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Assessing tin demand and supply pressures under terawatt-scale photovoltaic deployment

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Terawatt-scale photovoltaic (PV) deployment will materially increase demand for solder, for which tin is the primary constituent. We quantify potential tin demand to 2050 by combining historical global refined-tin production/consumption (1999–2024) with trend-based machine-learning (ML) forecasts and exogenous PV deployment scenarios. The analysis uses an accounting approach in which the ML forecasts form a trend-continuation baseline (BAU) and PV demand is overlaid to explore conditional supply risks. Under BAU, refined production grows slowly while consumption stabilises; when realistic PV trajectories and replacement demands are added, several scenarios generate substantial and persistent gaps between refined tin demand and plausible BAU supply paths. Sensitivity analysis shows that raising the Recycling Input Rate (RIR) materially reduces the shortfall, while reductions in tin intensity and diversification of supply also mitigate risk. Recent declines in refined output reflect supply disruptions and a post-2020 slowdown in consumption; available data do not indicate a clear global decline in tin ore grades. Policy measures combining increased recycling, reduced tin intensity, and targeted supply diversification are therefore the most effective near-term responses to reduce vulnerability.

Sustainability spotlight

Terawatt-scale photovoltaic deployment will significantly increase demand for tin, a critical material widely used in PV interconnections. This study highlights potential long-term supply constraints and underscores the importance of recycling, material substitution, and investment in future tin supply to support a sustainable energy transition.

1. Introduction

In recent years, global photovoltaic (PV) capacity has expanded rapidly reaching approximately 2.2 TW by 2024, yet current deployment remains well below the levels required to meet climate targets such as limiting warming to ~1.5 °C. To be consistent with these targets, PV deployment must accelerate both in annual installation rates and cumulative scale throughout the coming decades.[1,2] While tin is not currently classified as a Critical Raw Material by the European Union, it is identified as a critical mineral in other jurisdictions, including the United States and the United Kingdom, reflecting growing concerns over its supply security in the context of emerging technologies.

Several studies have projected the scale of PV installations needed to support the climate target. For example, Goldschmidt *et al.* estimate that the world will require around 20–80 TW of cumulative PV installations by 2050,[3] while Verlinden (2023) argues that PV installations should reach approximately 70 TW by 2050.[4] Assuming a 25 year PV module lifetime, Haegel *et al.* report that current annual global PV installations must increase from about 1 TW to around 3.4 TW by 2037 and then be sustained at that level until 2050, reaching a cumulative 75 TW by 2050 to remain compatible with climate targets.[5,6] In comparison, Breyer *et al.* suggest a somewhat lower cumulative requirement of around 63 TW by 2050.[7] Incorporating performance degradation further amplifies these requirements: assuming 0.7% annual degradation and a 30 year lifetime, Leung *et al.* estimate that achieving 75 TW of installed PV capacity by 2050 would require annual installations of 4.58 TW per year, increasing to 6.99 TW per year if the module lifetime is shortened to 16 years.[8] Table 1 highlights projected PV installation capacity by different studies.

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Table 1 Projected PV installation capacity by different studies[2]

	PV installation capacity (TW)			
Year	Bloomberg New Energy Finance (BNEF)	International Technology Roadmap for Photovoltaic (ITRPV)	PV Cell Tech	Chinese PV Association
2023			0.43	0.27
2024			0.51	0.29
2025	0.45	0.48	0.63	0.3
2026			0.76	
2027			0.87	0.37
2028			1	
2029			1.15	
2030	0.433	1.34	1.27	0.42
2035	0.78	1.62		
2040	0.84	2.5		
2045	0.763	2.76		
2050	1.15	4.45		

As the world increasingly turns to solar energy, such terawatt-scale PV deployment trajectories make it imperative to understand future material demand to identify critical materials and develop strategies for sustainable resource management and resilient supply chains.[9] Numerous studies have quantified the future material demand for PV under various deployment scenarios. For instance, the demand for glass and antimony at terawatt scale has been examined in ref. 10 and 11, while future requirements for aluminium, silver, indium, and other raw materials have been explored in ref. 12–15. Several regional and country-specific assessments have also examined PV-related material demand and supply-chain constraints in key markets such as the European Union (EU), the United States of America (USA) and China.[16–18] However, these studies focus on specific regions and policy contexts and generally cover limited timeframes.

Most prior work on PV material demand focuses on region-specific or short-term policy questions and, despite their value, generally neglects the long-term demand–supply dynamics of tin. Tin is the primary component of solder alloys used for cell interconnection and module stringing in crystalline–silicon modules; solder manufacturing therefore scales with cumulative PV capacity and module replacement cycles. Tin demand in PV is also mediated by regulation (*e.g.* RoHS exemptions for PV), competition from non-PV sectors, geographic concentration of mining, geopolitical risks, and modest end-of-life recycling rates. Given these factors, terawatt-scale PV deployment could materially increase pressure on tin supply, with implications for price volatility and supply security. Yet, despite its strategic role, there is a paucity of systematic long-term assessments of tin under high-growth PV scenarios. This paper addresses that gap by using historical refined-tin data to construct trend-based baselines and by overlaying external PV trajectories to evaluate supply adequacy, reserve sensitivity, and the potential contribution of recycling—aiming to inform policy rather than to produce a fully endogenous market forecast.

2. Methods and data

2.1. Data sources

The data used in this analysis comprise global refined tin production and consumption, as well as historical data on global tin reserves and mine production. Historical data on global tin reserves and mine production were collected from the United States Geological Survey (USGS),[19] while refined tin production and consumption data were collected from [20] (Fig. 1). Tin is consumed across a range of applications, including solder, tinplate, alloys, and tin chemicals; however, these downstream uses are normally recorded at the refined-metal stage in global statistics. We therefore track tin flows at the refined metal, which allows direct comparison between historical production, consumption, and future projections while avoiding uncertainties associated with country-level trade flows and semi-fabricated products. The mass balance in this study is formulated using the following equations:

$$\text{Primary refined tin production} = \text{mine production} + \text{ore imports} - \text{ore exports} \tag{1}$$

$$\text{Refined tin production} = \text{primary tin production} + \text{secondary refined tin production} \tag{2}$$

Mass-balance equations define the system boundary and ensure accounting consistency at the global (refined-metal) level. For the global system, ore imports and exports between countries largely cancel out, and we therefore use the world totals of mine production, refined tin production, and refined tin consumption directly as reported in ref. 19 and 20. As a result, the mass-balance equations are not used to impose dynamic constraints on production growth or demand evolution but rather to provide a consistent framework for tracking refined tin flows within the defined system boundary.

Future global refined tin production and baseline consumption are projected independently using a trend-based,

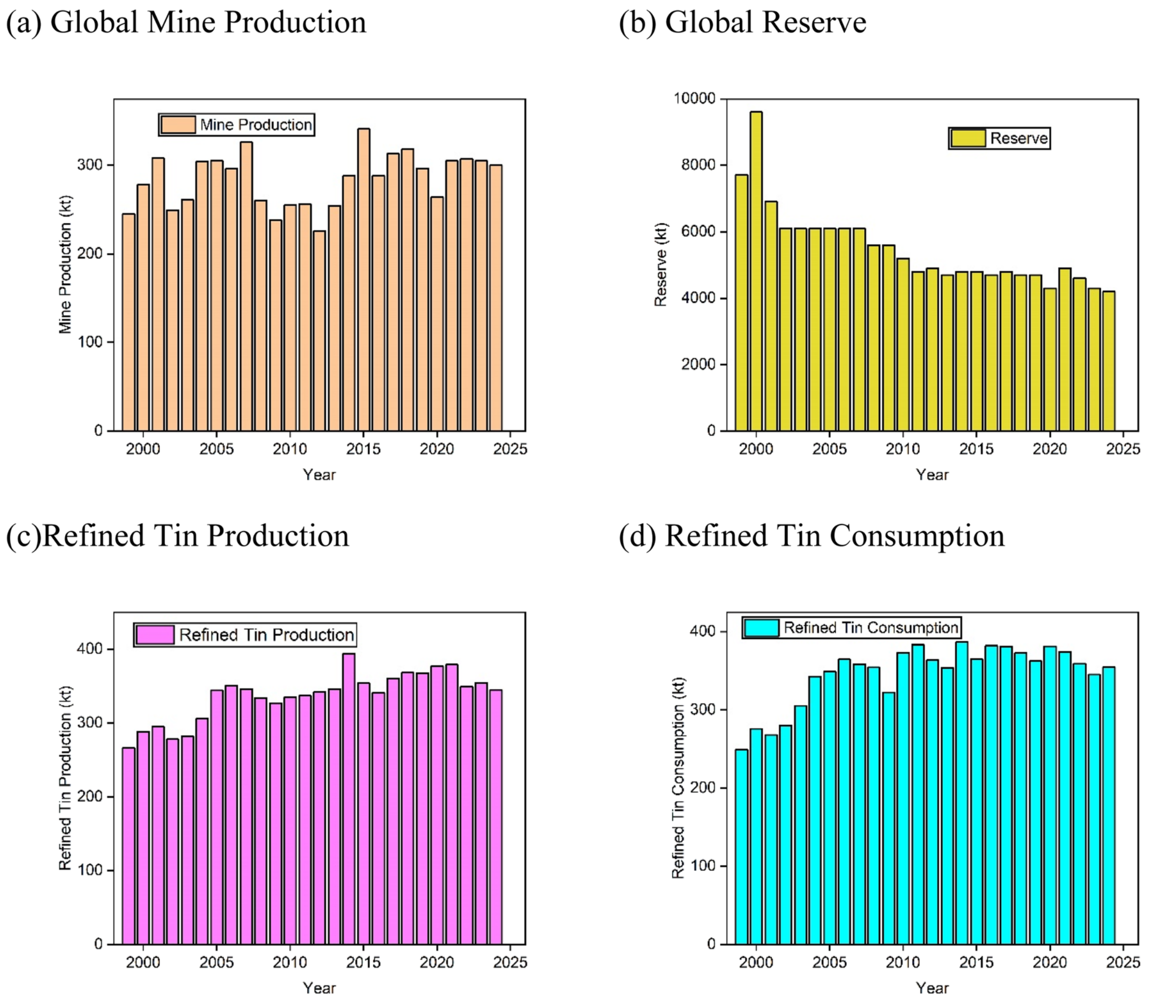

Fig. 1 Historical data from 1999 to 2024 on global tin mine production (a), global reserve (b), refined tin production (c), and refined tin consumption (d). Note: recent declines in refined production and consumption after 2020 reflect supply disruptions and demand slowdown; no ore-grade time series are shown.

machine-learning approach trained on historical data from 1999 to 2024. These projections represent a continuation of historical patterns under the assumption that no major structural changes occur in the tin industry. PV installation data up to 2050 were collected from ref. 6 and 8 (Fig. 2). Given the global requirement for approximately 3.4 TW of PV installations per year (theoretical capacity), the production of PV solder will entail a substantial demand for tin. To estimate future tin demand associated with PV soldering, we first calculated the total PV module mass corresponding to a theoretical annual installation of 3.4 TW. Installed capacity was converted to mass using a mass-to-power ratio of 56.54 t MW^{-1} for PV modules, consistent with ref. 21 and 22. The mass of tin was subsequently estimated by assuming that tin represents approximately 0.1–0.2 wt% of total module mass as metallic Sn.[23,24] The same method was then applied to a capacity pathway that includes a 0.7% annual degradation rate so that the theoretical 3.4 TW per year requirement (without degradation) is adjusted to the actual PV installation capacity and corresponding tin demand. This PV-related demand is not endogenously coupled to the

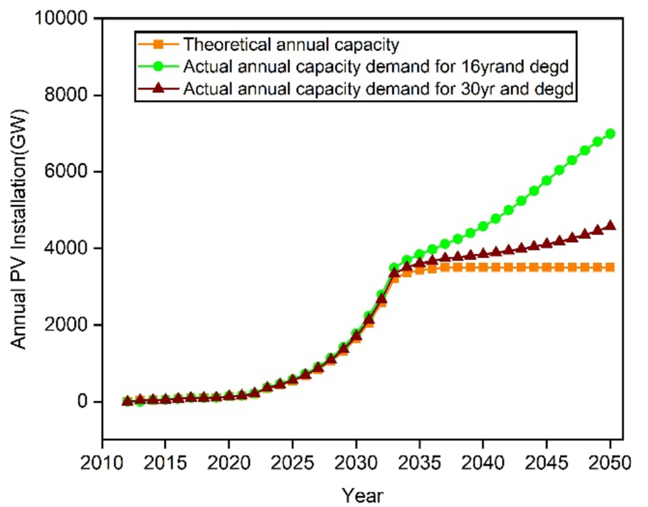

Fig. 2 Global PV installation scenarios from 2010 to 2050 (theoretical and actual demand).

projection model; instead, it is added ex-post to the projected baseline refined tin consumption.

2.2. Machine learning model

Forecasting refined tin consumption and production to 2050 is needed to assess whether rapid solar PV growth could face tin shortages. Tin markets do not follow a smooth linear trend because production and use are influenced by technology shifts, policy changes, economic cycles, and geopolitical disruptions, so more flexible forecasting tools are required.[25] Machine-learning (ML) approaches can better capture such complex, nonlinear dynamics by learning patterns directly from the data. In contrast, standard time-series models such as Auto Regressive Integrated Moving Average (ARIMA) and exponential smoothing are based on relatively stable, linear dynamics over time, which is difficult to justify for tin without strong additional assumptions.[26,27] On the other hand, more complex ML models such as Long Short-Term Memory (LSTM) networks and other deep-learning approaches typically require long, high-frequency datasets, but, with only 26 annual observations for refined tin (1999–2024), these models would be prone to overfitting and would likely produce unreliable long-range forecasts. Therefore, this study applies classical ML models that are appropriate for short, noisy time series. Each time series (refined tin production and refined tin consumption) is converted into a supervised learning problem by creating simple time-based features: a time index and its squared term, three years of lagged values, and short rolling averages. These features capture persistence, short-term smoothing, and gradual change without imposing a rigid functional trend. Two models were tested: Ridge Regression and Gradient Boosting Regression. Ridge Regression is a regularised linear model that helps prevent overfitting and handles correlated lag features well,[28] while Gradient Boosting is an ensemble of small decision trees that can capture non-linear patterns even with modest data.[29] Model selection was based on expanding-window time-series cross-validation, ensuring that each test period occurred after the corresponding training period, and accuracy was evaluated using mean absolute error (MAE). Ridge regression achieved the lowest MAE for both refined production and refined consumption, so it was selected for the final forecasts. Annual values from 2025 to 2050 were then generated using a recursive approach, where each predicted year is fed back in to update the subsequent year's lag and rolling features. Overall, the machine-learning projections presented here represent a baseline continuation of historical refined tin production and consumption trends and are used as a reference against which the potential impacts of externally defined, terawatt-scale PV deployment scenarios are assessed, rather than as a definitive prediction of future tin market outcomes under structural demand shifts.

2.3. Scenario design

These scenarios are constructed through exogenous, accounting-based adjustments to aggregate refined tin projections and are intended to explore alternative demand trajectories under assumed PV deployment pathways, rather than to represent internally consistent, endogenous responses of the global tin system to supply constraints or cross-sector competition. Firstly, a Business-As-Usual (BAU) case was modelled by applying the ML forecasted data on refined tin consumption and production trained on the 1999–2024 dataset. Because the historical dataset does not separate PV from non-PV uses, the BAU scenario assumes that refined tin production and consumption follow historical sectoral trends and maintain the existing balance between PV and non-PV applications, without structural shifts. Secondly, a PV plus non-PV BAU scenario was developed in which PV tin demand is treated separately from the BAU baseline. We first removed the PV related share that is implicitly contained in the BAU forecast, using the current sectoral share of PV applications. To remove the PV share, we use the sectoral consumption of solder and assume that 20% of solder production is attributable to PV ribbon and interconnects, based on industry estimates.[30] Fig. 3 shows the current sectoral application of tin.[30] We then added an exogenous PV tin demand trajectory constructed by combining the global PV installation projections reported by ref. 6 with assumed tin contents of 0.1 wt% and 0.2 wt% by mass in crystalline silicon module solder, where 0.1 wt% is taken from ref. 23 and 0.2 wt% is assumed as a conservative upper bound.[24] The tin–copper category reported in ref. 30 includes applications where tin is used as a coating or alloying element on copper products, such as tin-coated copper conductors. While a minor share of this category may relate to tin-coated PV tabbing wires, broader uses such as PV cabling are not module-specific and cannot be reliably disaggregated. Therefore, these applications are acknowledged qualitatively but excluded from the quantitative scope to avoid overestimation of PV-related tin demand.

Third, the High-Demand Energy-Transition scenario is based on the projections reported by Thunder Said Energy[31] (Fig. 4). In this scenario, the model starts from the current refined tin market and projects demand by end-use sector. Each sector is linked to its main activity drivers, such as annual PV

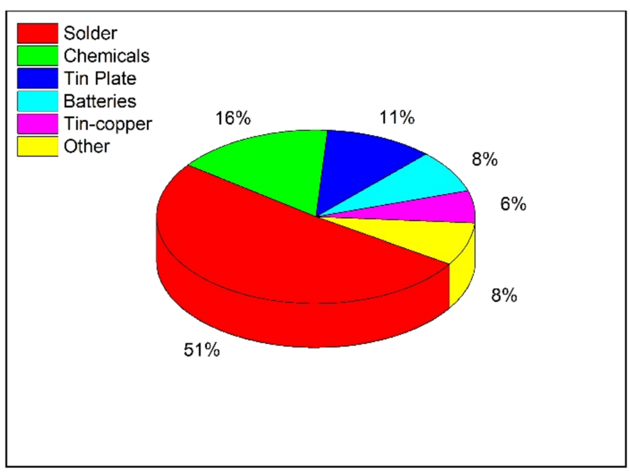

Fig. 3 Tin consumption by sector worldwide in 2023.

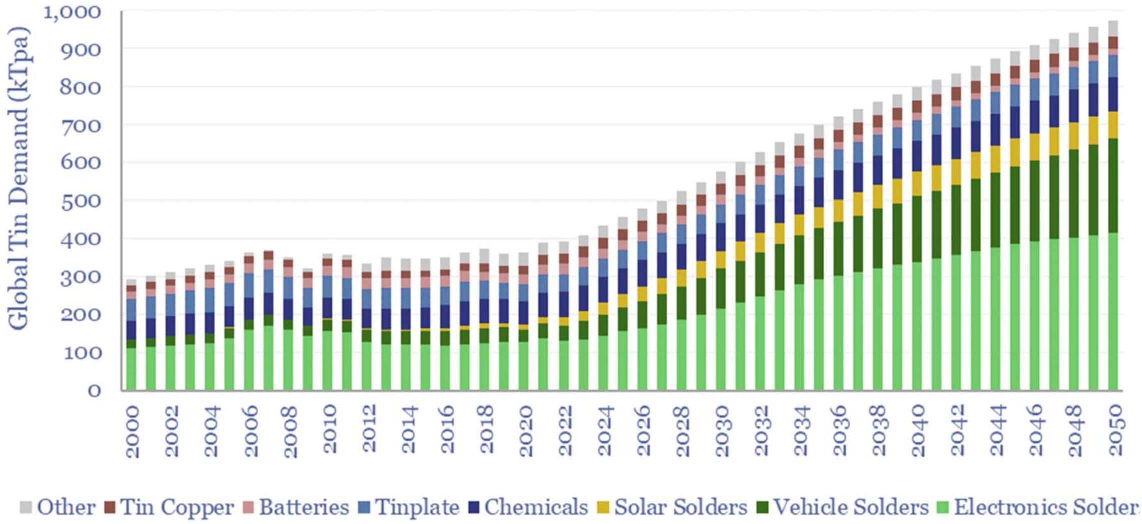

Fig. 4 Global tin demand till 2050 (source,[31] written permission obtained from Thunder Said Energy).

additions, EV sales, production of digital devices and semiconductors, electricity demand, and GDP, using tin intensity factors (for example, grams of tin per kilowatt of PV or kilograms per vehicle). This structure leads to much faster growth in total refined tin demand and to a changing application mix. In this scenario, we keep Thunder Said's non-PV demand pathway, remove the PV share that is embedded in it, and then add a separate PV tin demand trajectory derived from ref. 6.

3. Results and discussions

3.1. Scenario 1: forecasting refined tin production & consumption

Fig. 5 presents the ML results for BAU scenario for refined tin production and consumption till 2050. The objective of this scenario is to show how the tin market is likely to evolve if future conditions continue along the same general path observed over the past 25 years, without assuming any major structural changes. The figure also includes upper and lower confidence bands, labelled "BAU High" and "BAU Low," which represent plausible ranges around the central forecast. Together, these curves indicate how global tin supply and demand could shift under BAU conditions and help reveal whether the global tin market tends toward surplus, balance, or shortfall. In the BAU refined production results (Fig. 5a), the central line shows a steady upward trend in output. This reflects a continuation of long-term historical behaviour in which global refined production increases gradually as new mining projects come online, recycling steadily improves, and existing producers expand capacity in response to prices and market opportunities. The BAU High line sits above the central forecast and represents a case where production grows more strongly, for example,

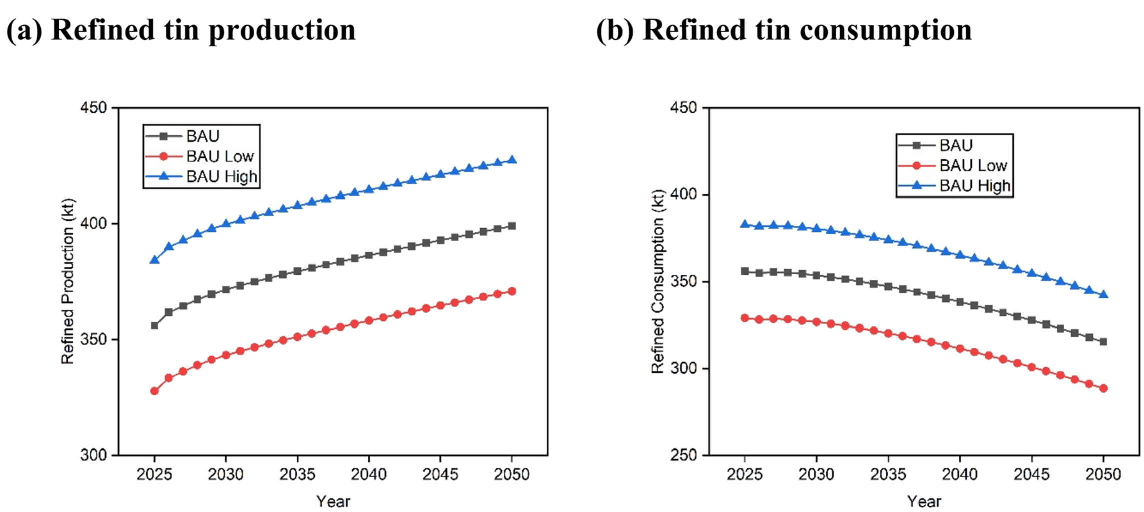

Fig. 5 ML forecasting of refined tin production (a) and consumption (b) to 2050 under BAU. Shaded bands show model confidence ranges (90%). The BAU forecast is a trend-continuation baseline and does not model endogenous supply responses.

through higher investment, favourable resource development, or improved technological efficiency. In contrast, the BAU Low line indicates a slower pathway with weaker production growth, which could occur if market conditions remain weak or if primary supply faces constraints.

Fig. 5b shows forecasted tin consumption to 2050. The central BAU line rises slightly in the early forecast years, reflecting continued demand from different industrial applications. However, after the early 2030s, consumption levels stabilise and then decline slightly, consistent with recent post-2020 trends in Fig. 1. This behaviour is consistent with historical patterns in which global refined tin demand has shown signs of slowing, partly due to improvements in material efficiency, substitution in selected applications and more stable growth in electronics manufacturing. The BAU High consumption line represents a stronger potential demand case, perhaps linked to higher manufacturing activity or renewed expansion in electronics. The BAU Low line, on the other hand, suggests weaker demand growth, aligning with lower industrial output. A key aspect of this figure is the way the BAU Low and BAU High bands were constructed. These bands are not separate scenarios but statistical confidence ranges. They are derived by analysing how well the ML model fits the historical data. After the model is trained, we calculate the difference between the model's predictions and the actual historical values known as residuals. The standard deviation of these residuals indicates how much the model typically under or over-predicts. To build a 90% confidence range, we multiply this residual standard deviation by 1.64 and add it to the central forecast (to produce BAU High) or subtract it (to produce BAU Low). This gives a transparent and data-grounded indication of how much real-world refined tin production or consumption could reasonably vary around the central trend. Comparing the central BAU production and consumption lines provides insight into the likely balance of the tin market if historical patterns continue. Under BAU, production grows at a moderate pace while consumption grows more slowly and eventually begins to decline slightly. This means that, based on past behaviour alone, the tin market is not naturally heading toward a major shortage. Instead, the BAU outlook indicates a surplus-leaning trajectory, with refined tin production materially outpacing consumption toward 2050. However, the widening confidence bands also highlight that there is meaningful uncertainty. These confidence bands therefore help illustrate the potential variability in future outcomes even when following the same underlying BAU trend. The central paths suggest a relatively balanced market, but the confidence intervals demonstrate that uncertainty is unavoidable, particularly in long-term projections. The BAU results shown in Fig. 5 should therefore be interpreted as a counterfactual trend-continuation benchmark based solely on historical refined tin production and consumption patterns, in which PV-related demand and other structural energy-transition drivers are intentionally excluded and the projected trajectories do not represent mechanistic responses to factors such as supply expansion, recycling improvements, material substitution, or demand shocks.

3.2. Scenario 2: BAU non-PV + PV tin consumption

In this section, we present the results of the BAU non-PV + PV solders tin consumption scenario. PV installation projections from ref. 6, are used, varying tin content in PV solder between 0.1–0.2 wt% of module mass and assuming a range of module lifetimes (theoretical lifetime and shorter and larger lifetimes of ~16 and ~30 years). For comparison on the supply side, we use the projected refined tin production from the ML model, considering both the central BAU and the optimistic BAU-high path (Fig. 5a). The results are shown in Fig. 6.

The PV tin demand curves (assuming continuing RoHS exemption for PV) in Fig. 6a increase rapidly over time and clearly illustrate how sensitive future tin use is to both tin intensity and module lifetime. Under the lower intensity assumption of 0.1% tin, PV demand starts from relatively modest levels in the late 2020s but rises steadily through the 2030s as global PV installations grow. By the 2040s, PV alone consumes several hundred kilotonnes of tin per year. When the tin content is doubled to 0.2 wt%, the PV demand curves are exactly proportionally higher, especially in the later years when cumulative installed capacity is large. Shorter lifetimes add another layer of demand, as early replacement PV systems require new modules and therefore new solder. The 16 year lifetime case produces the highest PV demand, because modules installed in the 2030s must be replaced before 2050.

When these PV trajectories are combined with the non-PV BAU baseline, the total refined tin demand in Fig. 6b grows much more strongly than in the BAU case. In the conservative PV assumption (0.1% tin and longer lifetimes), total demand increases from just under today's level to well above 0.5 Mt by 2050. For the higher-intensity and shorter-lifetime combinations, total demand climbs even more steeply, approaching or exceeding 1.4 Mt per year by mid-century. This behaviour reflects the fact that non-PV uses grow only modestly under BAU, so nearly all the additional growth in total demand is driven by PV expansion and the need to replace ageing modules. On the supply side, Fig. 5a shows that refined tin production under the BAU and BAU High scenarios grows slowly. The central BAU path increases from approximately 350 kt in the late 2020s to just over 420 kt by 2050, while the BAU High path reaches around 450–460 kt.

Comparing demand and supply across the figures (Fig. 6 and 5a) highlights a substantial and persistent gap. For the lowest PV tin assumptions, total demand begins to approach the BAU production line in the early to mid-2030s and then exceeds it for the rest of the period. By 2050, even the most conservative PV + BAU case lies well above BAU production and is similar to or higher than the BAU-high production path. This means that, even if the industry achieves production near the optimistic BAU-high projection, there is still a sizeable deficit between total demand and available refined tin. For higher PV tin intensities and shorter lifetimes, the gap becomes very large. By mid-century, total demand in the 0.2%-tin, 16 year-lifetime case is more than three times the BAU production level and comfortably more than double the BAU-high level. Overall, the BAU + PV scenarios show that incorporating realistic PV growth

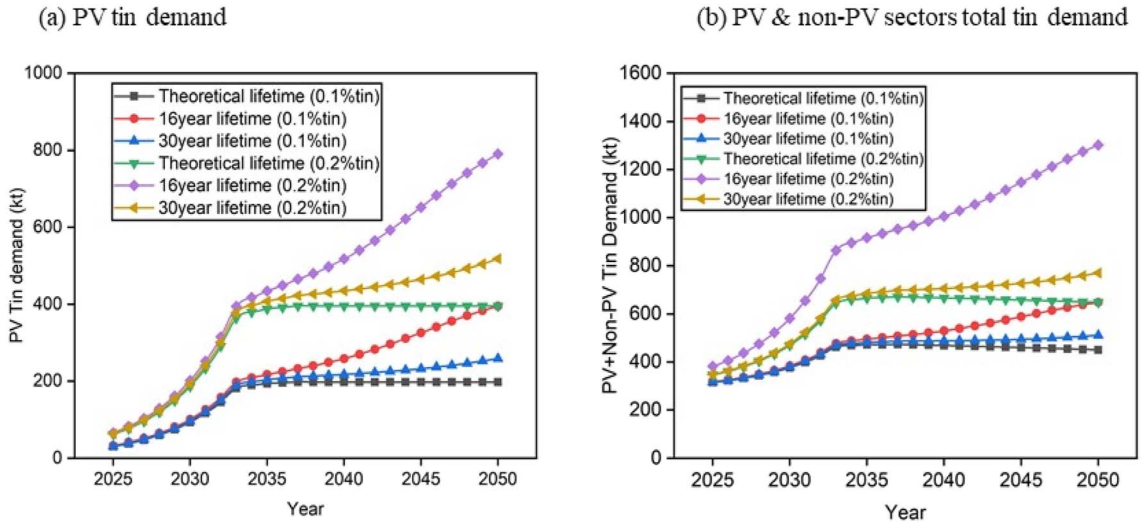

Fig. 6 Annual PV solder tin demand (a) and total refined tin demand (PV + non-PV) (b) under alternative tin intensities (0.1–0.2 wt%) and module lifetime assumptions.

transforms an otherwise balanced BAU system into a persistent structural shortfall. The size and timing of the gap depend strongly on assumptions about tin content in PV solder and actual module lifetimes, but the direction of the effect is unambiguous. Accordingly, the widening demand–supply gap shown in Fig. 6 should be interpreted as a scenario-based accounting comparison in which exogenously defined PV-related tin demand is overlaid on trend-based refined tin production projections, rather than as a predictive representation of endogenous market responses such as supply expansion, price-mediated demand adjustment, or cross-sector competition.

3.3. Scenario 3: high PV and non-PV tin consumption

In this scenario, we assume that a larger amount of tin will be consumed across both PV and non-PV applications. As in Scenario 2, PV tin demand is calculated using PV installation projections from ref. 6, applying the same tin-intensity assumptions. For the non-PV sector, we use application-level demand estimates from the Thunder Said Energy model.[31] Because the Thunder Said model already contains its own PV solder demand pathway, we remove the PV component from their projection to avoid double-counting. The resulting non-PV demand is then combined with the independently calculated PV tin demand from [6] (Fig. 7). From this figure, demand rises steeply from the mid-2020s, reflecting rapid PV deployment and strong growth in non-PV uses. Even with the lowest assumed tin intensity (0.1 wt%) and the longest lifetimes, total refined tin demand passes 1 Mt by 2040 and reaches around 1.17 Mt by 2050. Increasing tin content to 0.2 wt% or shortening module life to 16 years lifts demand markedly, with the highest curve approaching about 1.8 Mt by 2050.

Against this, refined tin production grows only modestly in the BAU forecasts from the ML model (Fig. 5a). Central BAU production rises from roughly 360 kt in the late 2020s to just over 420 kt by 2050, while the BAU-high case reaches only about 450–460 kt. This level of supply is less than one-third of the most conservative combined demand estimate and less than one-fifth of the highest demand case. The implied gap opens during the early 2030s, when demand first moves significantly above 500–600 kt while production remains in the BAU high 300 kt range, and it widens every year thereafter. By 2050, even under the most favourable production assumptions, refined output would have to more than triple relative to the BAU-high projection to meet the lowest of the combined demand trajectories and increase by around five to six times to match the highest.

Fig. 4 shows the tin demand across all major sectors from the Thunder Said model.[31] The Thunder Said Energy projection shows a steep rise in total tin demand across all major applications, with both PV and non-PV uses contributing to

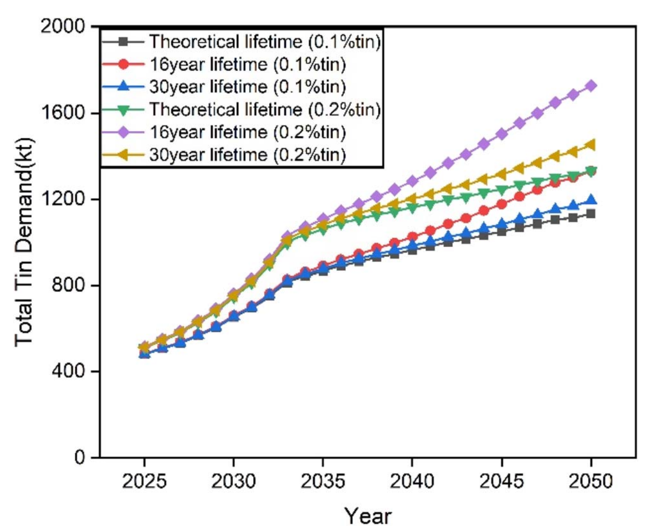

Fig. 7 Projected total tin demand under high PV and non-PV growth.

sustained growth through to 2050. Demand is around 400 kt in 2023 and increases to nearly 1000 kt by mid-century, driven by strong growth in all tin application sectors. PV grows from a minor share in the early 2000s to a significant component of total demand after 2030, reflecting the global shift toward large-scale PV deployment and electrification. At the same time, non-PV applications, including consumer electronics, industrial solders, and emerging battery systems, continue to expand in line with rising digitalisation, EV uptake, and broader electrification trends. When this combined sectoral demand is compared against the projected refined tin production from the ML model (Fig. 5a), a clear and persistent imbalance appears. This means that by 2050, Thunder Said demand is roughly double the BAU-high supply estimate and more than double the central BAU production path. This high-demand scenario should therefore be interpreted as a hybrid, accounting-based illustration that combines externally defined end-use demand pathways under consistent material-intensity assumptions, rather than as a fully unified or endogenously resolved representation of future global tin supply–demand dynamics.

3.4. Sensitivity of recycling input rate (RIR)

In this section, we conduct a sensitivity analysis by varying the recycling input rate (RIR) in global refined tin production. RIR is the share of total refined tin production that comes from recycled scrap rather than from primary mining.[32] An RIR of 30% means that 30% of refined tin is produced from secondary (recycled) sources and 70% from primary ore. In the context of growing tin demand from PV and other sectors, a higher RIR can therefore help to narrow the gap between demand and supply without a corresponding increase in primary tin production. Historical data indicate that the global tin RIR has been around 30–35% over the past decade.[32] In this study, the ML forecast of refined tin production to 2050 reflects this historic mix of primary and secondary sources. To explore how higher recycling might relieve future pressure, we first decomposed the ML production series into primary and secondary components using a baseline RIR of 35%. For each year, the primary component was taken as 65% of the ML total, and the remaining 35% was attributed to recycling. We then held the primary component constant and recalculated total refined production by adjusting the secondary component for higher target RIR values of 40%, 45%, 50%, 55%, and 60%. For a given primary output, increasing the RIR raises total refined supply because a larger share of production is provided by recycled tin. Fig. 8 shows that moving from current recycling levels towards 50–60% could substantially increase available refined tin, partly offsetting the projected demand growth and reducing, though not necessarily eliminating, the future supply–demand gap.

3.5. Projected tin demand from alternative PV deployment studies

Table 2 reports PV-only tin demand derived using PV deployment projections from four external sources: BNEF, ITRPV, PV Tech (2023), and the Chinese PV Association. These sources project future PV deployment rather than tin demand directly; tin requirements are calculated here by applying the tin-intensity assumptions described in Section 2.1 to each deployment pathway. The resulting values can be compared directly with the ML-based projections of total refined tin production to assess what fraction of future supply would be absorbed by the PV sector alone.

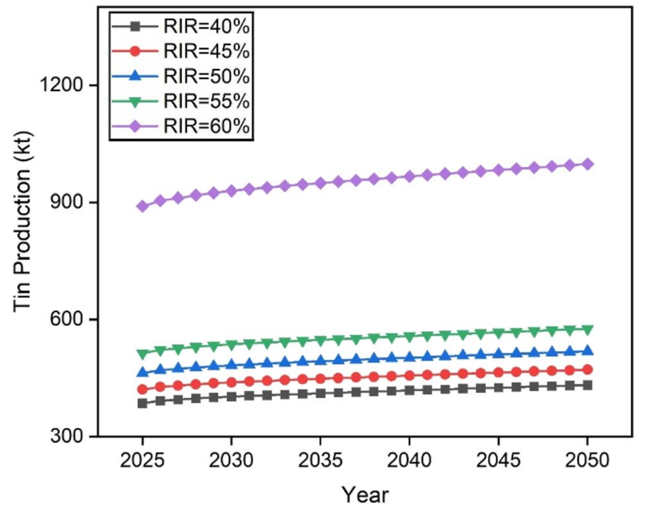

Fig. 8 Sensitivity of total refined tin production to Recycling Input Rate (RIR).

In the near term (mid-2020s), the derived PV-related tin demand spans roughly 30–70 kt per year across the alternative deployment projections. For example, in 2025, BNEF-based projections correspond to an annual PV tin demand of about 51 kt, ITRPV to about 54 kt, PV Tech (2023) to around 71 kt, and the Chinese PV Association to about 34 kt. Over the same period, the ML model suggests total refined tin production of the order of 360–380 kt. This implies that PV would account for roughly 10–20% of global refined tin output, leaving most of the supply available for other uses.

In 2030, however, the picture becomes more varied. PV-related tin demand derived from more conservative PV

Table 2 Projected PV tin consumption from other studies in kt (different PV installation projections data collected from ref. 33–36)

Year	Tin consumption BNEF	ITRPV	PV Tech23	Chinese PV Assoc.
2023			48.6244	30.5316
2024			57.6708	32.7932
2025	50.886	54.2784	71.2404	33.924
2026			85.9408	
2027			98.3796	41.8396
2028			113.08	
2029			130.042	
2030	48.96364	151.5272	143.6116	47.4936
2035	88.2024	183.1896		
2040	94.9872	282.7		
2045	86.28004	312.1008		
2050	130.042	503.206		

deployment pathways, such as those reported by BNEF and the Chinese PV Association (around 47–49 kt), would still correspond to only about 10–15% of projected refined tin production. In contrast, roadmap-based and high-growth PV deployment projections, particularly from PV Tech (2023) and ITRPV, imply substantially higher PV-related tin demand (around 140–150 kt). Under these high-growth pathways, PV alone would absorb approximately one-third to two-fifths of the total refined tin supply in 2030.

The divergence becomes more pronounced after 2035. Under BNEF's pathway, PV-related tin demand remains relatively modest, at around 88–130 kt between 2035 and 2050. Even in 2050, this would correspond to less than one-third of projected refined tin production (around 420–460 kt under the BAU and BAU-high scenarios). In contrast, the ITRPV deployment trajectory implies substantially stronger growth, with PV-related tin demand of about 183 kt in 2035, nearly 283 kt in 2040, and over 500 kt in 2050. Under this high-demand case, PV would consume roughly half to two-thirds of total refined tin production by the 2040s and would exceed the ML-based projection of total global refined tin production by 2050. In other words, if the ITRPV trajectory were realised while tin production followed BAU or BAU-high trends, refined tin supply would be insufficient to meet PV demand alone, even before accounting for other applications. Overall, this comparison indicates that while some PV deployment pathways appear manageable within current supply trends, higher-demand scenarios would face substantial challenges.

3.6. Strategies to reduce the demand-supply gap

Minimising future tin supply shortages will require coordinated actions on both the demand and supply sides, supported by stronger policy frameworks. Significant investment is needed to sustain primary tin production, extend the operating life of existing mines, and develop new deposits. Recent declines in global refined tin output reflect supply disruptions in key producing regions, particularly Indonesia, and a post-2020 slowdown in global tin consumption, highlighting the fragility of highly concentrated supply chains.[37] Available data does not indicate a clear global decline in tin ore grades, suggesting that short-term supply volatility is driven primarily by geopolitical, regulatory, and operational factors rather than geological depletion. Geological studies show that significant untapped resources exist in countries such as Russia, the Democratic Republic of the Congo (DRC), Australia, and the United Kingdom (UK), suggesting that diversification away from a few Southeast Asian producers is technically possible.[38] Bringing these resources into production will require long-term finance, stable regulation, and better environmental and social standards so that new projects are acceptable to host communities and downstream buyers. Strengthening responsible mining schemes, such as the International Tin Supply Chain Initiative (ITSCI) and other related due diligence initiatives, can also improve access to finance and reduce reputational risks.[39]

Primary mining alone is unlikely to close the gap, so recycling and circularity need to play a much larger role. Recent material flow analysis suggests that global end-of-life recycling input rates for tin may be as low as ~11%.[40] This number contrasts with historical estimates of a global tin RIR of around 30–35%,[32] which largely signify the contribution of new scrap generated during manufacturing rather than recovery from discarded products. As a result, the effective recovery of tin from EoL products remains scarce. Raising the recycling input rate towards 40–60% would significantly increase refined tin supply from the same level of mining, as our sensitivity analysis shows. This requires better collection and treatment of tin-bearing waste streams, especially waste electronics and PV modules, which contain large numbers of tin solder joints.[41] Investment in developing recycling technologies to recover tin from waste streams could be another viable option.[42] Recently, new recycling technologies were developed to recover tin and tin based alloys from PV waste, which could reduce pressure on virgin material.[43–45] Industrial implementation of such technologies should be ensured. Policy measures could include extended producer responsibility for electronics and PV, minimum recycling targets, and support for advanced separation technologies that can recover tin economically from complex scrap. On the demand side, reducing tin intensity in key applications is essential. Solder currently accounts for around half of refined tin use, driven by electronics, EVs and solar inverters.[46] Process improvements such as optimisation of solder ribbon plating thickness and refined interconnect designs have been shown to influence tin usage in PV module assembly, and research into these approaches continues to explore reductions in material intensity without undermining electrical performance and reliability.[47] Where possible, partial substitution by other materials (for example, alternative alloys in non-critical connectors or aluminium-based alloys in some bearings) can also ease pressure, although full substitution is often limited by performance and safety requirements. Extending product lifetimes, particularly for PV modules and electronics, standardisation together with supportive policies to reuse second life products, reduces the rate at which new tin containing products must be manufactured and delays the point at which tin becomes embedded in end-of-life waste.[48,49]

Finally, policy and market frameworks need to recognise tin as a strategic material for the energy transition. Australia, China, the UK, the USA, and other regions are already moving tin onto critical or strategic materials lists and calling for diversification of supply and development of domestic processing.[50–53] Integrating tin explicitly into national critical minerals strategies, funding exploration and research on recycling technologies, and supporting long-term offtake contracts can all help to de-risk investment.

4. Conclusions

This study explores potential pressures on global tin supply arising from terawatt-scale photovoltaic (PV) deployment by comparing externally defined PV deployment pathways with trend-based projections of refined tin production and consumption. Using historical data from 1999 to 2024, baseline trends were projected to 2050 and evaluated against additional tin demand implied by large-scale PV expansion. Under a continuation of historical production and consumption patterns and in the absence of major structural changes, the projections do not indicate immediate aggregate shortages of refined tin. However, when additional demand from accelerated PV deployment is overlaid, increasing pressure on the tin value chain emerges, particularly in combination with rising demand from electronics, electric vehicles, and other solder-intensive applications. These results are conditional on the assumed trends and scenarios and should be interpreted as indicative of potential risks rather than as definitive forecasts of future market outcomes. The findings highlight the importance of proactive strategies to mitigate supply pressure, including increased recycling from solder-rich waste streams, improvements in recovery efficiency, diversification of supply sources, and reductions in tin intensity through materials innovation. Together, such measures can help support resilient and sustainable PV expansion under terawatt-scale deployment trajectories.

Author contributions

Piyal Chowdhury, Priyom Das: conceptualization, writing – original draft, methodology, formal analysis, data curation. Tamal Chowdhury: writing – original draft, visualization, methodology, formal analysis. Hemal Chowdhury: writing – original draft, methodology, formal analysis. Elza Bontempi: writing – review & editing, supervision, project administration. Richard Corkish: writing – review & editing, supervision, project administration.

Conflicts of interest

The authors declare that they have no competing interests.

Data availability

The data that support the findings of this study are available from the corresponding author, Mr Hemal Chowdhury, upon reasonable request.

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