Examining cost of ownership for front- and back-side metallization of crystalline-silicon solar cells

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ABSTRACT

This paper, the third in a series covering cost of ownership (COO) studies for photovoltaics [1], examines the need for metallization of silicon-based solar cells and how it has evolved over the past few years. The technologies and techniques that are being developed for this part of cell manufacturing in the foreseeable future are also discussed. The paper will conclude with a COO case study using the DEK Solar PV3000 as an example.

Solar cell production outline

Metallization is the final step in the solar cell manufacturing process and, as such, its success depends very much on the steps that precede it. A discussion of metallization and its development must therefore take into consideration the entire solar cell production cycle. So before describing the process of cell metallization, it is worth first outlining the entire process through which the silicon wafer travels on its way to becoming a fully-fledged cell.

First, the silicon wafer is sliced from a monocrystalline or polycrystalline silicon ingot. This step can be carried out either directly at the silicon foundry or by the solar cell manufacturer. The sliced wafer then goes through four distinct manufacturing steps, finishing with metallization, after which it is ready for mounting into a solar panel.

The first step in the cell manufacturing cycle is wet etching, which is described in depth in the second paper in this series [2]. Here, the imperfections created in the sawing process are removed and the wafer's surface is texturized to create the microscopic pyramid structures that will enable it to trap and absorb sunlight rather than reflecting it.

As described in the first paper in this series [1], the second step is a thermal diffusion process whereby an n-type layer is diffused through the wafer's top layer and down into its structure. Typically made of phosphorous-rich material, this combines with the wafer's own n-type material to create the cell's p-n junction, a planar semiconductor device that will generate electrical current. During the diffusion process, a layer of glass is created on the surface of the cell that is removed in an additional etching and de-glassing process.

In a further print step, the cell's antireflective layer is laid down in a plasma-enhanced chemical vapour deposition (PECVD) process that gives the cell its blue colour, after which the cell is ready for metallization.

Metallization explained

The photovoltaic industry uses screen-printing as the method of choice for depositing silver and aluminium onto its solar cells. Inkjet printing, the only commercially available alternative to screen-printing, is little used, principally because its use calls for an additional plating process, which adds extra cost and which does not lend itself to the solar industry's inline production approach.

Today's metallization process typically consists of three separate print phases, two on the cell's back-side and one on the front-side. The order of the printing steps depends on the manufacturer's operations. In the first back-side print step, silver contacts are printed in the form of two bus bars or, less frequently, in the form of simple tabs. In the second print operation, a thin layer of aluminium is laid down across the entire back-side, creating the cell's back-side field, or contact (see Fig. 1). In a further print step, the front-side of the cell is printed with a silver conductor grid (see Fig. 2).

The aluminium and silver act as the terminals of a battery, routing the electricity off the cell. The electricity is generated by photons of sunlight hitting the cell's p-n junction and releasing electrons that migrate through the n-type silicon to the cell's front face. Here they are captured by the grid of silver conductor fingers and routed through the cell's electrical circuit to the back field, their movement creating an electrical current that generates the cell's electricity. In the meantime, the atoms at the p-n junction that are now without their electrons are in turn attracted by the aluminium back field, where they recombine with their electrons, and then migrate back into the wafer.

Clearly, the more electrons the silver conductor grid harvests, the more efficient the solar cell, so ideally, the conductor grid should be printed across the entire front surface of the cell. Unfortunately, this is not possible, as the same grid that collects electrons actually prevents their generation by putting the underlying silicon into shadow. Thus, there must be a trade-off between electricity generation and harvesting efficiencies. The solar industry has access to numerous mathematical formulae that calculate the best grid size and density for any cell design.

Typically, the wafers are presented to the metallization line either on a conveyor straight from the PECVD

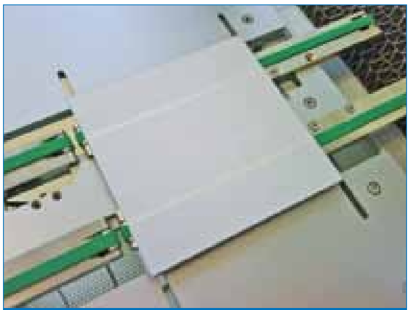

Figure 1. Back-side metallization of a solar cell.

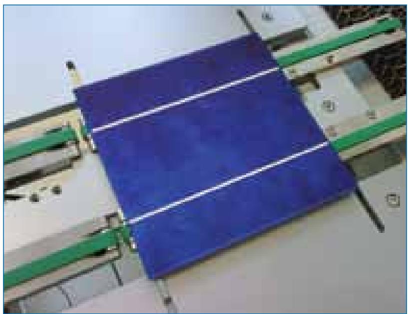

Figure 2. Front-side metallization of a solar cell.

process or in coin stack boxes or cassettes. The first piece of equipment in a metallization line is usually an unloading mechanism and possibly an inspection station that checks the wafers for damage from previous processes. At this point, they will go into the first screen printer, where they may be loaded singly into a completely flat nest that supports them and holds them down using a vacuum. A camera system is used to align the image on the printing screen with the edges of the wafer, or alignment features or fiducials on its surface, after which the wafer is presented to within approximately 1mm of the screen, depending on the print gap.

In some cases, an automatic paste-dispensing system will dose the print paste onto the screen prior to the print stroke but often, and especially in lower labour cost areas, this is achieved manually. DEK's equipment, for example, uses a print flood process whereby a floodbar, or doctor blade, first spreads a very thin layer of paste across the surface of the print screen, after which the squeegee sweeps across the screen, pushing the paste through the mesh onto the wafer. After the print stroke, the screen and the cell part company, and the cell is transferred to an inspection station that will check for print quality and accuracy, alignment, breaks, shorts, width violations, and, in the case of the aluminium, back-side contact and voids.

Unlike electronics manufacturing, solar cell production does not include rework as a standard process. A few breaks in a cell's printed features will, of course, affect its functionality, but not enough to warrant the time and expense of rework. Once the cell gets to the end of the line, it will be tested and graded according to its efficiency. Lower-efficiency cells will simply be less expensive and will be sold into less demanding applications.

After print inspection, the cell is loaded into a dryer, such as a hot-air convection oven, to drive the solvents out of the printing paste, and then it is transported on to the next printing station. Once all three print processes have been completed and the wafer dried, it goes through a sintering furnace that fires the front-side silver through the antireflective coating and into the silicon's n-type to create an electrical connection. Here it is essential that the silver is fired to a controlled depth and that it does not contact the p-n junction, since this would create a shunt, or short-circuit.

The industry standard beat rate is currently at around 3 seconds, and on a standard DEK printing line this three-print process takes around 4 to 5 minutes, including all handling and inspection operations. One cell at a time is printed on all DEK machines, to allow for individual alignment of each cell – a factor that is becoming increasingly important in the industry.

Developments in metallization

Over the past few years the front end of the solar manufacturing cycle – the etching and antireflective processes – have changed a great deal. Now, those changes are moving down the production line and metallization is up for some major developments, driven by a number of important factors. The following is a brief description of some of these factors and their effects on the metallization process.

Wafer handling

Until a few years ago, wafer thickness was typically in excess of 300-400µm. Then, as the solar industry started competing with the semiconductor industry for its limited supply of silicon, efficient ingot use became paramount and wafers came down to 200µm, then 180µm in 2009. Today's standard – 160µm – is even thinner, and some manufacturers are even considering wafers just 120µm thick. At the same time, wafer sizes have gone from being 100mm to 125mm square, and they are now at an industry standard 156mm square.

The general move away from monocrystalline silicon to the more fragile and less expensive polycrystalline silicon has brought with it several fundamental changes to the wafer handling process. Today, edge contacting is absolutely prohibited and, therefore, so are edge grippers and the practice of driving a cell into a hard stop for alignment. This means that only vision and sensors can be used, and the wafer is picked up from the underside or is moved on belts. Indeed, it is now the case that the only time the wafer is put under stress is during the print stroke – and development work is under way to address this issue as well.

Feature size and repeatable accuracy

When DEK started its involvement with the solar cell industry some 30 years ago, the widths of the features being printed were up to 300µm. Now, as a direct consequence of the need to reduce the shadows cast by the cell's front-side silver conductor fingers, print features have become progressively finer over the past few years. The industry has, accordingly, seen linewidths shrink from a standard of around 150µm three years ago to 120µm in 2010, with some manufacturers looking to achieve sub-100µm features. The inherent challenge in this degree of miniaturization is to ensure that the conductors lose none of their current carrying capacity, and so it is imperative that if they are to be printed narrower, they stand higher.

A whole new set of technologies is being developed that will allow high-aspect-ratio grid features, but these demand extreme precision from the printing process. Print-on-print, for example, allows manufacturers to print ultrafine silver conductor lines twice but calls for a highly accurate and repeatable printing process.

Selective emitter technology also resolves the problem of shadowing by depositing extra n-type dopant in a pattern mirroring that of the collection grid. Thus, like print-on-print, this requires a second front-side printing operation in the metallization line that will enable both print patterns to be aligned with each other to within a few microns. The added challenge here is that the dopant, the first pattern to be deposited, is invisible, and normal vision alignment systems cannot be used to align the subsequent silver collection grid pattern to it. Most manufacturers, therefore, use two small 0.5mm-diameter fiducials, printed at the outer extremes of the cell, to which both deposition processes must be precisely aligned.

As can be seen, in just a few short years the industry has gone from fairly wide features and noncritical alignment requirements to today's ultrafine features. This change must be accurately registered to either internal and invisible parameters or to previously printed patterns.

A further route to increased efficiencies is to move the relatively wide busbars from the front of the cell to the rear, connecting them to the collection grid by means of metal wrap-through holes, a more complex version of the electronics industry's plated-through holes. This process also relies on high print alignment accuracy and repeatability.

Print throughputs

Print throughputs have increased enormously, but so too have other demands that on first glance are incompatible with today's increased speeds. Five years ago, solar cell manufacturers mainly focused on throughput because they were dealing with thick, fairly stable wafers. As wafers became thinner and thinner, the focus changed to include yield and breakage, and now features have become so fine and technologies have changed so much that accuracy is paramount. Speed, yield, throughput, accuracy, and now equipment footprint are the parameters that guide equipment design and development. Concerned that increased print speeds could result in increased wafer damage and decreased accuracies, DEK has developed its PV3000 printing line (see Fig. 3) to increase throughputs threefold without increasing the speed at which the wafer is printed. It has achieved this by tripling the number of printing heads at any one printing station, allowing three cells to be printed at the same time and effectively reducing the line's beat rate from 3 to just 1 second per cell.

Printing pastes

Other areas where the metallization process is undergoing rapid transformation are in pastes and screens. Pastes are typically made of silver or aluminium together with the binder complexes and solvents that render them printable. In the case of front-side silver print pastes, the glass frit allows the silver to fuse down into the silicon during the co-firing process. Pastes for front-side printing are exclusively based on silver, while the back-field pastes are based on aluminium. The pastes used to put the silver contacts on the back-side, on the other hand, are often a mix of the two as the silver lends solderability while the aluminium creates an electrical contact. Considerable concern around the future availability and cost of silver compared to other conductors such as copper is fuelling development work around other, less expensive alternatives, but no viable alternative has yet been identified.

Transparent and semi-transparent conductor materials such as indium tin oxide (ITO) are also undergoing research, as they are potential remedies for the problem of shadowing. The problem is that in order to achieve the electrical properties required the material must be applied at a thickness that renders it opaque. Some manufacturers are studying the possibility of printing hybrid conductor grids using a thin layer of transparent conductor and a reduced number of silver conductors.

In the meantime, the standard off-the-shelf pastes of five years ago have been tuned for higher speed printing, faster drying, better rheology for higher aspect ratio features, better conductivity, and even for the way in which, and the depth to which, they fire into the wafer during the co-firing process. This has become particularly important for today's thinner wafers, where the p-n junction sits much closer to the wafer's surface.

Printing screens

Screen manufacturers have put a lot of work into improving paste transfer properties and, therefore, conductor grid structure and efficiencies by reducing the diameter of the wire used in print screen meshes to a current industry standard of 20-25µm. Apart from this, however, little has changed in the last decade in terms of the screens used for solar cell printing.

However, DEK's research has led to the development of an innovative hybrid screen design that combines the advantages of mesh-printing screens with those of two-layer electroformed stencils. This enables the repeatedly accurate printing of new, high-aspect- ratio features getting the industry closer to technologies such as print-on-print, selective etching, and selective emitter.

Case study

This case study will look at the COO of front- and back-side metallization using the DEK Solar PV3000 as an example. The base costs will be examined then contrasted with a single head system; sensitivity analyses also will be performed to find those areas for future cost improvements.

COO review

A more detailed discussion of COO can be found in the first paper in this series in the sixth edition of *Photovoltaics International* [1]. To review, the basic COO algorithm is described by [3]:

$$C_U = \frac{C_F + C_V + C_Y}{L \times TPT \times Y_C \times U}$$

Where:

C_U = Cost per good unit (wafer, cell, module, etc.)

Figure 3. Integrated screen printer and drying equipment.

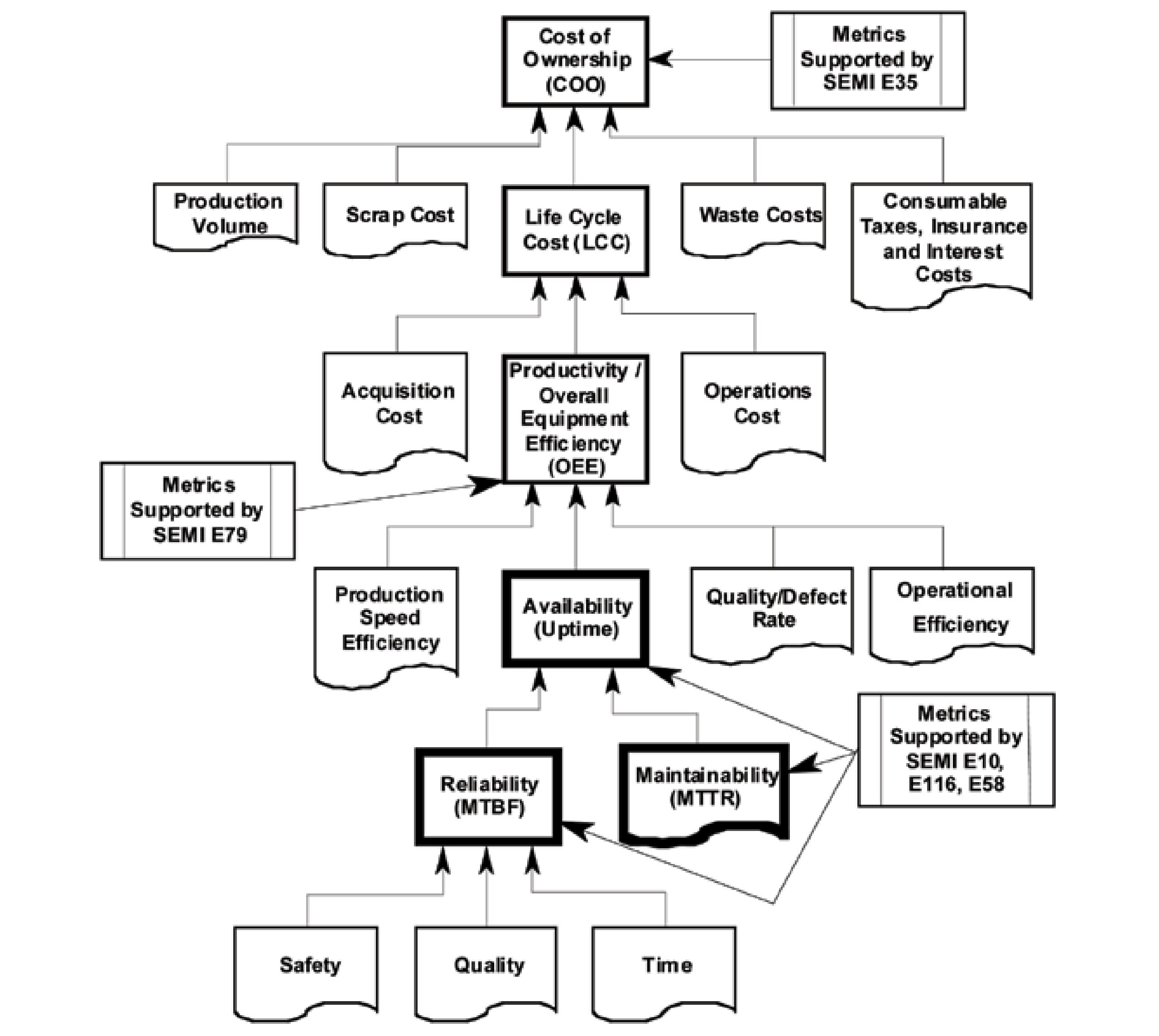

Figure 4. Hierarchy of equipment performance metrics [5].

C_F = Fixed cost

C_V = Variable cost

C_Y = Cost due to yield loss

L = Process life

TPT = Throughput

C_C = Composite yield

U = Utilization

Overall equipment efficiency (OEE) review

One of the most popular productivity metrics is OEE [4]. It is based on reliability (MTBF), maintainability (MTTR), throughput, utilization, and yield. All these factors are grouped into the following four submetrics of OEE.

- Availability (joint measure of reliability and maintainability)
- Operational efficiency
- Throughput rate efficiency
- Yield/quality rate.

If the accuracy requirement is not a critical factor, use the following formula to calculate an approximate OEE value:

OEE = Number of good units output in a specified period of time/(theoretical throughput rate × time period)

There are many equipment performance metrics at different levels, as depicted in the hierarchical tree in Fig. 4. As shown in the figure, when a time dimension is added to quality and safety, it becomes reliability. Reliability and maintainability jointly make up availability. When production speed efficiency and production defect rate are combined with availability, it becomes productivity (OEE). Acquisition and operational costs make up life cycle cost (LCC). When scrap, waste, consumables, tax, and insurance cost are added to LCC and the total is normalized by the production volume, it becomes COO.

Cost of ownership inputs

The following are the results of the COO analysis run on the PV3000 metallization line. Table 1 highlights the major input parameters.

In addition to the Table 1 parameters, where required, we used example values from SEMI E35 for administrative rates and overhead [3]. These values where provided by SEMI North American members and may not be applicable to other geographic regions. However, it is our experience that these example values do not impact the COO results on a relative basis.

Cost drivers

Examination of the detailed cost of ownership model in Table 2 highlights the main cost and productivity factors [6]. Recurring costs are approximately 30× initial capital costs over the life of the process, which are driven primarily the cost of aluminium paste used for back-side metallization. Next, the top cost drivers and opportunities for improvement will be closely examined.

Table 3 takes a closer look at the cost breakdown according to the 13 categories specified in SEMI E35. The top pareto costs are materials/consumables, which includes utilities, supplies, consumables, and waste disposal; labour; depreciation, which is impacted by equipment costs, throughput rate, and utilization; scrap; and maintenance, including repair parts and technician labour.

The top three cost drivers account for 97% of the total COO, so attention will be focused on those areas as the cost sensitivities to input parameters that drive material/consumable costs, labour, and depreciation are scrutinized.

Cost driver sensitivities

The first factors to be examined are supplies and consumables. Table 4 shows the annual costs per system by supply item. One of the issues involved in defining a sensitivity analysis for some of these items is their interrelationship with other factors. Changing the price/quality of the screens could impact throughput, paste consumption, or yield; paste consumption changes could impact throughput and the conversion efficiency of the device. Since silver paste is an industry concern, there needs to be an examination of the cost benefits that could be achieved by reducing the consumption or cost per kilogram.

As can be seen from the chart in Fig. 5, the usage of silver paste has a significant impact on the total COO. A 50% reduction in usage provides an approximately 20% reduction in the total COO for the process. While it may not be possible to achieve this level of reduction and maintain the cell efficiency, it certainly shows a significant opportunity for continued research in conducting materials.

Likewise, the price of silver paste has a similar impact on the total COO. A 50% reduction in price provides an approximate 20% reduction in the total COO for the process (see Fig. 6). As might be expected, much of the cost of silver paste is driven by the cost of the metal. This is clear from a look at the pricing for both aluminium (US$85/kg) and silver (US$700/kg) pastes; with more of the cost of the aluminium paste being driven by the cost of the included polymers. Given the annual costs for both pastes, it would be well worth the effort to examine alternatives.

The industry is looking at transparent and semi-transparent conductor materials such as ITO as a replacement for silver. While working to achieve lower shadowing on the front-side to improve cell performance will help drive down the cost per watt, it appears that finding a replacement or reduced usage or price for aluminium would perhaps provide an equal cost-per-watt improvement.

The next factor to be examined is labour content, which represents 3% of the total cost of these integrated process steps. Labour is defined as direct operator labour, and the model is based on one operator overseeing one machine. Since these are highly automated machines with sufficient throughput to support a 30MW line, it is not likely that the factory would be significantly larger in order to allow for

Parameter	PV3000
Throughput	3,000 wafers/hour
Wafer size	156mm
Wafer cost	$3
Mean time between failure (MTBF)	2,000 hours
Mean time to repair (MTTR)	2 hours
Equipment cost	$2.3 million
Equipment yield	99.7%
Utilities	$41,470/year/system
Consumables	$8,713,308/year/system
Maintenance	Owner provided

Table 1. Major COO inputs.

Cost per system	$2,300,000
Number of systems required	1
Total depreciable costs	$2,355,000
Equipment utilization capability	97.52%
Production utilization capability	97.52%
Composite yield	99.70%
Good wafer equivalents out per week	490,009.49
Good wafer equivalent cost	
With scrap	$0.44480
Without scrap	$0.43578
Average monthly cost	
With scrap	$947,079
Without scrap	$927,858
Process scrap allocation	
Equipment yield	100%
Defect limited yield	0.00%
Parametric limited yield	0.00%
Equipment costs (over life of equipment)	$2,541,145
Per good wafer equivalent	$0.00995
Per good cm^2 out	$0.00005
Recurring costs (over life of equipment)	$111,108,291
Per good wafer equivalent	$0.43486
Per good cm^2 out	$0.00228
Total costs (over life of equipment)	$113,649,436
Per good wafer equivalent (cost of ownership)	$0.44480
Per good cm^2 out	$0.00233
Per productive minute	$22.17

Table 2. COO results.

Cost drivers per good wafer equivalent	
Material/consumables	$0.41138
Labour	$0.01254
Depreciation	$0.00922
Scrap	$0.00903
Maintenance	$0.00133
Floor space costs	$0.00070
Support personnel	$0.00057
Training	$0.00001
System qualification costs	$0.00001
ESH preparation and permits	$0.00000
Moves and rearrangements	$0.00000
Other materials	$0.00000
Other support services	$0.00000

Table 3. Pareto of cost drivers.

Supply/consumable	Annual cost per system
Electricity	$28,470
Exhaust	$13,000
Screens	$768,821
Aluminium paste	$4,356,654
Silver paste	$3,587,833

Table 4. Annual supply/consumable costs.

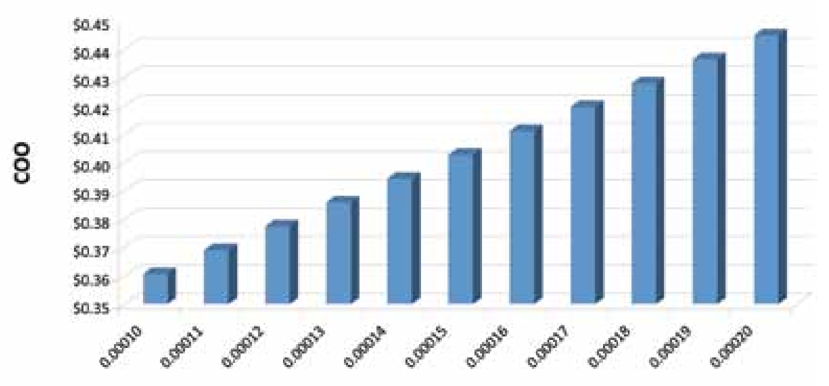

Figure 5. Sensitivity analysis of silver paste quantity vs. COO.

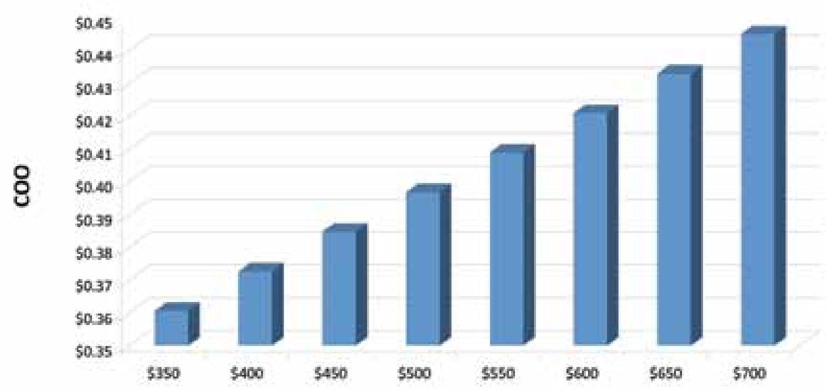

Figure 6. Sensitivity analysis of silver paste price vs. COO.

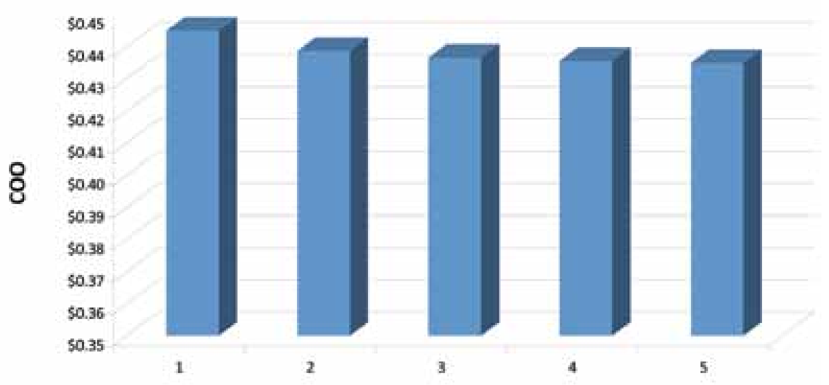

Figure 7. Sensitivity analysis of labour vs. COO.

further amortization of labour content. However, Fig. 7 does examine COO sensitivity to labour content should such opportunities present themselves.

Lastly, we look at the factors impacting depreciation: purchase price and throughput (see Figs. 8 and 9).

Purchase price has a modest impact on COO in high-throughput tools, especially those with higher variable costs. The cost impact in this case is approximately US$0.0047 (1%) per US$1.2 million (~50%) change in purchase price. This indicates that even if the purchase price were zero, the impact on COO would only be approximately 2%.

However, as Fig. 9 shows, improvements in throughput can have a significant impact on COO, depending on where on the curve the equipment is operating. In this case, the printing line is operating at an average throughput of 3,000 wafers per hour (wph), and ±200wph near the average only impacts COO by 0.4%.

Another question that arises from the previous discussion is whether the assumption that a three-printhead system is, in fact, a lower cost alternative to the traditional single-printhead systems. For this analysis, the model was modified from a throughput of 3,000wph to 1,200wph and from a capital cost of US$2.3 million to US$1.2 million. The design throughput of the PV3000 is 3,600wph, but a more conservative value of 3,000 was used in this study. The same assumption was not made for the single-printhead system, so the actual costs for that system may be higher. The consumables per wafer were also assumed to be the same since the end product should have the same specifications.

Even with the above assumptions, the COO value for the single-head system was found to be US$0.47 per good wafer compared to the US$0.44 for the PV3000. Therefore, the multiple-head system is estimated to have approximately a 7% cost advantage over traditional systems.

Overall equipment efficiency

Table 5 shows the OEE of the PV3000, which shows the OEE in excess of 81% based on a maximum throughput rate of 3,600wph. If that factor is eliminated, the OEE is over 97%, leaving little room for improvement.

Conclusion

The photovoltaics industry has gone through some immense changes over the past few years, yet it is still developing rapidly in many ways. This means that while this paper can offer a snapshot of the metallization process and its costs today, these will very likely look quite different even a year from now. The upstream processes in solar cell manufacturing have gone through a practical revolution in the past few years and this, combined with the pressures inherent within the metallization process itself, are now driving huge transformations within this part of the production cycle.

As the industry moves forward, it will continue to focus on faster throughputs, better yields, higher accuracies, and higher aspect ratios. There will also be higher levels of automation, right through to the end of the line, approaching the ultimate goal of having a hands-off, lights-out operation where the materials are automatically fed into a line which monitors and runs itself. The surface mount technology industry is almost there, so there is every possibility that the solar industry will achieve the same.

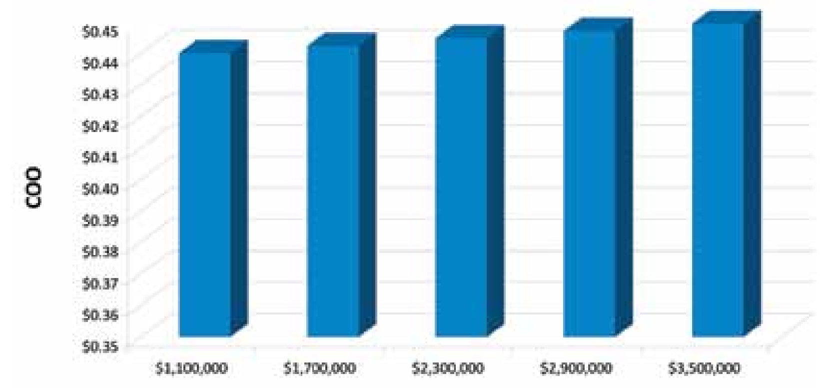

Figure 8. Sensitivity analysis of purchase price vs. COO.

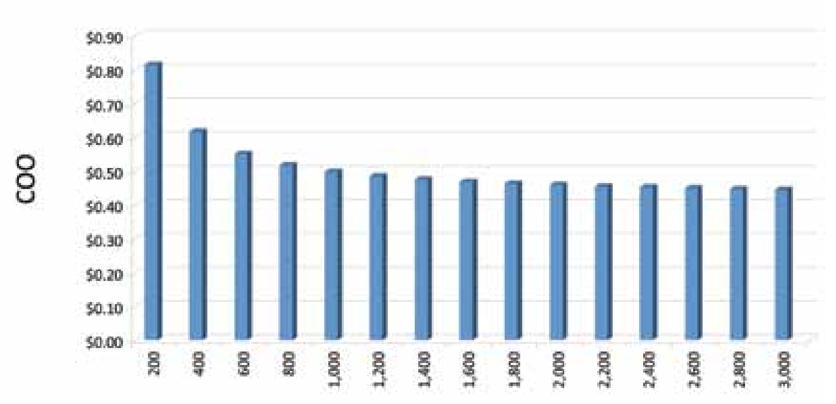

Figure 9. Sensitivity analysis of throughput vs. COO.

Each improvement in the process has its development costs and while, in many cases, COO will be reduced as a result of their adoption, in other cases it may actually increase. While this seems counterproductive in a world of lean manufacturing and cost pressures, it should also be remembered that COO should be measured against changes in cell efficiency. For the solar industry, the combination of these factors gives the most crucial metric of cost per watt, and there is no doubt that the many developments mentioned here have brought or will bring significant improvements to the cost per watt of solar power and will continue to make solar energy a cheaper proposition for the future.

Overall equipment efficiency	81.02%
Availability efficiency	97.52%
Engineering usage	0.00 hr/week
Standby	0.00 hr/week
Hours available/system (productive time)	163.83 hr/week
Downtime	4.17 hr/week
Scheduled maintenance	4.00 hr/week
Unscheduled maintenance	0.17 hr/week
Test	0.00 hr/week
Assist	0.00 hr/week
Non-scheduled time	0.00 hr/week
Equipment uptime	163.83 hr/week
Total time	168 hr/week
Performance efficiency	83.33%
Throughput at capacity/system	3000 layers/hr
Theoretical throughput	3600 layers/hr
Operational efficiency	100%
Rate efficiency	83.33%
Quality efficiency	99.70%
Equipment yield	99.70%
Redo rate	0.00%

Table 5. OEE results.

Acknowledgement

The authors would like to thank DEK's senior process development specialist, Tom Falcon, for his contributions to this work.

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Darren Brown is the global business manager of DEK's alternative energy group, responsible for maintaining the company focus on solar PV and hydrogen fuel cells and developing processes and equipment for these new and emerging technologies, including the PV1200 metallization line and the next-generation PV3000. Since joining DEK in 1995, Brown has held positions as a support engineer, global applied process engineer, and U.K. sales manager before heading up the alternative energy business unit. He has contributed articles and conference presentations on both fuel cells and solar throughout Europe, Asia, and the United States.

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