The role of silver in terawatt PV production – Perspectives and options

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Abstract

As the PV industry rapidly advances towards annual PV production and installations on a terawatt scale, many aspects that are currently not critical will need to be considered. Among these, material availability is probably one of the most pressing ones. Established production routines will need to be changed, which may pose significant time constraints in the light of the fast-growing market. The focus of this paper will be on the use of silver for solar cell metallization. Past developments are discussed and an overview is given of the fast-growing number of relevant publications from the scientific community that deal with the problems associated with silver. There is increasing recognition that silver will become a concern in a terawatt-scale PV landscape. The authors present their own thoughts on how this issue will be addressed, taking into account the various cell and metallization technologies. It seems highly likely that, at least in some cell technologies, copper-based cell metallization will become a reality in the next 5–10 years.

Introduction

Multi-terawatt-scale PV production will be necessary in order to realize the worldwide energy transformation and to achieve the Paris climate goals. While even conservative players such as IEA [1] and BP [2] predict PV production to rise to 0.3–0.7TWp/a by 2030, depending on the scenario, many scientists and organizations predict multi-terawatt per annum PV production to become a reality between 2030 and 2035 [3,4]. PV production will be increased by roughly one order of magnitude compared with the present-day situation. This will impose all sorts of challenges, ranging from building lots of factories and manufacturing tools and ensuring the availability of different materials, to bringing in the (qualified) labourers needed both in the factories and especially for the installation of the PV power plants.

With regard to materials, the availability of aluminium [5], flat glass [5] and other critical raw materials [4,6–8] needed for solar cell fabrication are currently a topic of interest. Of the cell materials, silicon seems the least critical from a geological perspective, as it is the second-most-abundant material in the earth’s crust. Obtaining enough wafer material is a question of installing enough refining, ingot pulling and sawing capacity (which will still be difficult). Materials such as bismuth, indium and silver, which are commonly used in cell and module electrodes, are far less available and are therefore widely discussed in detail in the PV community. A few examples are:

- General considerations on a terawatt-scale PV were reported by Haegel et al. [9] in 2019, including the statement: “For current manufacturing, silver consumption is 20 metric tons (±5 tons) per GW of production. At these levels, terawatt-scale production could exceed total worldwide silver production by 2030. Targeted R&D is needed to reduce Ag use, perhaps via replacement by Cu, coupled with recycling efforts.”

- Verlinden [7], in 2020, offered the estimation: “On a 156mm wafer, typically 120mg–130mg of paste is used, corresponding to 96–104mg of Ag or about 20mg/W. The PV industry currently uses about 20 tons of silver per GW of production (2,400 tons of silver in 2019) or a bit more than 10% of the global production of silver. If nothing changes in the consumption of Ag in PV production, at the 1TW level of production (around 2028), the PV industry will use 100% of the global production of silver.” Note, however, that this was conjectured on the basis of standard passivated emitter rear cell (PERC) technology, which uses less silver than more advanced approaches.

- More detailed aspects for silver specifically were considered by Zhang et al. [6] in 2021, who also looked into material use for different cell technologies. A silver usage of less than 2mg/Wp was suggested for sustainable growth to a terawatt production level, which far exceeds the targets aspired to in the ITRPV roadmap.

- Goldschmidt et al. [4] examined the effect of a terawatt PV market on different materials, including silver. They found: “If the silver consumption per cell remained constant such that only device efficiency increases reduce the per Wp silver consumption, the demand of the PV industry will exceed today’s global...”
silver production as early as in the year 2027, considering an aggressive growth scenario.

- In 2022 Ballif et al. [10] considered terawatt-scale PV production options and concluded: “Substitution materials can be used for critical elements (for example, silver has been replaced with copper and indium with zinc and/or tin in SHJ cells).”

This paper aims to give an overview of the current state of knowledge regarding the use of silver in PV production, its limitations and possible alternatives.

Looking back – learning rates and price fluctuations

In the early stages of PV development, evaporated and plated contacts were mostly used for solar cell metallization. In the 1980s, printed silver contacts were introduced and became state of the art in production, with a few exceptions [11]. Initially, printed contacts had poor conductivity and contact resistivity [12], large feature size and high material consumption. As the general state of development was not very advanced for silicon solar cells, these contacts still fulfilled the requirements of the solar cells that existed at the time.

More importantly, the introduction of screen-print technology into solar cell production represented a major cost reduction in comparison to the use of vacuum evaporation (see Table 1), which typically had poor material utilization and was both time consuming and labour intensive [13]. Although the metallization cost of screen-printed silver contacts was considerably higher than that in today’s solar cells, it only accounted for less than 0.2% of total module costs back then, providing little incentive to reduce silver paste usage for cost benefits.

With the rapid uptake of screen-printed contacts in the 1980s, the use of plated contacts also declined until BP Solar revived this approach in their ‘SATURN’ cells, which were manufactured from the 1990s to 2008 using an electroless copper (Cu)-plating sequence [14]. The main driving force of using Cu-plated contacts was to overcome a series of limitations of screen-printed silver contacts in the 1990s, such as poor metal conductivity, large finger width, poor aspect ratio and mandatory requirements imposed on heavily diffused emitters [15]. In 2009 Suntech introduced the ‘PLUTO’ cell, which featured simpler processes for forming the Cu-plated contacts using a combination of high-throughput laser doping and electrolytic plating equipment.

Even though BP Solar and Suntech both discontinued the production of Cu-plated cells, significant progress has nevertheless been made in the last two decades in addressing the challenges linked to Cu-plated metallization.

Table 1. Metallization costs for evaporated contacts in 1975, and for screen-printed contacts in 1975 and 2020.

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<tr>
<td>1975 evaporated titanium-palladium-silver [13]</td>
<td>45</td>
<td>110.3</td>
<td>40.8%</td>
</tr>
<tr>
<td>1975 SP Ag [13]</td>
<td>0.203</td>
<td>110.3</td>
<td>0.18%</td>
</tr>
<tr>
<td>2020 SP Ag [3]</td>
<td>0.0128</td>
<td>0.2</td>
<td>6.42%</td>
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Figure 1. (a) Learning curve of the mean front-side finger width using screen and stencil printing, based on published results from 2008 to 2021 (modified and updated version based on Lorenz et al. [19]). (b) Historical metallization cost from silver paste usage and share of metallization costs in total module costs.
as reviewed by Lennon et al. [11]. SunPower has been commercializing high-efficiency Cu-plated interdigitated back contact (IBC) cells and modules since 2008, with excellent performance and reliability. In addition, several institutes and companies are now demonstrating excellent efficiencies, reliability and manufacturability using Cu-plated contacts in TOPCon [16] and HJT [17] cells. For this reason, approaches based on Cu-plated contacts are still expected to play an important role in the future, as will be discussed further in a later section.

Continued development of printing technology, and especially of paste materials, has enabled silver screen printing, as a dominant metallization technology, to remain suited to meeting the challenges encountered in subsequent cell development. For instance, the transition towards lightly doped emitters has led to the requirement for smaller finger spacings and finger widths in order to reduce losses due to emitter lateral resistance and optical shading from the fingers, as well as prompting the development of silver pastes designed to form low-resistivity metal-semiconductor contacts with such emitters [18]. Meanwhile, increases in wafer dimensions and reduced optical reflection have significantly augmented the current output of solar cells, which imposed much stricter requirements on the conductivity of silver pastes. A major boost of innovation was triggered around 2010/2011 when silver costs skyrocketed to above US$1,500/kg, primarily because of speculation, and the share of silver paste cost reached an all-time-high level of ~6%, compared with just 1% of total module cost in 2000, as shown in Fig. 1(b). This made the goal of reducing silver usage in screen-printed contacts one of the top priorities in the PV industry to bring down module manufacturing costs.

Since 2011, cell interconnection technologies have been rapidly evolving towards interconnection concepts with more numerous and narrower busbars, as shown in Fig. 2(a) (data from ITRPV 2015–2021 [3]). This evolution effectively triggered the development of fine-line screen-printing processes and materials, as the usage of such interconnection concepts substantially decreased the requirements regarding the lateral resistance of the front-side contacts, as shown in Fig. 2(b) [6]. Concurrent with this evolution, rapid progress was made regarding paste formulation and development of new screen architectures for fine-line printing. This impressive progress, primarily within the last 15 years, is clearly visible in the steep ‘learning curve’ of the mean finger width of typical c-Si solar cells, based on published results, as shown in Fig. 1(a). As a result, the silver usage (mg/W) has been significantly reduced by a factor of four during the past 20 years, leading to a sevenfold reduction in the metallization cost associated with the use of silver pastes.

Notably, the cost ($/W) of silver pastes has remained within a tight range (1.28–1.55¢/W) during the last five years because of the relatively stable silver price and significantly slower rate of reduction in silver usage, as shown in Fig. 1(b). The silver usage per cell has only reduced by ~30mg/pcs during the last five years, compared with almost 200mg/pcs from 2010 to 2015. This shows that, after aggressive silver reductions with a remarkable evolution of screen-print technology, further reductions in silver usage are becoming more and more challenging. Meanwhile, the total module cost has fallen dramatically by ~75% during the last five years, making the slow decrease in cost of silver pastes an increasing concern to the PV industry.

In 2020 the production of ~180GW of PV modules consumed approximately 12.7% of the global annual silver supply [20]. As the PV industry heads towards a terawatt manufacturing capacity, despite ongoing
efforts in reducing the silver usage in industrial silicon solar cells, the silver demand by the PV industry will most likely rise significantly. Therefore, besides costs, the issues surrounding supply and availability of silver are setting the alarm bells ringing in the PV industry. Goldschmidt et al. [4] show that the demand from the PV industry could exceed today’s global silver supply as early as 2027 if the silver usage per cell remains unchanged. With a historical learning rate of 15–20% in silver usage, by 2050 the PV industry will have an annual silver demand of 10–18kt, corresponding to 40–75% of today’s global silver supply. To allow sustainability with regard to material consumption in terawatt-level PV production, silver usage needs to be swiftly reduced for all cell technologies to less than 5mg/W, or even 2mg/W [6,7] – a level that will not be met in the next decade according to the current trajectory from ITRPV. This highlights the need for urgent technological advancements in existing screen-printing technologies to allow more aggressive reductions in silver usage, or a transition towards alternative metallization techniques.

Looking forward – predictions and considerations

Silver availability – abundance, supply and price fluctuations

While silver is geologically far less abundant than copper [23], the main supply risks related to

<table>
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<tr>
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<th>Ag</th>
<th>Cu</th>
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<tr>
<td>Mine production</td>
<td>2kt</td>
<td>20,67kt</td>
</tr>
<tr>
<td>Actual price range from 1990 to 2021</td>
<td>US$195.5–1.569.3/t</td>
<td>US$2.0–11.7/t</td>
</tr>
<tr>
<td>Main mining countries</td>
<td>Mexico (23%), Peru (14%), China (14%), Chile (6%), Russia (5%), Poland (5%)</td>
<td>Chile (28%), Peru (12%), China (8%), Congo (7%), USA (6%)</td>
</tr>
<tr>
<td>Mining market concentration</td>
<td>Low – 0.11</td>
<td>Low – 0.12</td>
</tr>
<tr>
<td>Ranges from 0 (low) to 1 (monopoly)</td>
<td>Low – 0.11</td>
<td>Low – 0.12</td>
</tr>
<tr>
<td>Political stability of mining countries</td>
<td>Medium – 32</td>
<td>Medium – 55</td>
</tr>
<tr>
<td>Ranges from 0 (low) to 100 (high)</td>
<td>Primary Ag (27%), Pb/Zn (32%), Cu (25%), Au (16%)</td>
<td>Primary Cu (9%), Ni (5%), Au (2%), Pb/Zn (2%)</td>
</tr>
<tr>
<td>By-product dependency</td>
<td>End-use market shares</td>
<td>Industrial (54%), investment (22%), jewellery (7%), silverware (4%), photography (3%)</td>
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<tr>
<td>Demand</td>
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Table 2. Comparison of silver and copper supply and demand [21–26].

Figure 3. Companonality of silver mining, i.e. the percentage of silver stemming from mining activities dedicated to mining silver/other metals.
silicon for PV in the short term originate from its price volatility, by-product dependency and an anticipated mismatch between demand and current mining production (see Table 2). Over 70% of silver mining is derived from by-product sources [21]. This companionality means that silver supply is mostly dependent on the market for the host metals lead/zinc, copper and gold, and less reactive to changes in silver demand (see Fig. 3). *(Companionality is the degree to which a metal is obtained largely or entirely as a by-product of one or more host metals from geologic ores.)*

Silver mining activities are geographically relatively well scattered but partially located in countries with a relative risk of politically-motivated violence – and therefore of supply constraints – such as Mexico, Peru, China and Russia [25]. An overall huge increase in demand for metals is additionally expected in the next few years in the context of the global energy transition [27]. Besides PV, electromobility will be one of the main drivers for silver demand. The consumption of copper, as a key material in all energy technologies and grid infrastructures, is projected to increase as well [28] (see Fig. 4).

While from these factors it is not straightforward to formulate a prognosis on silver cost, the mere fact remains that silver is intrinsically more expensive than copper by a factor of 50–100, and that an annual PV production on a terawatt scale will consume substantial shares of silver, irrespective of how much the consumption per Wp can be reduced.

In the case of copper, even considering a fairly high consumption of 30mg/Wp, a 3TW annual PV production would only consume 0.5% of the current annual mining volume, or 1% of the current annual recycling volume.

### Silver usage in PV

If PV production capacity increases to a terawatt level, at least 30% of the annual silver production will be consumed.
footprints are larger than those for copper. This may be important in markets that have established incentives for sustainable PV (such as France).

The rate of increase of PV production is hard to predict. Ambitious growth trajectories are desirable, considering climate goals and an increased amount of green energy in PV production itself and other sectors. This, however, would advocate an even faster transition to copper metallization, both from a carbon footprint and a silver usage point of view.

**Metallization of future solar cell concepts**

Solar cell producers are expected to rapidly transition from currently dominant standard bifacial p-type PERC to future solar cell concepts such as n-type tunnel oxide passivated contact (TOPCon), silicon heterojunction (SHJ) and IBC (significant market shares until 2025), and eventually silicon–perovskite tandem technologies, in order to maintain an efficiency improvement rate of ~0.5–0.6%/year (Fig. 6).

Unlike the current bifacial PERC technology, which makes use of aluminium pastes for the rear-side metallization, industrial TOPCon and SHJ cells require silver grids on both sides, and so a major issue is that silver consumption is significantly higher. Recent publications indicate that the silver usage for TOPCon cells manufactured in 2020 was about 25.6mg/W (66% more than for PERC), while for SHJ cells it was 33.9mg/W, which is too high to sustain terawatt-scale production of SHJ cells, given the global annual supply of Ag [6].

Silver usage per cell in TOPCon and SHJ cells is expected to rapidly decrease in the coming decade because of the constant progress made in screen-printing technology, the rapid introduction of pastes with lower silver content by weight (e.g. low-temperature Cu pastes for SHJ cells), and the adoption of advanced metallization concepts enabling lower Ag usage, such as laser transfer printing, dispensing, rotary printing and plating [29,30].

In the long run, the transition to tandem solar cell concepts, such as silicon–perovskite or perovskite–perovskite, seems very likely. While the current is lower for these types of cell, it is more difficult to achieve highly conductive metal lines because of temperature restrictions and incompatibilities with wet-chemical processes. As a consequence, modifications to existing solutions for screen printing, physical vapour deposition (PVD) or plating approaches will be necessary.

Messmer et al. [33] discuss the requirements for the minimum line conductivity of the front-side metallization of a Si–perovskite tandem solar cell as a function of the transparent conductive oxide (TCO) thickness, finger pitch and interconnection design (e.g. number of wires), highlighting the challenges for all existing metallization approaches. State-of-the-art low-temperature pastes for screen printing are applicable for contacting tandem solar cells [34] but face the challenge of either high silver content or low line conductivity for these low-temperature ranges.

Alternative metallization approaches, such as plating, provide low line resistance and low process temperatures but run the risk of exposing the perovskite to aqueous solutions and acidic or alkaline electrolytes. A proof of concept for plated contacts for perovskite solar cells was demonstrated by Hatt et al. [35] using PVD layers to protect the perovskite from exposure to the chemical environment.
environment. The ideal metallization for perovskites has yet to be found, but economizing silver is advisable in any case, even though less metal might suffice for loss-free current extraction.

As regards silver availability, the market share of perovskite-containing solar cells in 2030 is expected to be only a few per cent. While these types of cell may relieve the pressure in relation to silver usage in the long term, their small market share in the near future will not lead to significant savings in silver.

**Interconnection technologies**

Besides the progress made with regard to the metallization technology itself, the development of new interconnection approaches has played an important role in the past two decades and has to be considered to be closely connected to the evolution of the metallization process (see above). Depending on the choice of interconnection technology, the metallization can be greatly influenced, which affects the Ag consumption.

The conventional approach by soldering does not involve any Ag regarding interconnection. A few years ago, Sn63Pb37Ag2 was the established solder alloy, but has now been replaced by near-eutectic Sn60Pb40, totally eliminating Ag within the solder joint. New concepts using multiple round wires instead of flat ribbons allow further material consumption economies, as well as savings in the solar cell metallization (i.e. small contact pads instead of continuous busbars).

Commercial approaches have been launched by Meyer Burger GmbH with its SmartWire Connection Technology (SWCT) [36], or by Schmid with a multi-busbar interconnection. Both of these allow considerable reductions in Ag paste consumption for the electrodes: for example, 20–25mg is required for modern busbarless solar cell designs for the front side, whereas 60–80mg is needed per side for current 9 BB to 12 BB H-pattern grids for PERC or TOPCon [37]. In addition, a lean and reasonable pad design in combination with wave-shaped wires offers the possibility of realizing stress-reduced interconnection of high-efficiency solar cells [38]. Another approach is to omit the rear-side Ag pads of monofacial solar cells and directly solder onto the Al rear-side electrode [39,40]; however, new challenges arise with respect to critical resources such as indium and bismuth, which are needed for the solder coating during low-temperature interconnection [6].

An alternative to the conventional soldering process is the low-temperature and lead-free interconnection with electrically conductive adhesives (ECAs). Beside the polymeric matrix, ECAs contain electrically conductive particles, typically Ag with a filler content between 25 and 30 vol%. Additionally, the ribbons used in combination with ECAs feature a thin Ag coating to protect the Cu core from oxidation. In the past few years, efforts have been made to decrease the amount of ECA for ribbon interconnection in order to reduce material consumption and save costs [41].

Another important trend is the so-called *shingled cell interconnection*, based on a concept developed in the late 1950s [42]. Multiple cell stripes are cut out from a metallized and fired host cell with a special, screen-printed metallization layout on the front and rear sides. The cell stripes are interconnected into a shingled string by overlapping and connecting the rear busbar of one stripe to the front busbar of the next stripe [43]. Because of the edge interconnection nature of a shingle cell, fingers with a higher lateral conductivity as well as a busbar for interconnection are needed, which increases the total silver usage. In addition, Ag-containing ECAs are used for interconnection. However, the demand for alternative and flexible interconnection technologies is very high. PV modules with high requirements in terms of aesthetic appearance are needed in the growing market of integrated PV. The so-called *shingle matrix technology* offers high energy densities in the module as a result of the increased active area, which in turn lowers the costs per Wp [44].

In short, wire interconnection offers the greatest promise for reducing silver consumption (unless other materials are used to print busbars), but still faces important technological- and material-related challenges. Busbar-based interconnection will remain very important in the coming years. To pave the way for terawatt PV production, advanced module interconnection can play a large part, but that alone will not fix the material issue.

**Technologies for silver reduction and replacement**

**Improvements in ‘standard’ printing**

Steady progress in silver paste printing technology is expected as a result of the continuous optimization of screens, pastes and printing processes. Further progress in the field of flatted screen printing towards even finer front-side contacts can be anticipated. Recently devised models [45] for the advanced simulation of screens and pastes will enable a focused development of these materials. The use of high-performance fine-mesh screens and so-called *knotless screens* with a mesh angle of 0°, as well as the continual optimization of silver pastes, already enable reliable printing of contacts down to a width of approximately 20µm with high aspect ratio and good lateral conductivity for high-efficiency PERC solar cells [37]. Additional breakthroughs can be
expected which will enable reliable screen-printing processes for contacts down to a width of 10–15µm in the near future.

In parallel, further promising printing technologies which have been extensively evaluated and developed in recent years are approaching the industrial application stage and might challenge flatbed screen printing as the dominant technology for solar cell metallization. Rotary screen printing, multi-nozzle dispensing, high-resolution stencil printing and pattern transfer printing [46] have recently produced impressive results regarding fine-line metallization and substantial silver reduction. Nevertheless, the economic and technical benefits of these innovative approaches have yet to be proved, and it is unclear whether these technologies will achieve a ranking among the applied metallization methods in industry.

It is important to recognize that the amount of silver used cannot be reduced indefinitely. Ever narrower and lower printed lines may give rise to reliability issues or introduce complications regarding contact formation and interconnection.

On the basis of the historic learning rates of silver printing technology, a silver consumption of approximately 10mg/Wp can still be expected in a terawatt production environment, which would clearly be too much considering the data presented earlier in this discussion.

Plated contacts have been successfully demonstrated in PERC, TOPCon and SHJ solar cells, leading to record efficiencies of 22.7% [48], 24.6% [49] and 26.07% [50] respectively. The development status and learning curve of screen-printed contacts for c-Si solar cells is about 15 years ahead of the development of plated contacts. The main research topics for plated contacts address improvements in process throughput, tool footprint, capital expenditure (CAPEX) cost reductions and optimizations in the process sequence to further improve solar cell efficiency. Major factors in the comparison of cost of ownership calculations for silver screen-printed metallization and plated metallization are printed silver mass and silver price for screen printing and CAPEX costs of the plating cluster. In particular, solar cell designs with increased silver consumption, such as TOPCon and SHJ, are the most likely scenarios for implementing plated contacts. Since plating tool development is at the beginning of its learning curve, it is estimated that scaling effects will lead to a decrease in CAPEX costs and an increase in process throughput.

Overall, plating seems to be a possible technology replacement for tackling the upcoming silver dependence in a multi-terawatt market. However, this will require a market penetration over the next few years that exceeds that of the early adoption phase.

### Printed copper metallization

Replacing silver pastes with similarly conductive copper pastes has the big advantage of being a drop-in replacement in current production environments, as the same production equipment can be used. Yet, copper metallization also poses great challenges with respect to paste manufacturing, handling in the metallization process (oxidation of Cu particles) and possible negative effects on the solar cell because of diffusion of copper into the cell [50,51].

The use of copper paste for the metallization of c-Si solar cells is easier to realize for cell concepts like SHJ using low-temperature silver paste, since particularly sophisticated problems such as copper in-diffusion during the fast-firing process can be avoided, as the TCO layer acts as an effective diffusion barrier for copper [52]. Furthermore, the considerably lower temperature of the curing process is less critical with regard to oxidation [52]. The use of copper pastes for SHJ solar cells gained particular interest in the early years after 2010 because of the high silver price at that time. Early investigation with newly developed low-temperature copper pastes showed promising results with respect to printability, finger geometry, lateral resistance, contact resistance and adhesion on Si material with a TCO layer on the front side [53–55]. Furthermore, oxidation during the printing process and subsequent curing was not considered a major problem.

Another promising approach is the application of a dual printing process using non-contacting copper paste for the busbars and silver paste for the fingers [55,56]. This method can result in considerable savings in silver without the additional problems related to copper-printed fine-line fingers. Yet another approach is the use of pastes based on silver-coated copper particles, which effectively
eliminates the problems related to oxidation [57]. While good results on SHJ solar cells could be obtained using this type of paste, the economic benefits were not entirely convincing, as the fabrication of Cu-coated Ag particles is an elaborate and rather costly process.

Applying a printed metallization with Cu paste in high-temperature sintering cell concepts, such as PERC and TOPCon, is far more complicated, as additional problems become relevant: for example, fast oxidation during fast firing, diffusion of copper into the silicon bulk material at elevated temperatures, and degradation due to Cu precipitates which penetrate the p-n junction. Usually, an effective diffusion barrier below the copper metallization is needed in order to prevent the copper from migrating into the bulk material; this can be realized, for example, by a printed seed layer diffusion barrier using silver or nickel pastes [51]. The results of a few studies indicate realistic prospects for implementing this approach on solar cell concepts using high-temperature pastes, such as PERC [58,59]. However, certain important aspects, for example the contact behaviour between the contact grid and the emitter, oxidation of Cu particles and long-term stability in the module, have not yet been fully resolved.

Conclusion
On the basis of the knowledge collected above and on the authors’ experience, the following conclusions are drawn.

Status and ‘standard’ printing perspectives:
• Silver cost and availability will become a growing issue in PV production. Innovation will be needed in order to lower the silver consumption or to replace silver.
• Flatbed screen printing continues to make rapid progress in reducing finger width and silver lay-down for all cell concepts.
• Several innovative technologies, e.g. rotary printing, dispensing, high-resolution stencil printing and pattern transfer printing, compete with screen printing with regard to throughput, fine-line metallization and reduced silver lay-down. The technological path which will provide the most benefits for industrial mass production in the future is not absolutely clear at present.
• The evolution of silver printing will continue, but physical limitations for the minimum amount of silver per cell are expected without sacrificing too much efficiency. The precise amount depends on cell type and interconnection strategy and should be the subject of research efforts.
• From historical data (for various cell types), an average ~10mg/Wp silver for TWp production capacity may be realistic.

Advanced module interconnection can make a contribution to reducing silver consumption, but in itself will not fix the material issue.

Disruptive approaches:
• Printing of copper pastes is a strong point technologically, as any solution based on printing can be a drop-in replacement and has low process complexity and CAPEX but printing of copper pastes faces technological challenges (conductivity, oxidation, printability, etc), with it being currently unclear if these can be overcome pastes based on silver-coated copper particles can fix the oxidation issue, but face higher costs and still significant silver usage
• Copper plating, which has been demonstrated to a very high level, has technological benefits over printing technologies. Silver consumption can be reduced to negligible levels, or even to zero but plating has a lower technology readiness level (TRL), higher process complexity, higher CAPEX and higher maintenance cost the cost learning curve for plating is still in its early stages

Future cell concepts:
• Perovskite–silicon tandem technology will increase cell efficiency, and the lower current/higher voltage will enable reduced metal consumption.
• It is highly likely that production capacity for standard silicon PV will be increased to critical levels before perovskite–silicon tandem cells reach market maturity, and so metallization innovations are still needed.

Overall, it is clear that innovations in metallization and interconnection technologies are much needed, and are likely to pay off in the near, or at least in the not-too-distant, future. Of course, the exact technology that will make it to production cannot yet be identified without uncertainty. The authors believe that some copper-based cell metallization will probably be realized for at least some, if not all, cell concepts, which will take some pressure off the silver supply situation.

“The authors believe that some copper-based cell metallization will probably be realized for at least some, if not all, cell concepts, which will take some pressure off the silver supply situation.”
On the one hand, this will mean a disruption to the current mainstream, but on the other, copper-based metallization approaches have been used successfully in the past in silicon PV.

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