?	The key building block of any design is a mechanical drawing representation. Standardization of the representation saves time and effort when attempting to locate particular design features.	73%
1.4. Are 3D modeling tools used ?	Three dimensional modeling tools offer the designer and others the ability to visualize more completely how design decisions effect the end product. PV, in many cases achieves little benefit from a 3-D representation as the products are one dimensional	45%
1.5. Are integrated design and manufacturing teams present?	A design team composed of designers and manufacturing personnel has a wider view of the impacts of design decisions. Manufacturing process knowledge must be incorporated into the designs in order to achieve the best possible product at the lowest possible price.	100%

1.5.1. Are formal reviews held?	A formal review of a design opens the design to constructive criticism and a final approval by all parties involved. At this point representatives throughout the company either buy into the design or force changes that make it acceptable.	64%
1.6. Are procedures established for maintaining drawing control?	A rigorous drawing control procedure ensures that all drawings in use through-out the company are up to date.	82%
1.7. Is prototyping and testing performed prior to production?	Prototyping provides a view of the activities required to manufacture in compliance with the design. It also gives the entire company a chance to review the final product, before a full scale commitment to manufacturing.	100%

Topic: 2. Operations Management	Benefit	Industry Average
2.1. Are the number of hours, cost of materials. and services recorded for each job?	Capturing data on a by job/order basis provides a better view of product cost. Economies of scaling product can more readily be observed.	82%
2.1.1. Is this data electronically collected on a by job basis?	Capturing job data immediately at the source offers the advantage of reducing paperwork and reducing the overhead and errors associated with subsequent key-punching of data.	9%
2.1.2. Is this data ever incorporated into a historical database?	Incorporation of the by job data into a larger historical database allows analysis over time. Trends in quality, product costs, and yield can be readily observed.	64%
2.2. Are customers made aware of orders expected to be late?	100% on time delivery should always be the goal, however, when orders are expected to be late, some customer goods can be retained by appropriately revising delivery schedules.	100%
2.3. Is a formal job/order tracking system in place?	A job or order tracking system provides critical elements of information to the shop scheduling function. Scheduling of shop floor functions is a key element to achieving maximum productivity with minimal investment.	64%
2.3.1. Is this data electronically collected on a by job & by process basis?	Capturing job data immediately at the source offers the advantage of reducing paperwork and reducing the overhead and errors associated with subsequent key-punching of data.	9%
2.3.1.1. Are pre-determined levels of WIP established?	Work in Process (WIP) represents a non-value added investment of the company. Any product sitting on the floor which is not a shippable product is of limited market value, thus a rigorous allotment of how much WIP is allowable is considered necessary.	9%
2.3.1.2. Does a system monitor WIP levels?	Monitoring of WIP levels provides factory management with the ability to see problems in the near future.	36%
2.3.1.3. Does a system monitor yield by process?	Monitoring yield on a by process basis provides immediate insight into the true output of the factory at any time.	27%

2.3.2. Can anyone at any point in the factory readily determine the current order status at any process?	The ability to effectively communicate the status of any job on the shop floor simplifies shop floor management. Operators can clearly observe what jobs are due into their area and their effect on downstream processes.	27%
2.3.3. Is any part on the floor easily associated with its work order?	Job tracking is of little value if a particular part on the floor is not easily associated with its job/order.	82%
2.3.4. Are process bottlenecks identified as they arise?	Short term bottleneck in the manufacturing process arise due to unexpected downtimes, material failures, and a variety of other causes. Systems which can quickly identify these allow for quicker correction and minimize impact on the manufacturing schedule.	36%
2.4. Is the current shop capacity known and used to forecast daily loading?	Daily scheduling of the shop floor is ideally based on the near term available capacity of the factory processes and other factors. This method accounts for near term bottlenecks and current factory status.	73%
2.4.2. Does capacity consider inventory on hand?	Consideration of inventory on hand is vital to any scheduling effort. Unless supplies from vendors can be immediately tapped, capacity must consider inventory on hand.	73%
2.4.4. Is raw material delivery time considered in shop capacity?	Raw material delivery time is also part of longer term scheduling. In order to effectively plan next weeks or next months product runs, delivery time of materials to inventory on hand should be utilized.	82%
2.4.5. Is equipment downtime considered in shop capacity?	Equipment down time should also be considered as part of the capacity assessment process. In near-term capacity planning, actual machine states and preventive maintenance should be considered, longer term capacity assessment requires these factors.	64%
2.5. Are standard operating procedures documented?	Documentation of standard procedures provides a guide to operators on the floor. Defective products which are processed according to a specific set of procedures can more readily be traced through the manufacturing process, thus making error resolutions.	73%
2.5.1. Are standard operating procedures readily available when needed?	Documentation is of little use if it is not made immediately accessible to the operator.	64%
2.5.2. Are standard operating procedures used by employees	Documentation is of little use if employees do not use it.	64%
2.6. Are manufacturing aids / tools available?	Manufacturing aids and tooling to assist operators simplify and standardize production operations. Standard operations simplify problem resolution and theoretically produce more consistent, better parts.	91%
2.6.1. Are manufacturing aids / tools appropriate to the task?	Tools and aids are only useful if appropriate to the task at hand.	45%

2.7. Are chemicals used in processing parts ?	This question determines if responses to question 2.71 & 2.72 should be considered in the average.	91%
2.7.1. Are chemicals used per established, documented procedures?	Documentation of appropriate handling procedures for chemicals is both a safety and process control issue.	82%
2.7.2. Are chemicals labeled with appropriate warnings	Appropriate warnings should be part of any chemical usage.	91%
2.8. Are procedures established for handling, storage, packaging & delivery?	Standard procedures for handling, storage and shipping provide once again a consistent set of operations. True causes for defective products are more readily traced when all operations are standardized.	82%
2.9. Are employees authorized to interrupt non-conforming processes?	Direct labor is the best source for problem detection and correction. Employees who are at the work site should be equipped and authorized to stop processing of parts which are identified as unacceptable.	100%
2.10. Is an inventory tracking system in place?	Inventory tracking systems are a necessary function for capacity planning and shop scheduling.	100%
2.10.1. Is inventory appropriately sized and free of unusable items?	Excessive inventory is an indicator of either poor vendor relationships, or ineffective inventory management. Inventory is sunk cost.	91%
2.10.2. Is inventory stored in designated areas only?	Temporary, unplanned storage is a sign of ineffective inventory management.	55%
2.10..3. Is inventory free of excessive outdated parts?	Outdated inventory consumes company resources which could be utilized by necessary manufacturing processes. Useless inventory disguises the true value of a company.	82%
2.10..4. Is stored material easily accessible when needed?	Easy access to inventory reduces the through-put time and makes the factory more responsive to customer demands.	91%
2.10..5. Is material storage planned?	Planning of material storage increases access and reduces lost items. Inventory is of little use if it cannot be found.	73%
2.11. Are WIP material locations planned ?	Planning of WIP locations on the factory floor ensures a smooth flow between operations. Operators do not "hunt" for the next job.	55%
2.11.1. Is WIP only stored in planned locations?	Temporary storage of WIP increases the chance of lost jobs and damage. Planned locations for WIP fixes the amount of WIP on the floor and streamlines the flow between jobs.	27%
2.11.2. Do WIP levels appear appropriate?	Excessive WIP reduces the ability to respond to a defective process. Large stores of defective materials can result from large WIP stores. Additionally, WIP is a non-value added process of manufacturing. Goods which cannot be sold are of no true value.	36%
2.11.3. Are aisles free of WIP?	Cluttering of aisles with WIP is indicative of a poorly controlled manufacturing environment. Operators safety is also adversely effected.	45%

6.4. Is the plant free of poor material flow patterns?	At low production rates, poor flow can be tolerated, but as flow rates increase material handling becomes a bottleneck.	27%
6.5. Are aisles marked?	Marking of aisles is a safety as well as production issue.	36%
6.6. Are aisles clear?	Defined aisles makes everyone aware of overall plant housekeeping issues. Blocked aisles impede product flow and present safety hazards.	45%
6.6.1. Are aisles free of inventory?	Stacking of inventory in aisle indicates ineffective inventory management.	55%
6.6.2 Are aisles free of WIP?	Stacking of WIP in aisles indicates ineffective production management.	55%
6.6.3. Are aisles free of trash?	Trash in aisles is indicative of poor process planning and poor manufacturing floor management.	91%
6.7. Are aisles appropriate for operations?	Aisles which are too small or too large for required transfers either inhibit material transfer or waste valuable manufacturing floor space.	64%
6.7.1. Are aisles straight?	Aisles which are not straight slow the process of material transfer, impede access and egress and can increase product damage.	55%
6.7.2. Are aisles adequately interconnected?	Aisles that disappear into manufacturing centers are indicative of poor flow and poor flow planning.	73%
6.8. Is adequate material handling exhibited?	Poor material handling can cause excessive product damage and injuries to employees.	73%
6.8.1. Is the manufacturing flow free of long material movement	Long material movement cost time and removes operators from value added tasks. Moving material through the plant adds no value.	64%
6.8.2. Is the unit load concept applied?	Unit load concept is in essence moving product through the plant in appropriate number of units. If a machine operates on 12 parts at a time, handling it in load sizes of 7 makes little sense.	64%
6.8.3. Is material movement minimized?	Material movement adds no value to a product.	45%
6.8.4. Are material movements efficient (load, method...)	Moving material by less than efficient means increases the cost of material transfers.	55%
6.8.5. Are material handling procedures sufficient to ensure safety and efficiency?	Moving heavy materials by ineffective means increase the chance for operator injury and product damage.	91%

Appendix B - PV MANUFACTURING AUTOMATION SURVEY

Automation & Robotics Research Institute

Manufacturing Process Assessment Worksheet (1 of 4)

I. Process Information

Name ______________________________

Purpose ______________________________

Description

Production Rate ______________________________

Major automated equipment components (type of mechanism/controller, manufacturer's name, qty if more than one)

1. ______________________________
2. ______________________________
3. ______________________________
4. ______________________________
5. ______________________________

Input material (consumables delivered into the machine and tending method)

♦ ______________________________
♦ ______________________________
♦ ______________________________

Output material (finished product, scrap, rejects...)

♦ ______________________________
♦ ______________________________
♦ ______________________________

Manufacturing Process Assessment Worksheet (2 of 4)

II. Suitability to Task

a. Process quality

Identify failure modes affecting *product quality*. Examples: actuator does not stop work in a consistent location, dispense equipment does not produce a consistent shot, there is lack of strength in the soldering joint, input material feeders jam and components are not affixed to product. Give an indication of the severity considering such criteria as incidence rate, ease of detection, ease of recovery, etc.

♦ ____
♦ ____
♦ ____

b. Speed/throughput

Identify failure modes affecting *process speed or throughput.* This can be equipment that performs well but is slow, or equipment that runs well but occasionally jams and produces downtime.

♦ ____
♦ ____
♦ ____

c. Technology/process match

Explain (or guess) whether other actuator technologies or mechanism designs could be used to accomplish the same process either faster and with better quality (underdesign) or more economically and in a smaller space (overdesign). Example: on/off pneumatic actuator could be substituted with a servo device for quick part changeover.

d. Design for assembly

Explain (or guess) whether minor part design changes could significantly reduce the complexity, increase the reliability/quality, or increase the throughput of the process. Examples: addition of chamfers to facilitate insertion, addition of a feature to eliminate placement ambiguity.

Manufacturing Process Assessment Worksheet (3 of 4)

III. Maintenance

a. Preventive maintenance

- Is there a preventive maintenance schedule for this machine?
  - Yes, supplied by manufacturer
  - Yes, developed in-house
  - No

- If there is a preventive maintenance schedule, it is followed
  - regularly
  - occasionally
  - seldom

b. Downtime & repairs

- Equipment age is
  - 0 to 5 years
  - 5 to 10 years
  - older than 10 years

- This equipment is down for repairs
  - too many times (severe effect on production)
  - sometimes (noticeable effect on production)
  - seldom

- Repairs are typically performed by
  - by the operator
  - by local skilled trades/engineering personnel
  - by the manufacturer's field engineer

Please explain the typical nature of repairs.

Manufacturing Process Assessment Worksheet (4 of 4)

IV. Automation Strategy

a. Hardware proliferation

- Equipment controller is a
  - PLC (circle manufacturer: GE AB Modicon Siemens Other ____________)
  - Standard PC (circle operating system: DOS Windows UNIX Other __________)
  - Robot controller (circle: Adept Seiko GMF Other ____________)
  - Proprietary or custom-made design
  - Not applicable

- Equipment is programmed in a standard computer language
  - Yes (circle language: BASIC C V+ AIM KAREL Other ______________)
  - No, it uses a custom computer user interface
  - No, it uses a push-button/LCD screen interface
  - Not applicable

- Equipment was specified to use equipment from a particular supplier where possible
  - Yes, for the following components ________________________________
  - No

b. Networking

- Equipment has the ability to communicate with supervisory factory control modules via
  - ethernet
  - fieldbus (circle: Honeywell SPS, Interbus-S, DeviceNet, Other ______________)
  - RS-232/485
  - don't know or no networking capability

- This equipment is in some way tied to a supervisory factory control module
  - Yes (circle supervisory control: WonderWare FactoryLink Other _________)
  - Yes, software was custom developed
  - No

c. Flexible assembly

- Equipment adheres to flexible assembly principles through
  - use of fully re-programmable manipulators
  - use of interchangeable end-of-arm tooling
  - use of standardized process modules
  - not applicable

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
August 1998

3. REPORT TYPE AND DATES COVERED
Final Report

4. TITLE AND SUBTITLE
Photovoltaic Industry Manufacturing Technology Assessment, Final Report

5. FUNDING NUMBERS
C: AAX-7-17655-01
TA: PV805101

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Automation & Robotics Research Institute
7300 Jack Newell Blvd. S.
Fort Worth, TX 76118

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
SR-520-24823

11. SUPPLEMENTARY NOTES
NREL Technical Monitor: R. Mitchell

12a. DISTRIBUTION/AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report contains the results of the Photovoltaic (PV) Industry Manufacturing Technology Assessment performed by the Automation & Robotics Research Institute (ARRI) of the University of Texas at Arlington for the National Renewable Energy Laboratory. ARRI surveyed eleven companies to determine their state-of-manufacturing in the areas of engineering design, operations management, manufacturing technology, equipment maintenance, quality management, and plant conditions. Interviews with company personnel and plant tours at each of the facilities were conducted and the information compiled.

14. SUBJECT TERMS
photovoltaics ; Photovoltaic Manufacturing Technology ; PVMaT ; engineering design ; operations management ; manufacturing technology ; equipment maintenance ; quality management ; plant conditions

15. NUMBER OF PAGES
32

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT
UL