Towards Multi-TW Scale Manufacturing of PV Technologies: Challenges Related to Material Consumption

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Abstract

Key roadmaps suggest that for photovoltaics (PV) to play a significant role in avoiding climate change, a multi-TW market (~ 1-3 TW p.a.) needs to be established during 2030-2050. With a potential tenfold increase in the annual manufacturing scale, the consumption and availability of key materials such as silver, indium and bismuth will raise serious concerns for the PV industry. Currently, the mainstream solar cell technology, passivated emitter and rear cell (PERC) has a silver consumption level of 15.4 mg/W, which would require more than 160% of the global silver supply to support a 3 TW manufacturing capacity. Even with a projected 50% reduction in silver usage per cell in the next decade, a multi-TW market will still consume the majority of global silver supply. The potential transition from PERC to next-generation screen-printed tunnel oxide passivated contact (TOPCon) cell or silicon heterojunction (SHJ) solar cells represents a big step backwards for sustainable PV manufacturing due to limited efficiency gain and almost twice higher silver consumption. A transition to SHJ could also introduce new material challenges like indium and bismuth. Indium-based transparent conductive oxide (TCO) cannot be used in large-scale manufacture of any cell technology even for 30% tandem solar cells, indicating the need for indium-free TCO for both SHJ and tandem solar cells. The use of bismuth-based low-temperature interconnection technologies will also be limited to niche applications.

Keywords: photovoltaics (PV), terawatt scale, material consumption, screen print, sustainability

1. Introduction

To fulfill the requirement of The Paris Agreement, to limit the global warming to well below 2 °C or even 1.5 °C compared to pre-industrial levels (United Nations Climate Change, 2015), greenhouse gas emissions must be significantly reduced from now on, especially those from the energy generation sector, which is contributing more than 25% of total emissions (United States Environmental Protection Agency, 2021). With rapid developments in renewable energy technologies, several renewable energy sources such as solar photovoltaics (PV), geothermal, and wind have already achieved comparable or even lower costs than the conventional fossil fuels (LAZARD, 2019), providing not only technologically feasible but also economically viable alternatives. However, the large-scale deployment of renewable energy sources implies a significant increase in demand for raw materials such as copper, zinc, and silver, raising the risk of material shortage, increases in costs, and delayed transitions towards renewable energy sources. A study by the International Energy Agency (IEA) clearly highlights such a risk and concludes that today's mineral supply and investment plans fall short of what is needed to transform the energy sector from the traditional fossil fuels to green energy (International Energy Agency, 2020). For other more abundant materials such as steel, aluminum and copper, due to a high consumption level on the system level, the requirements for TW scale deployment of PV are massive. This raises concerns of the availability of these materials and also negative social and environmental impacts from the minerals production (Hund et al., 2020).

PV technologies have great potential to play a central role in the future clean energy system due to their pronounced advantages in accessing abundances of solar energy, predictable energy output based on the weather

doi:10.18086/swc.2021.04.01 Available at http://proceedings.ises.org

forecast, low land consumption, easy installation and maintenance, and low costs. Historically, the PV industry has already exhibited its capability of fast growth, where the annual production capacity rapidly increased from 16 GW to more than 130 GW during the past decade (ITRPV, 2021). Providing such a growth rate can be sustained, the PV industry is well on-track towards a terawatt manufacturing scale by 2030. In addition, key roadmaps also identify that a multi-TW market (~ 1-3 TW p.a.) needs to be established for the PV industry by 2040 to significantly fight against climate change and to avoid a major downturn in newly installed capacity due to the replacement of end-of-life modules (Haegel et al., 2019; ITRPV, 2020; Shell, 2018; Verlinden, 2020). However, such a rapid and continued growth will significantly increase the consumption of rare elements such as silver, indium, and bismuth, leading to continuously increased concerns associated with sustainable PV manufacturing at the terawatt scale. As a result, the PV industry must start to evaluate PV technologies in respect to their consumption of key materials, rather than purely focusing on efficiency and cost, to ensure the large-scale deployment of those emerging new technologies is feasible. In this mindset, we will primarily address PV material constraints of immediate concern such as silver consumption in screen-printed contacts, indium consumption in transparent conductive oxide layers (TCO), and bismuth consumption in low-temperature solders in both current and future cell technologies, with a secondary focus on efficiency increases to improve systems-level material consumption for all materials including abundant materials such as silicon, copper, aluminium and steel.

2. Silver Consumption in Silicon Solar Cells

The most pressing concern for TW scale PV deployment comes from silver(Verlinden, 2020; Zhang et al., 2021), as silver is currently used in the metallization of essentially all industrial silicon solar cell technologies, including aluminum back-surface-field (Al-BSF), passivated emitter and rear cell (PERC), tunnelling-oxide passivated contact (TOPCon) and silicon heterojunction (SHJ) solar cells. Even for the futuristic two-terminal (2T) tandem solar cells, screen printing of low-temperature silver pastes still offers a promising approach for metallization in mass production. In 2020, the PV industry already consumed 2800 tonnes of silver, corresponding to about 11% of the global silver supply (The Silver Institute, 2021a), with an annual production capacity of ~ 130 GW as shown in **Fig. 1 (left)**. With this consumption level, as the industry is heading towards a terawatt scale, PV will likely become the dominant consumer in the global silver supply chain, and the existing supply level might fall far short of meeting the demand of PV industry at a terawatt level. Given the global annual supply of 29,000 tons of silver in 2019 (The Silver Institute, 2021a), to allow a 3 TW manufacturing scale using no more than 50% of the global silver supply, silver consumption needs to be reduced to less than 5 mg/W regardless of the cell structure.

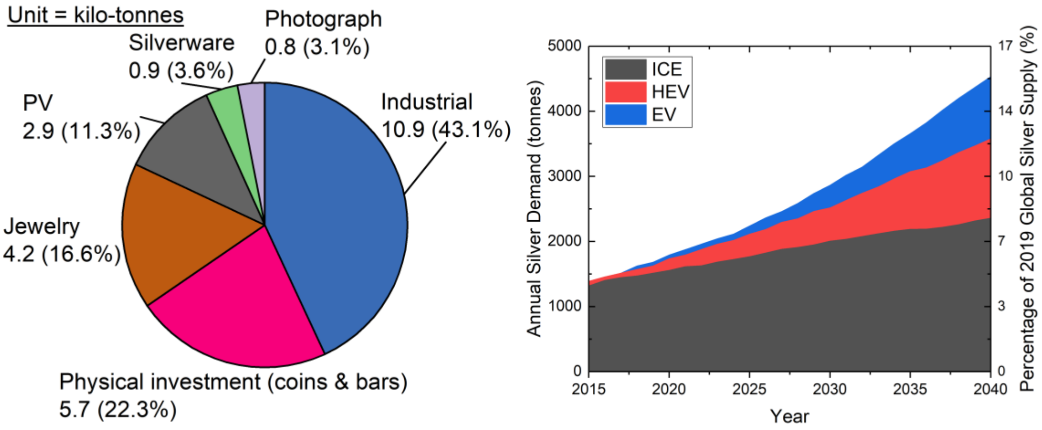

Fig. 1: (left) silver consumption by industries in 2019 (The Silver Institute, 2021a), (right) projected annual silver demand from the auto manufacturing industry (The Silver Institute, 2021b).

On the other hand, the demand for silver from other industries such as transportation and electronics is also expected to significantly increase over the next decade. As a key component in the clean energy transition, electric vehicles (EVs)/hybrid electric vehicles (HEVs) require 1-1.5 times more silver than conventional internal combustion engine (ICE) vehicles (The Silver Institute, 2021b). **Fig. 1 (right)** shows a potential 3.5 times increase in the silver demand from the auto manufacturing industry by 2040. There is no doubt that the increased demand from other industries will apply additional pressure to the global silver supply, which will likely reduce the amount of silver that can be used in the PV industry. Given the low selling price and high silver consumption of solar cells, the PV industry will have little tolerance to any silver price fluctuations and cannot afford paying more for silver in order to secure more silver supply in the event of supply shortage. As a result, from the long-term perspective, a target well below 5 mg/W should also be considered for all solar cell technologies in the future.

The silver consumption per cell has been substantially reduced from more than 400 mg per cell in 2010 to less than 100 mg per cell in 2020 owing to the largely reduced finger width and the transition from the traditional 3-busbars to a multi-busbar (>9 busbars) configuration. The increased number of busbars largely reduces the silver consumption in busbar regions and finger series resistance, which then allows further reductions in finger silver usage without increasing power losses from finger series resistance. However, there is a clear trend that the silver reduction is decelerating as shown in **Fig. 2**. Historically, it took less than 3 years to half the silver consumption per cell from 400 mg in 2010, and less than 5 years to reach a level of 100 mg per cell. As for today, reducing the silver usage from 100 mg per cell to 50 mg per cell will likely take more than 10 years in the future. That raises the question that if the silver reduction will be fast enough in the coming decade to maintain a reasonable total silver consumption level for the PV industry, providing a multi-TW manufacturing scale has been projected by many studies (e.g., 3 TW by 2030 from Verlinden (2020), 4.5 TW by 2050 from ITRPV for the broad electrification scenario (ITRPV, 2021)).

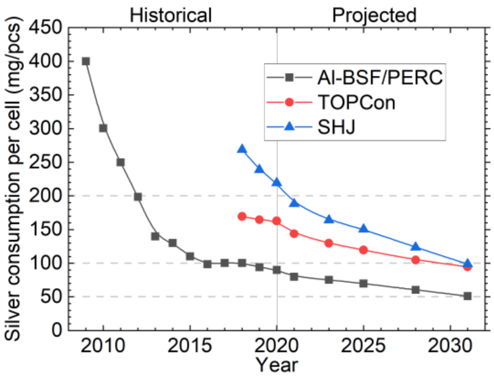

Fig. 2: Historical and projected silver consumption per cell for Al-BSF/PERC, TOPCon and SHJ solar cells (ITRPV, 2021) in G1 wafer format (158.75 × 158.75 mm^2).

The transition to different solar cell technologies can also impact the silver consumption level. Historically, the shift from traditional Al-BSF to PERC structure provided the scope of a 10-20% reduction in silver usage due to the increased efficiency. However, the same cannot be said for the potential transition of the industry from PERC towards next-generation TOPCon or SHJ technologies. The limited efficiency gain of TOPCon and SHJ does not justify the almost twice higher silver usage due to the need of silver fingers, busbars and soldering tabs on both sides of the devices. The high silver consumption in TOPCon and SHJ will not only result in significantly increased manufacturing costs, but also impose a much stricter constraint on the sustainable manufacturing capacity of those technologies for a given percentage of the global silver supply.

Tab. 1: Silver consumption of different solar cell technologies in 2020 and expected values in 2030 (ITRPV, 2021).

	2020			**2030 Expected (ITRPV)**		
	(mg/cell)	**(mg/W)**	**% of global supply for 3 TW**	**(mg/cell)**	**(mg/W)**	**% of global supply for 3 TW**
PERC	96	15.4 (η=22.8%)	159%	50	8.1 (η=23.9%)	84%
TOPCon	163	25.6 (η=23.2%)	300%	90	15.0 (η=24.5%)	155%
SHJ	150-240	25-41 (η=23.1%)	260-430%	90	14.0 (η=25.0%)	145%

Nevertheless, **Tab. 1** shows values of silver consumption of different cell technologies in 2020 and 2030 according to ITRPV’s analysis. In the coming decade, the mg/W usage of silver in all major industrial solar cell technologies is expected to be reduced by 40-50% due to improvements in efficiencies and reductions in silver laydown per cell. However, by 2030, the projected silver consumption is still well above 5 mg/W for all technologies. As a result, an annual production capacity of 3 TW will consume more than 80%, 155%, 145% of the global silver supply for PERC, TOPCon and SHJ solar cells, respectively. This suggests that the projected reduction in silver consumption of industrial solar cells will likely be insufficient to allow a 3 TW manufacturing scale in the coming decade, and it also rules out the option of having n-type technologies such as TOPCon and SHJ using screen-printed silver contacts as the mainstream technologies in a TW market.

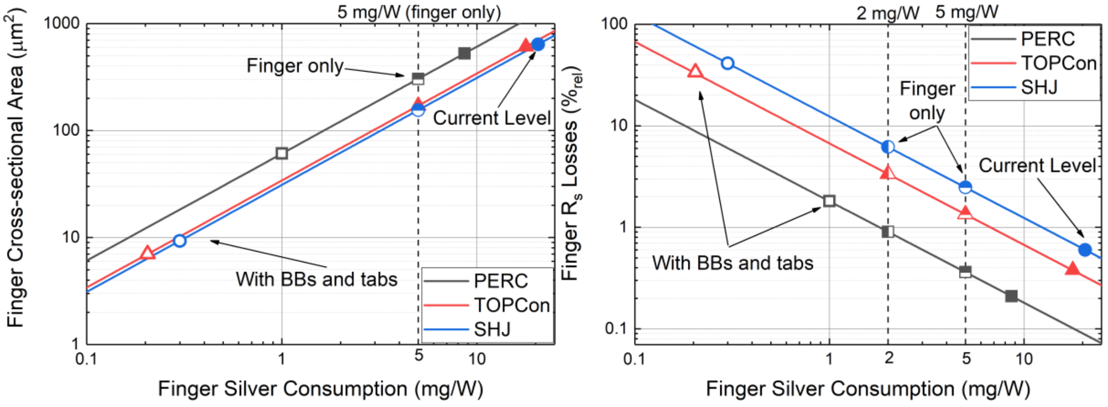

Fig. 3: (left) Allowable finger cross-sectional area as a function of finger silver usage, (right) relative finger resistive losses as a function of finger silver usage. All values are calculated for solar cells on G1 wafers (158.75 × 158.75 mm^2), with the assumed efficiency of 23.9% for PERC, 24.5% for TOPCon and 25.0% for SHJ based on 2031 predictions of stabilized efficiency in the 2021 ITRPV (ITRPV, 2021). Filled symbols provide values for current industrial cells, opened symbols represent a total silver consumption of 5 mg/W with silver busbars and tabs. Half-filled symbols denote the finger silver usage of 5 mg/W or 2 mg/W.

Given that the silver consumption in finger regions accounts for more than 50% of the total usage in PERC, and more than 70% for TOPCon and SHJ, further reductions in silver consumption level requires a substantial reduction in finger silver usage. For PERC solar cells, assuming a finger spacing of 1.3 mm, a finger silver consumption of 5 mg/W requires the finger cross-sectional area to be reduced to no more than 300 µm^2 as shown in **Fig. 3 (left) and Tab. 2**, which is not too far away from current value of 400-500 µm^2 in industrial solar cells. However, for TOPCon and SHJ solar cells, due to the need of silver fingers on both sides, 5 mg/W of finger silver usage can only tolerate a finger cross-sectional area of ~150 µm^2, which will likely point towards a target finger width of no more than 20 µm. Providing that the finger width of ~ 20 µm has already been successfully demonstrated in the laboratory, such a finger cross-sectional area can be considered as realistic and feasible in the near future. However, the impact of largely reduced finger cross-sectional area on the reliability and printability of such fingers needs to be carefully evaluated in the mass production environment.

Tab. 2: Allowable finger cross-sectional area (CA) and relative finger resistive losses of different solar cell technologies.

		PERC	**TOPCon**	**SHJ**
Current Industrial Cell	**Finger CA (µm^2)**	450	450	450
	$P_{\text{loss;finger Rs}}$ (%$_{\text{rel}}$)	0.21	0.38	0.6
5 mg/W fingers only	**Finger CA (µm^2)**	304	170	150
	$P_{\text{loss;finger Rs}}$ (%$_{\text{rel}}$)	0.36	1.34	2.48
5 mg/W with 9BB and soldering tabs	**Finger CA (µm^2)**	59	6.8	9.3
	$P_{\text{loss;finger Rs}}$ (%$_{\text{rel}}$)	1.95	33.6	41.3
2 mg/W fingers only	**Finger CA (µm^2)**	122	68	60
	$P_{\text{loss;finger Rs}}$ (%$_{\text{rel}}$)	0.91	3.36	6.20

On the other hand, silver is also needed in busbar and soldering tab regions for interconnection purposes. With the existing 9BB configuration in typical industrial solar cells, more than 4 mg/W and 4.7 mg/W of silver is used in those regions for PERC and TOPCon/SHJ solar cells, respectively. That means, with a target of total silver consumption of 5 mg/W, there is only 1 mg/W of silver which can be used in fingers for PERC, and less than 0.3 mg/W for TOPCon and SHJ solar cells. As a result, the maximum allowable finger cross-sectional area is dramatically reduced to less than 60 µm^2 for PERC and an unrealistic value of less than 10 µm^2 for TOPCon and SHJ. Therefore, eliminating the silver usage in busbars and tabs regions and the transition towards busbar-less interconnection schemes will be essential for all cell technologies to achieve a silver consumption level of 5 mg/W, especially for TOPCon and SHJ solar cells. Even with a busbar-less or silver-free-busbar configuration, the maximum allowable finger cross-sectional area for a total silver consumption of 2 mg/W will still be very challenging, suggesting that more innovations will be required to fundamentally change the way fingers are printed in order to achieve the 2 mg/W target.

$$Ploss_{finger\ Rs;rel} = \frac{J_{mp}}{V_{mp}} \cdot \frac{L_c^2 \cdot S_f \cdot \rho_m}{3 \cdot W_f \cdot t_f} = \frac{J_{mp}}{V_{mp}} \cdot \frac{W_{cell}^4 \cdot \rho_f \cdot \rho_m}{12 \cdot N_{BB}^2 \cdot M_{Ag}} \qquad \text{(eq. 1)}$$

In addition to the constraints imposed by the physical dimension of fingers, potential increases in the finger resistive losses as the finger silver usage reduced also need to be carefully evaluated. The relative finger resistive losses ($\mathrm{Ploss}_{\mathrm{finger\ Rs;rel}}$) are traditionally calculated based on half busbar spacing (L_c), finger spacing (S_f), finger resistivity (ρ_m), finger width (W_f) and finger height (t_f) as shown in Eq. 1. By rearranging this equation, a direct correlation between relative finger resistive losses, silver usage in fingers (M_{Ag}), the number of busbars (N_{BB}), finger resistivity (ρ_m), paste mass density (ρ_f) and the width of cell (W_{cell}) can be subsequently established. As such, reducing the finger silver usage will inevitably increase the finger Rs losses regardless of the finger spacing or the exact finger geometry. As shown in **Fig. 3 (right) and Tab. 2**, with a finger silver consumption of 5 mg/W (2 mg/W), the finger Rs losses will be increased by a factor of 1.7(4.3) for PERC, 3.5(8.8) for TOPCon, and 4(10.3) for SHJ, respectively. Finger Rs losses will be substantially higher if silver is also used in busbar and tab regions. With an existing 9BB configuration, a total silver usage of 5 mg/W will lead to a finger Rs loss of 1.95%$_{\mathrm{rel}}$ for PERC, 33.6%%$_{\mathrm{rel}}$ for TOPCon, and 41.3%$_{\mathrm{rel}}$ for SHJ, which again highlight the necessity of transitions towards a busbar-less configuration for all solar cell technologies in the future. Another striking feature of equation.1 is the inverse quadratic dependence of finger Rs losses on the number of busbars or interconnection wires. As a result, increasing the number of busbars/wires will provide an effective pathway to reduce the finger Rs losses, which should be considered as a necessary step to take in conjunction with reducing finger silver usage to avoid excessive increases in finger Rs losses.

The futuristic two-terminal (2T) tandem solar cells present a unique opportunity to not only achieve ultra-high efficiencies but also reduce the silver consumption significantly. The mg/W silver usage of tandem is naturally reduced by around 25% compared to existing industrial solar cells if an efficiency of 30% can be achieved on tandem. Another key feature of 2T tandem devices is the low current but high voltage output, which reduce the ratio of J_{mp} to V_{mp} by a factor of 6 (Sahli et al., 2018; Xu et al., 2020), leading to largely reduced resistive losses including finger series resistance and lateral resistance compared to PERC, TOPCon and SHJ solar cells. The choice of finger spacing in solar cells is essentially a trade-off between resistive losses and optical shading losses. With much lower resistive losses in 2T tandem solar cells, a much larger finger spacing can be used, resulting in a massive reduction in the finger silver usage. Based on our estimation, a total silver consumption of less than 5 mg/W could readily be achieved in bifacial 2T tandems with existing screen-printing technology and an industrial standard 9BB configuration. With further reductions in finger width and possible transitions towards a busbar-less configuration, 2T tandems are well on-track towards the long-term target of 2 mg/W silver usage.

In addition to innovations in screen-printing technology, copper (Cu) plating should be seriously considered as an alternative for TW scale PV manufacture. Since the copper required for plating is at a very small quantity, transitions towards plating will have negligible impact on the overall copper consumption on the system level, which will not introduce additional concerns related to copper consumption for the PV industry. Copper plating has been successfully adapted by a number of companies over the years, such as BP solar (Bmton et al., 2003; Wenham et al., 1994), Suntech (Shi et al., 2009; Wang et al., 2012) and Sunpower (Mulligan et al., 2003; Neuhaus and Münzer, 2007). Recently, a new record efficiency of 25.54% has been achieved by SunDrive and Maxwell on plated SHJ solar cells (PV-magazine, 2021). This new record efficiency marks an important milestone that shows copper plating can provide a viable path to high efficiencies not only in a lab environmental but also on industrial cells. However, several potential challenges still need to be evaluated and overcome for copper plating, such as the need of a diffusion barrier to avoid Cu penetration into the cell, potential issues with the adhesion and long-term reliability, and also the management of liquid metallic waste (Lennon et al., 2019).

3. Indium Consumption in Silicon Solar Cells

Indium is another material concern for the PV industry, which is commonly used as the form of indium tin oxide (ITO) in transparent conductive layers (TCOs) in SHJ and Perovskite solar cells or interlayers between top and bottom cells in tandem devices. It should be noted that TCOs are not needed in Al-BSF, PERC and TOPCon solar cells, hence imposing no constraints to the manufacturing capacity of those solar cell technologies. Indium is an extremely rare element, which has a global reserve 10 times lower than that of silver, and a 30 times lower annual global supply level (United States Geological Survey, 2020a). Indium is mainly produced as the by-product of zinc during extraction and processing. That means unless there is a significant increase in the demand and production of zinc, producing more indium will be not only difficult but also expensive. The secondary production from recycling (~1000 tonnes per year) also plays a critical role in the supply chain of indium, which accounts for more than half of the total global supply in 2019. However, the concern is that indium used in PV modules will be effectively locked up for 25-30 years rather than be recycled and reused every 3 years from touch screens (Islam et al., 2020), which subsequently will have a negative impact on the overall indium supply if a significant amount of indium is consumed by the PV industry.

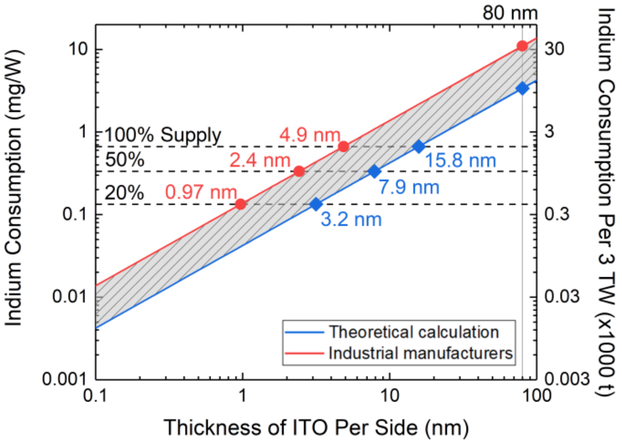

Fig. 4: Indium consumption with different thickness of ITO layers.

Currently, typical industrial SHJ solar cells use around 85 mg of ITO per cell, corresponding to an indium consumption level of 7.5-11 mg/W. With this consumption level, the planned capacity of SHJ solar cells in 2021 (40-50 GW) could already consume 30-60% of the annual global supply of indium. To achieve a 3 TW of SHJ production using no more than 20% of the total supply, the indium consumption in SHJ solar cells needs to be reduced to less than 0.2 mg/W, which then will only tolerate 3 nm of ITO per side being used instead of 80-100 nm in existing SHJ solar cells as shown in **Fig. 4**. The use of such thin layers is clearly unrealistic from either the performance or the production perspective. As a result, ITO can only be used in a niche application, which then will significantly limit the sustainable manufacturing capacity of solar cell technologies that requires ITO. Although the stacked layer configuration consisting of ITO and other indium-free dielectric layers can provide a promising pathway to significantly reduce the indium consumption (Boccard et al., 2019; Yu et al., 2018; Zhang et al., 2013), the use of 3 nm of ITO in such configurations would still be unrealistic. To enable sustainable manufacturing of SHJ solar cells and futuristic tandem devices at the TW scale, the use of indium-free TCO layers must be explored to completely overcome limitations imposed by the indium supply. Aluminum-doped zinc oxide (AZO), as one of the very few potential candidates, has attracted significant attention due to its low cost and abundant nature in material and capability of achieving comparable efficiencies to ITO-based SHJ solar cells. However, a significant amount of effort still needs to be put into battle with the relatively poor conductivity and long-term stability of AZO layers.

4. Bismuth Consumption in Silicon Solar Cells

Bismuth (Bi) is well known as a non-toxic replacement for lead in many applications such as pharmaceuticals, pigments and cosmetics. In the PV industry, the lead-free nature of Bi-based solders presents a more environmentally friendly option, which has long been criticized for the use of ribbon coating and soldering pastes containing lead, against the industry’s credentials of providing clean and green energy. Another key advantage of using Bi-based solder is the low soldering temperature, typically below 150 °C, compared to the soldering temperature above 200 °C needed for the conventional Sn/Pb solders (Faes et al., 2014). The low soldering temperature could help avoid cell breakage, cell bowing, and the formation of microcracks by reducing the thermal-induced stress caused by the mismatch of the thermal expansion coefficients of Cu ribbon wires and Si substrate, especially in solar cells fabricated on thinner and larger silicon wafers, a trend that is likely to continue in the future. In addition, low-temperature soldering is particularly beneficial for SHJ solar cells, of which the surface passivation quality of amorphous silicon layers could be jeopardized by any high-temperature thermal processing. Bi-based low-temperature interconnection methods such MBB in conjunction with bismuth coating or the busbar-less SmartWire technology will potentially become the standard interconnection technology for SHJ modules. The use of low-temperature alloys will likely also be important for future tandem solar cell technologies involving perovskites, again with temperature restrictions.

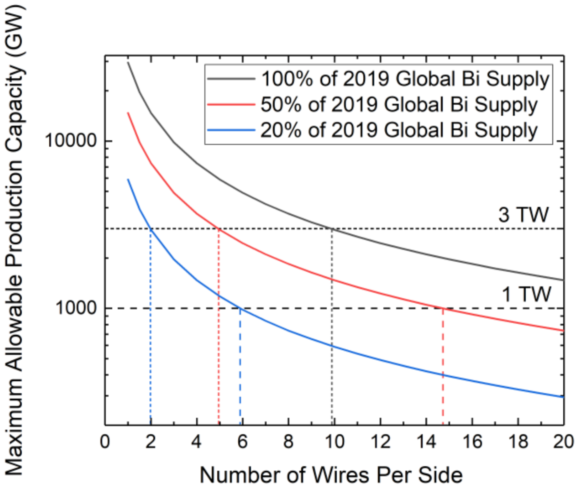

Fig. 5: Allowable annual production capacity using bismuth-based interconnection technologies as a function of the number of wires per side of the solar cell.

Assuming 18 wires per side with a coating thickness of 3 µm and a wire diameter of 300 µm, typical SHJ solar cells with 25% efficiency will have a bismuth consumption level of around 13 mg/W. This architecture is equivalent to using more than 60% of the global Bi supply in 2019 to produce 1 TW of solar cells. When limited to using 20% of global supply, only 325 GW of solar panels can be produced per year. For a 3 TW manufacturing capacity, the bismuth consumption needs be reduced to 1.4 mg/W assuming 20% of the global bismuth supply is available to use for the PV industry, which then will only allow no more than 2 wires per side for SHJ solar cells as shown in **Fig. 5**. Although reducing the number of wires provides one of the most efficient ways to reduce the bismuth consumption level, it will also significantly increase the resistive losses along fingers and along wires, not only leading to substantial power losses, but also making the silver reduction in fingers even more challenging. For instance, finger resistance losses will be increased by a factor of more than 20 compared to current industrial 9BB configuration if only 2 wires can be used per side. This will likely not be feasible for any single-junction technology, including PERC, TOPCon and SHJ solar cells. However, 2T tandem devices with a much lower resistive loss could potentially have better tolerance to the reduced number of wires, where it may be feasible.

5. Beyond the Scope of Supply and Availability

In addition to those scarce metals, materials like steel, aluminum and copper are also essential to solar PV. Steel is mostly used in the balance of system (BoS) components such as racking systems and transformers, and aluminum is commonly used in module frames. On the other hand, copper has wide applications from the cell to the system level including Cu tabbing ribbons for the interconnection between cells, modules, array and field cables, and transformer windings. Although the demand of these materials is much higher than scarce metals, thanks to the huge global supply chain and the well-established recycling industry, these more abundant materials are facing no significant supply issues with the current usage lower than the target usage for the upcoming TW manufacturing scale as shown in **Tab. 3**.

Tab. 3: Current material usage, target usage for 3 TW production scale, and material demand of steel, aluminum and copper.

	Current Usage (g/W)	**Target Usage (g/w)**	**2020 Global Annual supply (Mt)**	**Total Demand for 3 TW annual production (Mt)**
Steel	30-45	120	1800	90-135
Aluminum	9	8.6	130	27
Copper	2.8	1.8	24.6	8.4

However, the high consumption levels of those materials and substantially increased demand from the primary production will raise serious concerns for greenhouse gas emissions, negative environmental and social impacts from mineral production. A recent study by The World Bank has identified potential global warming issues with aluminum, claiming it will be responsible for more than 90% of the greenhouse gas emissions from aluminum production in next decade (Hund et al., 2020). IEA also highlights that failure to manage the environmental and social impacts from material production will slow down clean energy transitions (International Energy Agency, 2020). As such, the future growth of the PV industry needs to be not only sustainable but also responsible. On one hand, the reliance on materials from primary production must be significantly reduced by lowering the overall material consumption even there are no immediate supply concerns. The prioritized consumption of materials from secondary production should also be considered to minimize the material demand from primary production given that secondary production is less emissions intensive. On the other hand, new PV systems need to be designed and produced in a way that key materials can be easily reused or recycled in the future (Ardente et al., 2019; Norgren et al., 2020).

6. Conclusion

In summary, as the PV industry heads towards TW scale manufacturing, we need to shift our focus from efficiency and cost to understanding the limitations of material consumption and exploring options of reducing the usage of key materials. Silver is currently one of the biggest concerns for the PV industry, even for PERC. The high silver consumption in TOPCon and SHJ solar cells will impose significant challenges for them to become the mainstream technology in a future TW market. To allow a 3 TW of annual production capacity, we need to limit the silver usage to less than 5 mg/W or more preferably 2 mg/W regardless of the cell structure. As such, in addition to the natural reduction in finger width and possible transition towards a busbar-less configuration, more innovations are required for printing and we also need to seriously consider the Cu plating as an alternative, especially for TOPCon and SHJ solar cells. For indium, ITO is a no go for SHJ or even 30% tandem in large scale manufacturing. We need Indium-free TCO replacement or to fundamentally eliminate the use of TCO in those structures. Bismuth imposes another constraint to the sustainable manufacturing capacity of SHJ and tandem. Using bismuth based low-temperature interconnection technology is not feasible for TW manufacturing unless the number of wires or ribbons can be largely reduced. However, this will increase the finger Rs losses and make the reduction in finger silver usage even more challenging. But on the other hand, due to a much lower ratio of Jmp to Vmp, there could be scope for tandem to reduce the number of wires without causing too much increase in the power loss. And beyond the scope of material availability of these scarce metals, we also need to pay attention to the environmental and socials impacts from the huge demand of abundant materials such as aluminum, steel and copper to ensure the development of the PV industry is sustainable and responsible.

7. Acknowledgments

The program has been supported by the Australian Government through the Australian Renewable Energy Agency (ARENA) and Australian Center for Advanced Photovoltaics (ACAP). The views expressed herein are not necessarily the views of the Australian Government, and the Australian Government does not accept responsibility for any information or advice contained herein.

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