The present and future silver cost component in crystalline silicon PV module manufacturing

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ABSTRACT

The purpose of this paper is to determine how increased c-Si PV module production might affect future silver demand and prices, as well as the impacts on total c-Si module manufacturing costs. A bottom-up estimation of the current and potential material intensity (tonnes of silver per GW) for silver in c-Si PV cell fabrication is presented. Partly because of concerns about material intensity, and also because of the changing economics of manufacturing, there is some interest in shifting away from the traditionally higher material intensity approach of screen printing with silver paste to alternative metallization techniques, such as electroplating, which uses substantially less silver. To evaluate how PV's changing demand for silver might affect future silver prices, and the impact in terms of manufacturing costs, some scenarios of silver's contribution to c-Si PV cell manufacturing costs are compiled on the basis of projected changes in demand and price as a result of changes in material intensity. The analysis indicates that an expansion of c-Si production from 55GW/year to 250GW/year results in a 0.05–0.7¢/W increase in manufacturing costs because of higher silver prices. As an illustration of this, the current estimates of the manufacturing costs for the two contrasting methods – silver screen printing and nickel–copper–silver electroplating – are presented.

Introduction

With the growing demand for PV modules, it is natural to raise questions about potential material-availability constraints. Material availability for many of the thin-film PV technologies has received considerable attention, as their semiconductor materials require the relatively rare elements gallium, indium and tellurium. By contrast, it may seem to be of no concern for crystalline silicon (c-Si), since the semiconductor base material in this case is made from the world's second-most abundant crustal element. However, c-Si technologies still have a potential raw-material availability weak link: silver (Ag), which is typically used in the front- and back-side electrical contacts. Ag has a crustal abundance that is comparable to that of indium but lower than that of gallium [1]. It has a long history of use in currencies, jewellery and ornaments, partly because it is so rare. Moreover, silver markets (including the recent emergence of related exchange-traded funds that invest in physical silver assets) are price volatile by nature and have been vulnerable to speculative trading. The economics of silver are driven by these historical roles and characteristics, and the resulting price fluctuations affect c-Si cell manufacturing costs.

Solar electricity generation technologies make up a small but increasing share of total global silver use. From 2004 to 2014 the global silver demand from the solar PV industry grew from 0.4% to 7%; it is expected that the demand will have surpassed that from the photography industry in 2015, and that PV will become the third-largest end user of silver behind jewellery/silverware and electronics [2]. If the PV industry continues its growth trajectory, and if c-Si maintains a heavy reliance upon silver metal contacts, the increase in demand for silver could affect future silver prices [3]. In the available literature one can find evaluations of how c-Si PV module production may be *physically* constrained by existing silver resources, yet to the authors' knowledge no rigorous analysis has been done of how the reliance on silver may impact the future costs of c-Si PV module production.

> "From 2004 to 2014 the global silver demand from the solar PV industry grew from 0.4% to 7%."

The purpose of this paper is to determine how c-Si PV module production on an increased scale might affect silver prices and, in turn, have an impact on silver's contribution to total module manufacturing costs. Several scenarios of silver demand in PV module manufacturing are first derived using silver's material intensity (i.e. tonnes of silver required per GW of c-Si manufacturing production) and the projections of solar electricity generation by the International Energy Agency (IEA) and other organizations. Next, a partial equilibrium model of the silver market is constructed, and the effect of different silver demand scenarios on silver prices is simulated. Finally, PV cell manufacturing costs at different silver price levels are compared for the standard silver screen-printing metallization approach and the alternative method of electroplating, which typically requires much less silver.

Section 2 ('Literature review') discusses the available literature concerning silver availability and supply risks. Section 3 ('Scenarios for silver use in PV modules') develops some scenarios for future silver use in c-Si PV modules. Section 4 ('Method') describes the method and the data for the silver market simulation analysis. Section 5 ('Results') presents the results, and section 6 ('Comparison with Ni–Cu electroplating') compares the cost of silver screen printing with that of the alternative metallization

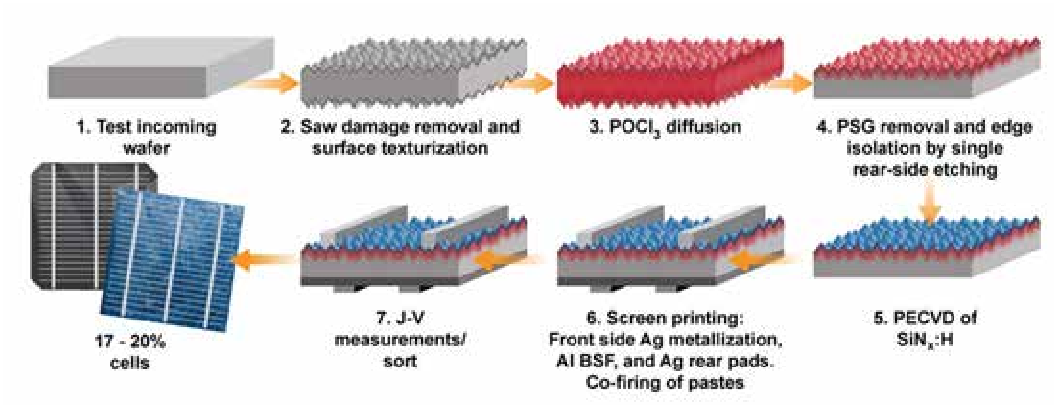

Figure 1. Process flow for the fabrication of a standard entirely screen-printed c-Si solar cell. For multicrystalline or monocrystalline cells, in commercial production using this standard process the projected cell efficiencies are estimated to be 17 to 20%.

approach of electroplating, in which the amount of silver required is significantly lower. Finally, section 7 ('Conclusion') states the implications and limitations of the analysis.

Literature review

Several articles discuss the raw-material constraints associated with c-Si PV module production, but they focus primarily on the *physical* limitations of silver resources [4–7]. Feltrin and Freundlich [4], Tao et al. [5] and Jacobson and Delucchi [6] find that, of all the elements used in c-Si PV modules, silver is ultimately the material that could constrain growth. Using the United States Geological Survey (USGS) estimates of US silver resources and the amounts of silver required in different solar technologies, Grandell and Thorenz [7] construct upper bounds for annual solar electricity generation: they estimate an upper bound of 530 terawatt-hours per year (TWh/year) for the electricity generation capability of c-Si solar cells. For comparison purposes, total global electricity generation in 2012 (from all fuel types) was 22,721 TWh [8].

Numerous studies evaluate the 'criticality' of various minerals, including silver, but the definition of what is considered critical differs between studies. Generally, a mineral's criticality is determined by: 1) its importance, either to an economy or to a specific sector of the economy; and 2) its supply risks. Supply risk has a slightly different meaning in each study, but typically relates to the vulnerability of production to decline or disruption. Erdmann and Graedel [9] review ten major criticality studies,

	Mid[a]	Low	High
Silver paste for front [mg/cell]	115	110	120
Silver paste for back [mg/cell]	45	40	50
Silver weight for front [%]	88	88	88
Silver weight for back [%]	58	55	60
Monocrystalline			
Wafer area [cm^2]	239	239	239
Power rating [W/m^2]	210	240	180
Market share [%][b]	24	24	24
Multicrystalline			
Wafer area [cm^2]	243	243	243
Power rating [W/m^2]	195	220	170
Market share [%][b]	65	65	65
Material intensity			
Monocrystalline[c] [tonnes/GW]	25.3	20.7	31.5
Multicrystalline[c] [tonnes/GW]	26.8	22.2	32.8
Weighted average[b] [tonnes/GW]	26.4	21.8	32.4

[a] Mid values are the average of high and low values.

[b] The weighted-average material intensity is weighted by the monocrystalline and multicrystalline market shares: 24% and 65% of global PV module production respectively, with thin films making up 11% [16].

[c] Material intensity is calculated by taking the total of silver paste usage on the front and back, adjusting for the paste's silver weight percentage, and converting from mg/cell to tonnes/GW using the wafer area and power rating. Note that material intensity is inversely related to solar cell power conversion efficiency.

Table 1. Material intensity of silver in c-Si modules.

only four of which analyse silver. Many of these studies were conducted by (or on the behalf of) governmental bodies and departments, such as the European Commission or the U.S. Department of Energy [10–13]. More recently, Graedel et al. [14] analyse the criticality of over 60 metals and metalloids, including silver, and use geological, technological, economic, social and regulatory, and geopolitical factors to assess supply risk. These studies regarding criticality do not have identical conclusions about silver's supply risk, partly because they differ in their purposes and methodologies. Nonetheless, some broad conclusions can be drawn from the literature. First, silver mine production is not concentrated in any one country, or even in a small group of countries; it is well distributed across the globe [10,12]. Second, a sizeable amount of silver is recycled from end-of-life products, although the efficiency of recycling varies across end uses [10]. Third, there is difficultly in substituting other materials for silver in electrical and electronic applications, which make up about a quarter of total silver use [10,12]. While these findings are useful for a qualitative evaluation of how increased silver demand could affect the silver market, they do not allow a quantitative assessment of the impact of an increased demand on prices.

This paper makes three primary contributions to the literature. First, it provides a recent bottom-up estimation of the material intensity (i.e. tonnes/GW) of silver used to make c-Si PV cells, along with an overview of how material intensity is projected to change. Second, to the authors' knowledge this is the first paper to estimate how a rise in silver demand from PV might affect future silver prices and the corresponding cost of silver usage in PV manufacturing. Several studies have looked at how silver resources can physically limit c-Si module production, but they have not analysed how silver prices might have an impact on manufacturing economics. Third, this paper compares the raw-material cost of screen-printed silver with that of the alternative metallization process of electroplating. A comparison of the costs of silver screen printing and electroplating is particularly relevant to c-Si PV module manufacturers that are considering either of these approaches in future manufacturing facilities.

Scenarios for silver use in PV modules

The metallization of a solar cell is necessary for collecting electrical current from the cell. The most ubiquitous approach used for c-Si solar cell metallization involves screen printing a silver paste onto a series of gridlines on the front, screen printing another full-area aluminium paste onto the back, and then screen printing a different composition of silver paste over the Al back, to make contact pads for eventual soldering into cell strings. This is broadly represented as step six in Fig. 1, and has been described in more detail elsewhere [3].

After the three-stage printing process, the entire cell is typically annealed in order to solidify the paste into solid metal. Also during the annealing step, additives of glass frit within the paste serve to melt through the hydrogenated silicon nitride (SiN_x:H) front-side anti-reflection coating, so that the silver can partially alloy with the underlying silicon wafer. Executing the screen-printing process in its entirety is very simple and predictable, and this process offers high yields in commercial production. If made correctly, screen-printed cells are also quite durable over many years of outdoor deployment. These are the primary reasons why the screen-printing approach currently enjoys a market share greater than 95% [15], and why it remains a formidable opponent of any alternative metallization technology.

The data from industry that are used to calculate the material intensity of silver in c-Si solar cells are given in Table 1. Using the weight percentages shown for the front- and back-side pastes, the estimate of the total amount of silver for each cell ranges from 119 to 136mg (with a midpoint of 127mg). For a monocrystalline wafer area of 239cm^2 and power ratings of 180–240W/m^2, the silver requirement per GW of manufacturing ranges from 20.7 to 31.5 tonnes (with a midpoint of 25.3 tonnes/GW). For multicrystalline cells, with a slightly greater wafer area of (243cm^2) and a lower power rating (170–220W/m^2), the material intensity is 22.2 to 32.8 tonnes per GW (with a midpoint of 26.8 tonnes per GW). The weighted-average silver material intensity for monocrystalline and multicrystalline, using their respective shares of global c-Si production (27%/73% split for monocrystalline/multi [16]), is 21.8–32.4 tonnes per GW (with an average of 26.4 tonnes per GW).

Few other recent estimates of silver material intensity are available for comparison. A 2013 report by the Silver Institute estimates that the silver material intensity in c-Si PV cells was 65 tonnes per GW in 2012, and notes that manufacturers had been reducing their overall silver usage [17]. Grandell and Thorenz [7] state that current silver use is about 10g/m^2, which translates to a material intensity of 47.6 and 51.3 tonnes per GW for monocrystalline and multicrystalline cells respectively, if using the midpoint module power ratings in Table 1. The data in Table 1 reflect the most recent 2015 guidance provided to NREL by

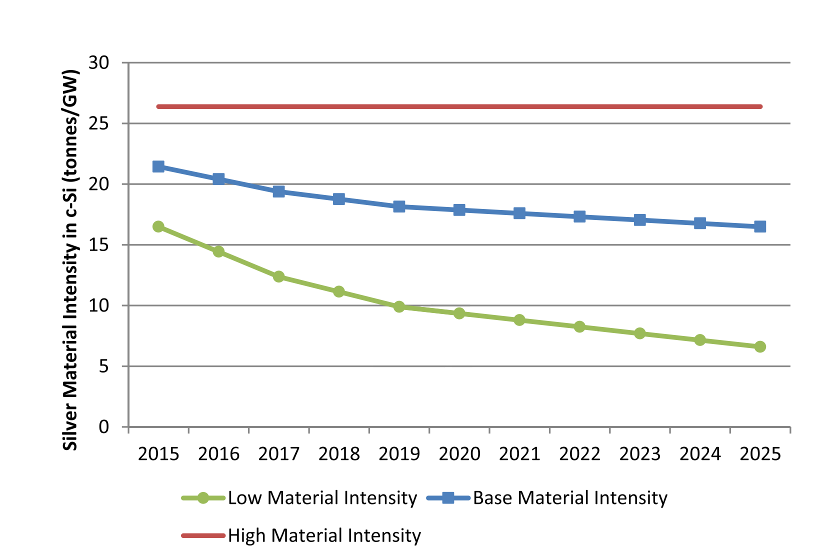

Figure 2. Silver material intensity (tonnes/GW) in c-Si cells. The low material intensity case estimates are derived from the 2015 ITRPV, the high material intensity case is equal to current material intensity estimated in Table 1, and the base material intensity case is the average of the low and high cases.

relevant industry players, including paste suppliers and equipment vendors.

There are, however, also multiple pathways to lowering the material intensity even further: these include the options of electroplating, stencil printing, inkjet or aerosol printing, or multiwire approaches (in which a mesh of base metals is overlaid onto a much smaller amount of printed silver). There is also the possibility to retain the screen-printing process but lower the material layout (for example, by using smaller screen line widths in order to reduce the amount of silver present in each finger). For these and other reasons, the 2015 International Technology Roadmap for Photovoltaic (ITRPV) anticipates that the recent declines in silver material intensity in c-Si cells will continue in the coming years. On the basis of the most recent survey, silver paste usage per cell is projected to fall from 130mg per cell in 2014 to 40mg per cell in 2025 [15].

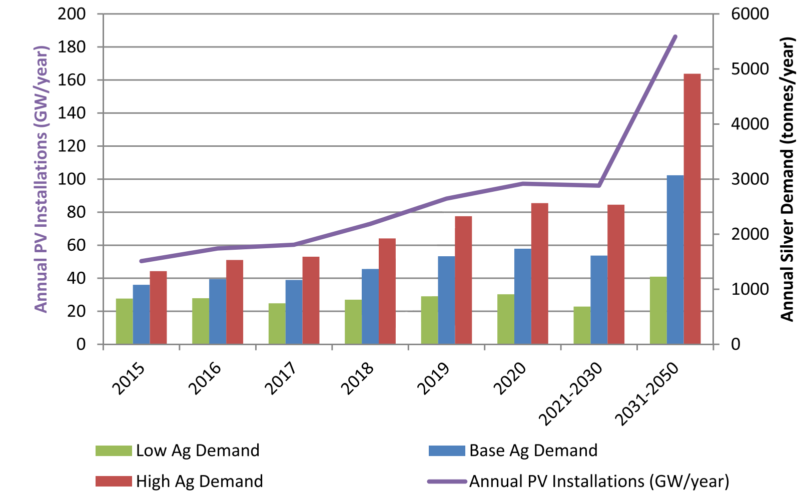

Figure 3. Annual PV installations and silver use in PV cells derived from industry analyst reports (2015–2020) and IEA projections of solar PV generation capacity (2021–2050). The estimates assume that 90% of global PV module production is c-Si modules.

> "Silver paste usage per cell is projected to fall from 130mg per cell in 2014 to 40mg per cell in 2025."

To account for the current and potential future reductions in silver material intensity, three future scenarios have been developed and are presented in Fig. 2. The low material intensity case in Fig. 2 is derived from the 2015 ITRPV projections of silver paste required per c-Si cell, and shows the material intensity declining from 16.5 tonnes per GW in 2015 to 6.6 tonnes per GW in 2025. The high material intensity case assumes that silver material intensity makes no progress from 2015, staying constant

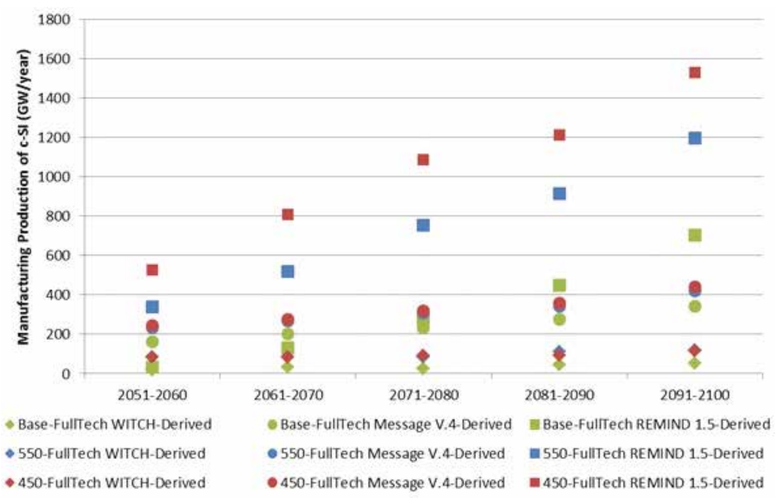

Figure 4. Global c-Si manufacturing (GW/year). All scenarios are derived from models reviewed in the Fifth Assessment Report of Working Group III of the IPCC. *Base*, *550* and *450* refer to no climate policies and policies enacted to limit greenhouse gas concentrations to 550ppm CO_2 and 450ppm CO_2 respectively. *FullTech* means that all technologies are available, and it contrasts with other cases (not shown here) which limit certain technologies.

Figure 5. Scenarios of average annual silver usage in PV cells, derived from projections of solar electricity generation.

at 26.4 tonnes per GW (see Table 1). The base material intensity case is the average of the low and high cases.

Using the three silver material intensity cases in Fig. 2, and the projections of solar PV deployment from various industry analysts and the IEA, three scenarios of silver demand for c-Si PV cells have been constructed: low demand, base demand and high demand (Fig. 3). The industry analyst projections are the median of forecasts made in 2015 by Bloomberg, Cowen and Company, Deutsche Bank, GTM and Navigant Consulting. In the base demand scenario, annual silver demand increases from 1,080 tonnes in 2015 to 1,736 tonnes in 2020, as annual global c-Si PV installations increase from 50 to 97GW but silver material intensity falls from 21.4 to 17.9 tonnes/GW. On the basis of IEA projections of cumulative installed solar electricity generation capacity [18], the silver demand averages 1,611 tonnes/year from 2021 to 2030 in the base demand scenario, as c-Si PV installations average 96GW/year. From 2031 to 2050, on the basis of IEA projections c-Si PV installations could average 186GW/year, which would correspond to an average silver use of 3,071 tonnes/year in the base demand scenario.

The IEA projections do not extend past 2050. For the years beyond 2050, solar electricity generation scenarios from the Fifth Assessment Report (AR5) of Working Group III of the IPCC are used to derive estimates of future silver use through 2100. The AR5 reviewed over a thousand different scenarios from 31 integrated assessment models (IAMs), which incorporate scientific and economic dimensions of climate change to evaluate its impact and the effects of various policies. Moss et al. [19] provide a comprehensive discussion of these models. Fig. 4 presents scenarios of c-Si manufacturing (GW/year) based on three scenarios (referred to as *Base-FullTech*, *550-FullTech* and *450-FullTech*) from three of the models (called *WITCH*, *Message V.4* and *REMIND 1.5*) that were reviewed in the AR5 and illustrate the range of potential silver demand by the PV sector. Details of these scenarios and the models can be found in Weyant et al. [20].

These scenarios do not detail how much solar electricity comes from PV versus concentrated solar power (CSP) technologies. In the IPCC-reviewed IAMs, the projected share of solar electricity generation from PV and CSP applications is initially split 90/10 and gradually changes to 60/40 by 2100 [21]. In estimating silver use in c-Si PV modules, it is assumed that PV constitutes 90% of solar electricity generation during the period 2021 to 2030, and that this share falls by 5% per decade until 2090, when it then remains at 60% in accordance with models reviewed by the IPCC. Of the total estimated PV module electrical generation capacity, 90% is assumed to come from c-Si modules, with the remaining 10% coming from thin-films. Fig. 5 shows scenarios of silver usage from 2050 to 2100, which are derived from the projections of annual installed solar electricity generation capacity in Fig. 4.

There is a wide range of potential silver use across different scenarios and models. From 2051 to 2060, the average annual silver use ranges from 274 to 8,670 tonnes; for comparison, the global silver use in PV was 1,950 tonnes in 2014 [2]. From 2091 to 2100, the average annual silver use ranges from 886 to 25,210 tonnes, where the latter figure represents more than 80% of the total global silver mine production in 2014 of 31,007 tonnes.

The scenarios in Fig. 5 demonstrate

Cell Processing

Zero-profit condition	Quantity variable	Complementarity
$MC_S(S) = (S/A_S)^{1/\varepsilon_S} \geq P$	$S \geq 0$	$MC(S) \times S = 0$
$MC_R(R) = (R/A_R)^{1/\varepsilon_R} \geq P$	$R \geq 0$	$MC(R) \times R = 0$
Market clearance condition	**Price variable**	**Complementarity**
$D(P) \geq R + S$	$P \geq 0$	$D(P) \times P = 0$

Notes:

1. $MC_S(S)$ and $MC_R(R)$ denote the marginal cost of primary and old scrap silver supply respectively.

2. The zero-profit conditions can be derived by solving P in Equations 1 and 2, then setting price equal to marginal cost. Alternatively, one can derive the zero-profit conditions from a producer profit maximization problem with a Cobb-Douglas production function.

3. This table is based on the concise and intuitive 'Energy Supply Model' in Böhringer and Löschel [25].

Table 2. MCP formulation of silver market equilibrium conditions.

Data input/parameter	Value	Source
2014 average price [$/tonne]	614,079	World Bank (2015)
2014 fabrication demand [tonnes]	26,914	CPM (2015)
2014 primary supply [tonnes]	31,007	CPM (2015)
2014 old scrap supply [tonnes]	6,687	CPM (2015)
2014 net investment demand [tonnes][a]	10,780	Calculation
Price elasticity of primary supply (ε_S)	0.342	Table 4
Price elasticity of old scrap supply (ε_R)	0.343	Table 4
Price elasticity of industrial demand (ε_D)	−0.453	Table 4

[a] Net Investment is calculated as the difference between total supply and fabrication demand.

Table 3. Silver market simulation model inputs.

$$\mathrm{Ln}S_{it} = \beta^{s}_{\mathrm{Ag}}\mathrm{Ln}AgP_t + \beta^{s}_{\mathrm{Cu}}\mathrm{Ln}CuP_t + \beta^{s}_{\mathrm{Pb}}\mathrm{Ln}PbP_t + \beta^{s}_{\mathrm{Zn}}\mathrm{Ln}ZnP_t + \lambda^{s}_{i} + \varepsilon^{s}_{it} \quad (4)$$

$$\mathrm{Ln}R_{it} = \beta^{R}_{\mathrm{Ag}}\mathrm{Ln}AgP_t + \lambda^{R}_{i} + \varepsilon^{R}_{it} \quad (5)$$

$$\mathrm{Ln}D_{it} = \beta^{D}_{\mathrm{Ag}}\mathrm{Ln}AgP_t + \gamma\mathrm{Ln}GDP_{it} + \lambda^{D}_{i} + \varepsilon^{D}_{it} \quad (6)$$

where

LnS_{it} is the natural log of primary supply for country i in year t

LnR_{it} is the natural log of old scrap supply for country i in year t

LnD_{it} is the natural log of demand for country i in year t

LnAgP_t, LnCuP_t, LnPbP_t and LnZnP_t are the natural logs of Ag, Cu, Pb and Zn prices in year t

LnGDP_{it} is the natural log of GDP for country i in year t

λ_i is the time-invariant or fixed effect for country i

ε_{it} is the idiosyncratic error for country i in year t

Equations 4, 5 and 6.

that, while there is much uncertainty about the levels of silver use in PV modules, there are several scenarios in which future use is substantially higher than current use. If such high levels of demand for silver were to occur, it is unclear how the silver market would respond and how overall global silver prices would be impacted. The remainder of this paper explores how such increases in demand from the PV sector might affect silver prices and, in turn, the cost of using silver in PV module manufacturing.

Method

To determine how a rise in silver demand from PV module manufacturing could affect future silver prices, a partial equilibrium model of the global silver market is developed, and different scenarios of silver demand are simulated. The partial equilibrium model for the silver market and the model inputs are described first.

Model of the silver market

The partial equilibrium model assumes that the silver market is perfectly competitive; that is, producers and consumers are price takers and no single agent is able to influence the market price. This assumption is reasonable, given the large number of silver end users and old scrap suppliers and the relatively low Herfindahl-Hirschman Index score of 700–800 for global company-level silver mine production [22]. The Herfindahl-Hirschman Index is a measure of market concentration, ranging between zero and 10,000; a score below 1,500 generally implies the market supply is not concentrated.

To construct the partial equilibrium model, its dimensions are established first: one market (global silver market), one commodity (silver), one representative supplier of primary silver, one representative supplier of old scrap silver and one representative consumer of silver.

Second, the functional forms for primary supply, old scrap supply and silver demand are constant elasticity, as described by Equations 1–3:

$$S(P) = A_S P^{\varepsilon_S} \quad (1)$$

$$R(P) = A_R P^{\varepsilon_R} \quad (2)$$

$$D(P) = A_D P^{\varepsilon_D} \quad (3)$$

The primary silver supply (S), shown in Equation 1, is a function of the price of silver (P), and ε_S is the own-price elasticity of primary silver supply. Note that the price elasticity of supply is defined as the ratio of the percentage change in quantity supplied and the percentage change in price. Old scrap silver supply (R) is also a function of the price of silver, and ε_R denotes the own-price elasticity of old scrap silver supply. Silver demand (D) is shown in Equation 3, where the parameter ε_D is the price elasticity of silver demand. The price elasticity parameters in Equations 1–3 are estimated through the regression analysis described in the next section ('Regression estimation'). The method for determining the values of the coefficients A_S, A_R and A_D is also discussed.

Third, the standard market supply and demand equilibrium conditions are expressed in Table 2 as a mixed complementarity problem (MCP), which is commonly used in partial equilibrium modelling (see Lanz, Rutherford and Tilton [23] and Zhuang and Gabriel [24] for examples). The zero-profit conditions, where $MC_S(S)$ and $MC_R(R)$ denote the marginal cost of silver produced from primary and old scrap respectively, ensure that if supply is strictly positive, then marginal cost equals price. The market clearance condition requires that if the price of silver is strictly positive, then market demand equals market supply. A solution to the MCP satisfies all equilibrium conditions in Table 2.

Fourth, the model is calibrated using 2014 data for silver supply, demand and price, as well as estimates of the elasticity parameters. In calibrating the model, the values for the coefficients A_S, A_R and A_D are chosen so that supply, demand and price outputs are consistent with baseline quantities, which are the actual levels of silver supply, demand and price observed in 2014. The price elasticity parameters ε_S, ε_R and ε_D are estimated through the regression analysis.

Table 3 presents the data inputs used in the silver market simulation model. The levels of global silver primary supply, old scrap supply and fabrication demand in 2014 are sourced from the CPM Group 2015 Silver Yearbook [2], and the average silver price during 2014 is taken from the World Bank Global Economic Monitor database [26]. The level of net investment demand is calculated as the difference between total silver supply and fabrication demand; this represents the net addition or withdrawal of silver from inventories. While investment demand has become a larger share of total silver demand in recent years, the development of a comprehensive model that incorporates the behaviour of silver investment demand and inventories is outside the scope of this analysis.

With the model calibrated and the baseline values for 2014 replicated, the impacts of various scenarios of silver demand from the PV sector are estimated. Given the wide range of potential future silver demand from the PV sector (see Figs. 3 and 5), PV module production ranging from 100GW/year to 500GW/year is considered. This range falls within the levels of future c-Si production projected in Figs. 3 and 4, which are derived from scenarios of solar electricity generation estimated by the IEA, industry analysts and models that were reviewed in the Fifth Assessment Report of Working Group III of the IPCC. The market is allowed to reach an initial equilibrium based on 2014 levels of supply, demand and price. New demand for silver from the PV module sector is then introduced using a new assumed level of PV module production (e.g. 100GW/year) and the estimates of material intensity of silver in c-Si PV modules (see Table 1).

Regression estimation

The price elasticity parameters of silver supply and demand required in the simulation analysis are estimated using a seemingly unrelated regression (SUR) model with annual country-level data. The SUR model – as opposed to equation-by-equation ordinary least squares (OLS) – is applied, because it will yield more efficient estimates when error correlations exist between equations. The model consists of equations for primary supply, old scrap supply and fabrication demand, as described by equations 4–6. Consistent with the conditions of a perfectly competitive market, each country is considered a price-taker on both the supply and demand sides, so that no country is able to influence silver market prices.

In Equation 4, the dependent variable is primary silver supply, and the independent variables are the logged prices of silver (Ag), copper (Cu), lead (Pb) and zinc (Zn). The world prices (in real terms) for copper, lead and zinc are included in the primary supply regression, because silver is often mined as a co-product with these minerals; thus, changes in the prices of these minerals may influence the level of silver supply. According to the 2014 World Silver Survey [27], 29% of primary silver supply was mined as the main product; 58% was mined along with copper, lead or zinc; and the remaining 13% was mined as a co-product of gold. In general, metal prices tend to move together; over the sample period, the price of silver is correlated with the prices of gold, copper and lead. For this reason, and because the supply of silver as a co-product of gold represents the smallest share of total primary silver supply, the price of gold is excluded from Equation 4. To account for time-invariant differences in primary silver supply across countries, country-level dummy variables are included in Equation 4. The primary coefficient of interest is β^S_{Ag}, the own-price elasticity of silver primary supply, and is expected to be positive.

Equation 5 has old scrap silver supply as the dependent variable, and the price of silver and country dummy variables as the regressors. The coefficient of interest is β^R_{Ag}, which is the own-price elasticity of old scrap silver supply, and is expected to be positive. In Equation 6, silver fabrication demand is the dependent variable; the logged price of silver, the logged country-level gross domestic product (GDP) and the country dummy variables are the regressors. GDP is included as a regressor because demand for silver is expected to increase with income. The coefficient of interest in Equation 6 is β^D_{Ag}, which is the own-price elasticity of silver demand, and is expected to be negative.

Regressor	Equation: Primary supply	Old scrap	Demand
Ln*AgP*	0.342*	0.343**	–0.453**
	(0.156)	(0.057)	(0.036)
Ln*CuP*	0.197		
	(0.263)		
Ln*PbP*	–0.310		
	(0.231)		
Ln*ZnP*	–0.192		
	(0.174)		
Ln*GDP*			1.241**
			(0.078)
Observations	189	189	189

Notes:

1. * and ** denote significance levels of 5% and 1% respectively. Standard errors are shown in parentheses.
2. Ln*AgP* = log of silver price, Ln*CuP* = log of copper price, Ln*PbP* = log of lead price, Ln*ZnP* = log of zinc price, Ln*GDP* = log of actual GDP.
3. Equations include dummy variables for each country. Ten countries are included in the sample (Australia, Brazil, Canada, China, India, Italy, Japan, Mexico, Thailand and the USA).

Table 4. Regression results for silver supply and demand equations.

Data for the annual quantities of silver primary supply and old scrap supply by country for 1994 to 2013 are sourced from the Silver Institute's world silver surveys [27]. The annual fabrication demand for silver is taken from the CPM Group's 2015 Silver Yearbook [2], and data for the actual country-level GDPs and the annual average world metal prices (in real terms) are sourced from the World Bank World Development Indicators and Global Economic Monitor databases.

Table 4 shows the estimation results for the SUR model in Equations 4–6: these results are consistent with expectations of the response of silver supply and demand to silver price changes. The first and second equations show that the responses of primary and old scrap supply to changes in silver prices are positive and significantly different from zero, with significance levels of 5% and 1% respectively. The coefficient for the logged silver price variable in the fabrication demand equation is negative and is statistically different from zero at the 1% significance level.

> "The responses of primary and old scrap supply to changes in silver prices are positive and significantly different from zero."

On the basis of the parameter estimates in Table 4, the own-price elasticity values for primary supply, old scrap supply and demand are estimated to be 0.342, 0.343 and –0.453 respectively. These estimates imply that both short-run elasticity of silver supply and short-run elasticity of demand are inelastic, which is consistent with the views of silver market experts [28,29,16]. Few studies have attempted to estimate silver supply and demand elasticities for comparison. Åstrom [30] offers estimates of US silver supply and demand elasticities of 0.179 and –0.105, while Evans and Lewis [31] estimate world silver demand price elasticity at –0.856. Given the uncertainty about the price elasticity estimates, a sensitivity analysis of the results is performed in the next section, to allow for a range of price elasticity values.

Results

Because of the wide range of potential future silver use scenarios shown in Figs. 3 and 5, the results of the simulation analysis are presented in Fig. 6 for an annual c-Si PV module production ranging from 100GW to 500GW. In the 2014 baseline, an estimated 1,950 tonnes of silver were used by the PV module sector [2]. Total silver use in other industries was 35,744 tonnes, which was a combination of fabrication demand (24,964 tonnes) and net investment demand (10,780 tonnes). The price of

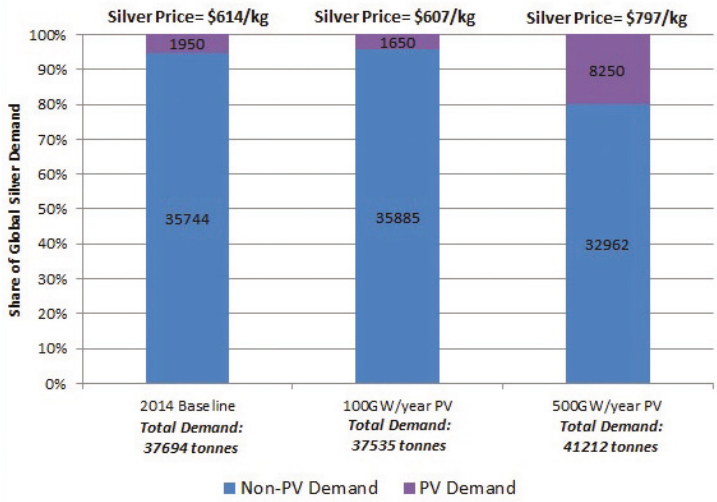

Figure 6. Effects of 100GW/year and 500GW/year c-Si PV module production on the silver market.

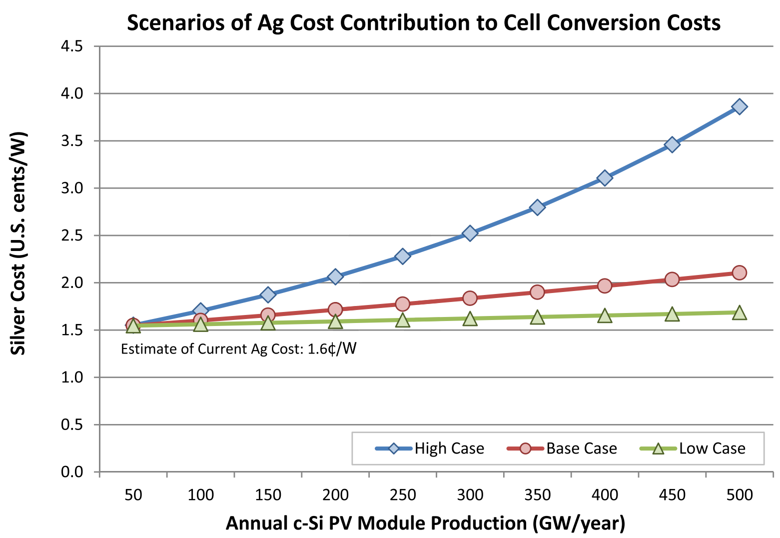

Figure 7. Simulation results for the effects of increased c-Si PV module production on silver costs as a result of increased demand. The high case assumes no reductions in silver intensity from 2015 (26.4 tonnes per GW), and the low case assumes gradual reductions according to the ITRPV projections (down to 6.4 tonnes per GW by 2025). The differences in material intensity affect projected supply and demand (and therefore pricing) scenarios.

silver averaged $614/kg in 2014.

With 100GW/year of c-Si PV module production, the price of silver is actually predicted to decline slightly, despite the rise in PV production, because the material intensity is projected to be lower than in the 2014 baseline. This reflects the fact that, while there may be growth in c-Si PV production, reductions in material intensity could mitigate growth in demand for silver by the PV sector.

The scenario of 500GW/year c-Si PV module production has a noticeable effect on the silver market: the price of silver increases to $797/kg as demand from the PV sector rises by 6,300 tonnes from the 2014 baseline. To accommodate this new demand, total silver supply increases by 3,518 tonnes and non-PV fabrication demand declines by 2,781 tonnes.

The major determinant of how increased demand from the PV module sector could affect future silver prices is the response of supply and demand to a change in price (i.e. the own-price elasticities of silver supply and demand). For example, if silver supply could easily expand to meet greater demand from PV module manufacturing, the impact on price could be modest. Similarly, if other end uses of silver (e.g. electronics, jewellery) substitute another material for silver, then greater demand from the PV sector may have a limited effect on silver prices. Alternatively, if it is difficult for silver supply to ramp up to meet the increased demand, and if non-PV end uses of silver do not replace the silver with something else, prices could significantly increase.

To demonstrate how different supply and demand price elasticity estimates have an effect on the results, the simulation results are presented for different elasticity estimates in Fig. 7. The high case uses estimates of 0.09, 0.25 and −0.39 for primary supply, old scrap supply and demand price elasticities respectively. The low case uses the estimates of 0.60, 0.44 and −0.51 for primary supply, old scrap supply and demand price elasticities respectively. These values correspond to the bounds of the 90% confidence interval for the own-price elasticity estimates in Table 4.

Fig. 7 shows annual c-Si PV module production and the corresponding silver cost contributions for the high, low and base cases. The high case represents silver costs when silver material intensity is relatively high (using the high material intensity case of 26.4 tonnes per GW in Fig. 2), and when silver supply and silver demand from non-PV end uses are relatively unresponsive to changes in silver prices. The low case in Fig. 7 shows silver costs when silver material intensity is relatively low (using the 6.6 tonnes per GW for the low material intensity case in Fig. 2) and when both silver supply and silver demand from non-PV end uses are relatively responsive to changes in silver prices. The base case presents silver costs when the base material intensity estimate of 16.5 tonnes per GW from Fig. 2 is used, along with the point estimates for price elasticities from Table 4 (i.e. the base case price elasticity estimates).

In the base case, for example, Fig. 7 shows that 250GW/year of c-Si production leads to a silver cost contribution of about 1.77¢/W. In the low and high cases, 250GW/year of c-Si production leads to silver costs of 1.61¢/W and 2.28¢/W respectively.

For comparison, at approximately 50GW of annual module production, the silver cost contribution of screen printing to total cost-of-ownership is currently estimated to be around 1.56¢/W; this figure is based upon the average 2014 silver price of $614/kg

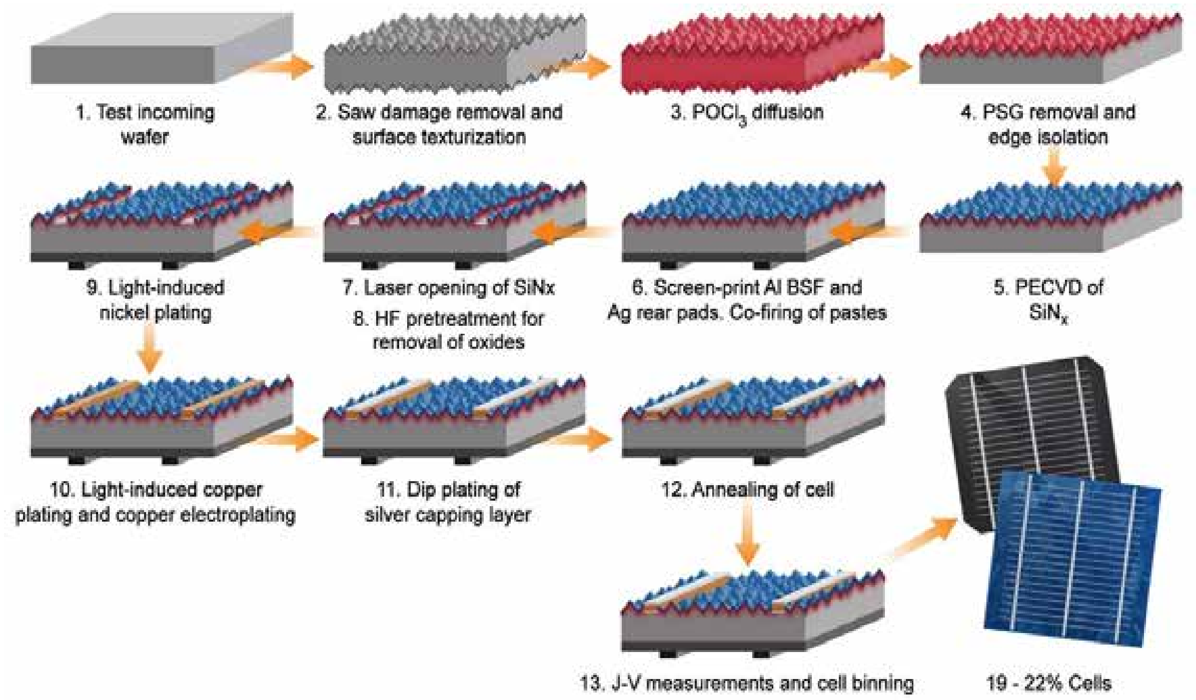

Figure 8. Process flow for fabricating a typical c-Si solar cell by electroplating.

and the usage rates detailed in Table 1. The current c-Si cell manufacturing costs under the standard screen-printing process are estimated to be around 35¢/W (see Fig. 9).

Comparison with Ni–Cu electroplating

One alternative metallization approach to screen printing is electroplating. The simplest and most widely discussed application of this process, for the short term at least, is front-side metallization, which is illustrated in Fig. 8. Here, a copper grid is deposited on top of a nickel seed layer that is formed by light-induced plating. In high-throughput production (of the order of thousands of wafers per hour per tool), the grid patterns can be defined through the use of lasers. The resulting SiN_x:H anti-reflection layer openings provide the appropriate channels for nickel deposition.

Primarily to inhibit oxidation, a very thin silver-capping layer is additionally applied on top of the copper. The silver requirement for this capping layer is around 8.0mg per cell, substantially less than the estimates of Table 1 (between 95 and 105 net mg per cell). To provide a counter electrode for the front-side electroplating process, the back-side aluminium and silver pastes can be printed and co-fired as usual.

There are several potential advantages of the electroplating process over screen printing. If done correctly, electroplating may allow higher aspect ratio gridlines, which can lead to improved cell efficiencies by reducing the amount of front-side shading by metals. Furthermore, there is the ability to contact higher-ohmic emitters formed within the underlying silicon, and solid copper is more conductive than silver paste after the co-firing process. These factors translate to lower emitter recombination and I^2R losses within the solar cell. In total, the efficiency benefit of electroplating over screen printing may be of the order of 0.5% [32].

The electroplating process nevertheless has its drawbacks. There is more cell breakage, and there are additional chemical handling and waste considerations (and therefore costs) associated with handling the electroplating electrolytes. Moreover, the capital expenditures and maintenance costs for electroplating equipment are higher than for screen printing. Electroplating also requires pinhole-free silicon nitride layers; without them, copper will be deposited within the pinholes, and the solar cell efficiency will drop precipitously, as a result of light being blocked and also because of electrical shunts.

By limiting the amount of silver required to just the back-side pads and the capping layer, a transition to front-side electroplating reduces the total amount of silver per cell from 120–140mg to 30–40mg. This reduction in silver usage would lower the material intensity from today's 21–33 tonnes per GW to 5–10 tonnes per GW. With certain solar cell architectures it is also possible to employ electroplating in such a way that the silver intensity is 0mg per cell; at least two large-scale cell manufacturers already have proprietary processes that employ such techniques.

Fig. 9 compares the manufacturing costs of standard screen-printed cells and electroplated cells at current silver prices. The figure is assembled from cost-of-ownership estimates provided by relevant equipment and materials suppliers. In comparison to the base case, the total direct metallization materials costs are lower for electroplating than for screen printing (0.5–1.5¢/W savings, including the expense of regular replacement of screens for printing). However, the use of electroplating equipment rather than screen printers requires an

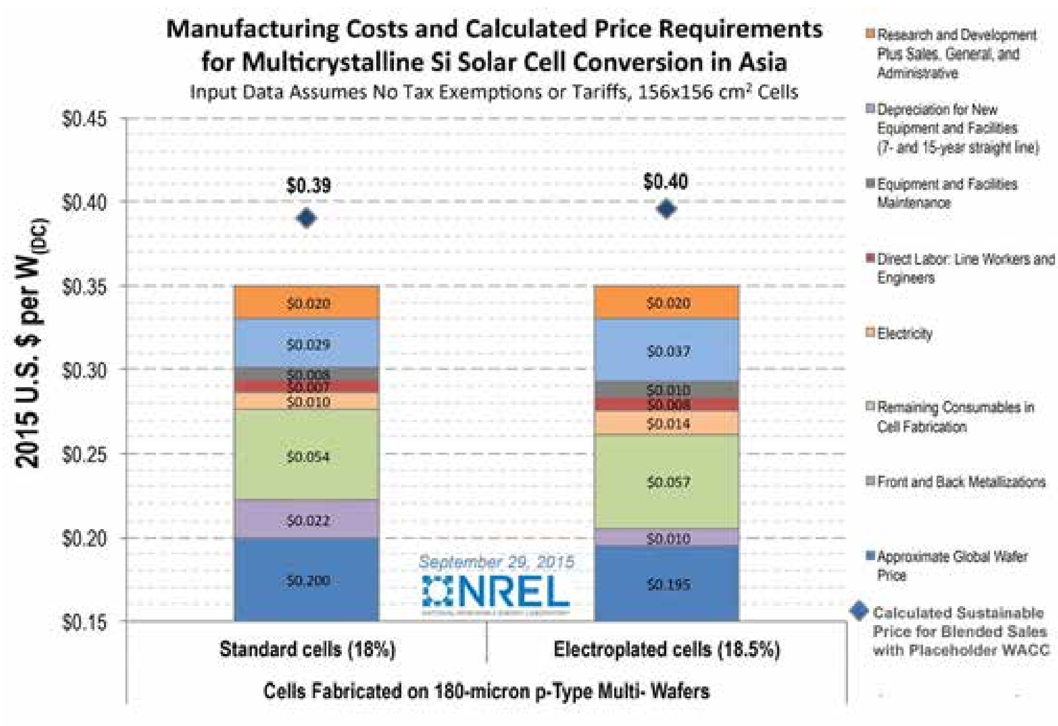

Figure 9. Comparison of manufacturing costs for standard and electroplated cells, based upon cost-of-ownership estimates provided by relevant industry players. The numbers beneath each bar correspond to the assumed cell efficiencies.

initially higher capital expenditure as well as greater maintenance costs. In total, from cost-of-ownership estimates these additional expenses are of the order of 1.0¢/W. Electroplating also entails higher waste water handling costs (0.1–0.3¢/W) than screen printing, and there are slightly higher yield losses (translatable to around 0.1¢/W estimated cost penalty). Utilizing more equipment in the electroplating case also carries with it greater electricity needs (with higher associated costs calculated to be 0.4–0.8¢/W).

Conclusion

Silver has long been considered the 'Achilles heel' of megascale c-Si manufacturing. While the PV sector currently represents a small share of global silver demand, at slightly less than 10% of the total, if c-Si solar cell production continues to grow, the PV industry could become a significant end user of silver. The impact on total silver demand and prices could have relevance for the cost competitiveness of traditional silver screen-printed cells vs. electroplated cells, as well as for developing concepts such as multiwire, stencil printing and inkjet printing.

In this paper the effects of a greater silver demand from the PV industry on silver prices was investigated, as well as the resultant effects on manufacturing costs. For the low to high scenarios, the analysis results indicate a 0.05–0.7¢/W impact on cell manufacturing costs when production is expanded from 55GW to 250GW, depending on the material requirements for metallization. Initial indications are that the cost competiveness of electroplating may be approaching that of traditional screen printing at current silver prices.

> "Initial indications are that the cost competiveness of electroplating may be approaching that of traditional screen printing at current silver prices."

Moreover, from NREL's cost models, an additional efficiency benefit of 0.5–1.0%$_{abs}$ (if enabled by a process such as electroplating) would correspond to savings of roughly 0.5–1.2¢/W and 4.0–7.8¢/W at the module level and the utility-scale balance-of-systems level respectively. On a levelised cost of electricity (LCOE) basis, this would correspond to approximately 0.20–0.36¢/kWh for a moderate solar resource in the USA [33].

From a total life cycle economics perspective, however, an important issue is whether the long-term outdoor reliability (and notably the metal adhesion) of electroplated cells is in general equal to that of screen-printed cells. All of these questions will influence whether, and by how much, the demand for silver may or may not concurrently grow with the PV industry.

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