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The aluminium demand risk of terawatt photovoltaics for net zero emissions by 2050

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The broad electrification scenario of recent photovoltaics roadmaps predicts that by 2050 we will need more than 60 TW of photovoltaics installed and must be producing up to 4.5 TW of additional capacity each year if we are to rapidly reduce emissions to 'net zero' and limit global warming to <2 °C. Given that at the end of 2020, just over 700 GW peak was installed, this represents an enormous manufacturing task that will create a demand for a variety of minerals. We predict that growth to 60 TW of photovoltaics could require up to 486 Mt of aluminium by 2050. A key concern for this large aluminium demand is its large global warming potential. We show that it will be critical to maximize the use of secondary aluminium and rapidly decarbonize the electricity grid within 10 years if cumulative emissions are to be kept below 1,000 Mt of CO_2 equivalent by 2050.

If global warming is to be limited to <2 °C, emissions need to be drastically curtailed to approach net zero before 2050[1]. Various technology mitigation scenarios have been proposed to address this challenge[2–7]. However, these scenarios differ in the extent that different clean energy technologies contribute to the required emissions reduction, particularly in terms of the anticipated role of solar photovoltaics (PV)[2,4–6]. Historically, technology roadmaps have substantially under-estimated the installed PV capacity[8,9], and energy agencies are continually revising their technology scenarios to take into account the driving effect that rapidly reducing PV module costs[4] are having on installed PV capacities worldwide. The International Energy Agency (IEA) recently markedly increased its renewable energy projections, with solar PV now predicted to provide 32% of the world's total electricity demand by 2050[3]. They estimate that this will require an installed PV capacity of ~14 TW peak (TWp) and annual installations of 630 GWp each year by 2050[3]. Despite this target representing a large increase in the predicted contribution of solar PV over their previous reports, it still falls short of the broad electrification scenario projections from the International Technology Roadmap for PV (ITRPV)[4]. This scenario forecasts that the total capacity of installed PV needs to be at least 60 TWp by 2050, with annual installations of 4.5 TWp being required close to that date[4]. This ambitious target is projected because of the extremely low cost of PV-generated electricity compared with all other energy sources. Although the PV module price is subject to changes in material costs (for example, in silicon (Si), silver (Ag) and Al), it has decreased by about 90% over the past 10 years to <US\$0.20 W^{-1} (ref. [10]). The median levelized cost of electricity from solar PV is now <US\$50 MWh^{-1}, which is less than the cost of electricity from both coal and gas in many countries, including the United States, China, India and Australia[11].

There is now consensus that we will need tens of terawatts of installed PV capacity and that annual production will need to approach terawatt levels by 2050[9], or even sooner, to decarbonize electricity grids[10]. Given that at the end of 2020 there was just over 700 GWp installed[12], with 130 GWp of that added in 2020 alone[4], this represents an enormous scale-up of manufacturing, requiring significant mineral resources. Consequently, the material sustainability assumptions made in the various emissions reduction technology scenarios need to be carefully evaluated[13,14]. So far, the sustainability of terawatt PV has typically focused on the elements required for the anticipated mainstream technology cells, such as Ag and indium[10,15,16]. However, the demand risk associated with other metals that will be required in large volumes, such as Al, also needs to be evaluated. Owing to its high conductivity, low weight and excellent corrosion resistance, Al is used in the mountings, frames and inverters, as well as in the cells, of terrestrial flat panel PV modules[17]. It is also heavily used by many other clean energy technologies (for example, batteries, wind turbines and associated power systems)[13]. However, despite its desirable attributes, its primary production comes at a high cost in terms of energy and associated greenhouse gas emissions through both direct and indirect emissions.

In its *Minerals for Climate Action* report[13], the World Bank identified Al as being a mineral of high demand risk because: (1) it is required by a number of clean energy technologies; (2) its predicted usage will require extensive increases in production by 2050; and (3) the required mining and primary production of Al has a large global warming potential (GWP)[13]. The report also showed that solar PV dominated this demand, contributing 87% to the total additional demand. However, the World Bank analysis followed the assumptions of the IEA's earlier 2 °C technology mitigation scenario, which predicted only 4 TWp installed PV capacity by 2050[7]. To place this in perspective, 4 TWp (in 2050) is only a sixfold increase from the installed capacity at the end of 2020. The question that we seek to address is, if we are going to have more than 60 TWp of PV installed by 2050 and plan to install an additional 4–5 TWp each year, what is the real demand risk for Al?

Aluminium (Al) is one of the most recycled and most recyclable materials on the market today[18]. It is attractive to recycle because its secondary production requires only ~5% of the energy required for primary production[19] and generates just 3–5% of the emissions from primary production[19–21]. Nearly 75% of all the Al produced is still in use today[22–24] and end-of-life recycling rates are estimated at 34–63%[20,22–24]. However, a key constraint for secondary production is the availability of Al scrap due to the finite supplies of in-product Al. Primary Al production involves two energy-intensive processes (Fig. 1): (1) refining of bauxite ore into alumina (Bayer process); and (2) Al smelting via electrolysis of alumina (Hall–Héroult electrolysis process)[25]. The energy requirements of the entire Al primary

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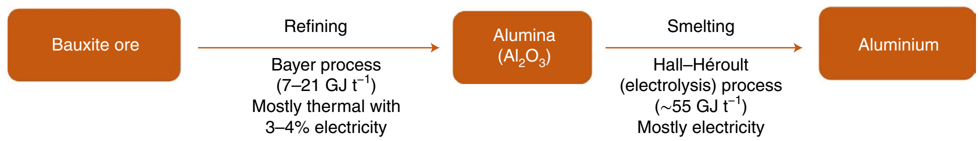

Fig. 1 | Flowchart of the Al primary production process. The refining and smelting processes are described in more detail in Supplementary Section 2. The energy requirements for both stages are listed below the arrows.

production process have been estimated to be 62.6 GJ per tonne of sawn Al ingot, which is substantially higher than for steel or copper (Supplementary Table 1). The emissions intensity of primary production is dominated by the indirect emissions from the required electricity. The global average emissions intensity for Al primary production in 2018 was ~16.5 t CO_2e t^{-1} (ref [18]) and the International Aluminium Institute predicts that this value could be reduced to ~5.5 t CO_2e t^{-1} with decarbonized electricity[18].

We used the most recent PV projections to more accurately evaluate the Al demand required to support the broad electrification scenario of the most recent ITRPV and its associated GWP. It was assumed that crystalline Si (including tandem) PV would remain the dominant PV technology[4,26], rather than reduce to a 50% market share as assumed by the World Bank analysis. Emissions were calculated assuming that both Al production and PV manufacturing occur predominantly in China, and that Al is obtained through both primary and secondary (recycled) production pathways.

In our GWP analysis, we used current estimates of primary production emissions intensity in China and considered different emissions reduction scenarios. Our modelling assumed that the available secondary Al in China is as forecasted by Li et al.[21], and we evaluated the sensitivity of the estimated GWP arising from the required Al demand to the fraction of the secondary pool, which is available for the PV capacity additions. We conclude by discussing paths by which this imminent Al demand risk can be addressed in terms of possible PV technology decisions and technology advancements that will be required to realize reductions in the Al emissions intensity.

Results

The Al demand and its GWP were estimated for the required PV capacity predicted for the 2021 ITRPV's broad electrification scenario[4]. Owing to the sensitivity of the GWP to the primary Al emissions intensity, a number of different primary Al emissions reduction scenarios were modelled and compared to establish the scale of emissions reduction required to ensure that net zero emissions (NZE) can be achieved by 2050.

Al demand. Figure 2 shows the annual and cumulative Al demand for the solar cells, module frames, mountings and inverters that is necessary for the PV capacity additions required for the 2021 ITRPV's broad electrification scenario[4], which demands a total of 60 TW of installed PV by 2050. In the base case shown, power derating due to module degradation in the field was assumed to be negligible with respect to the new capacity required and the share of rooftop modules was projected to decrease from 50% in 2020 to 40% by 2050[6]. Our analysis prediced a much larger cumulative Al demand of 486 Mt (for 60 TWp by 2050) than the 103 Mt (assuming ~4 TWp by 2050) predicted by the World Bank report in 2020[13]. The increase was expected due to the larger installed PV capacity associated with the ITRPV's broad electrification scenario. However, the 4.7 fold increase is much smaller than the factor of 15 increase in installed capacity due to our model assuming anticipated energy conversion and technology efficiency increases over the 2020 to 2050 timeframe. A comparative model for the IEA's net zero (NZE 2050) scenario predicts an Al demand of 121 Mt (for 14 TWp by 2050; Supplementary

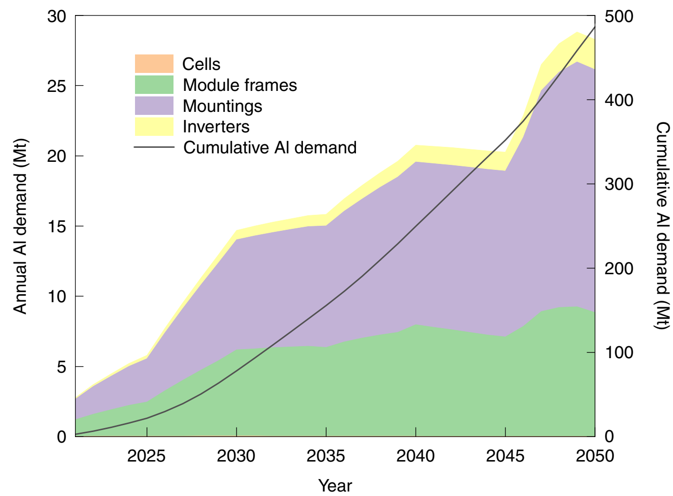

Fig. 2 | Annual and cumulative Al demand for the cells, module frames, mountings and inverters until 2050. Values were calculated for the ITRPV's broad electrification scenario from 2021–2050 for the base case where the share of rooftop PV installations decreases from 50% to 40% by 2050. Calculations were performed as described in the Methods using the parameters listed in Supplementary Table 1. We assumed that additional demand due to module degradation in the field was insignificant compared with the annual capacity additions predicted by the roadmap.

Fig. 1). This is consistent with the World Bank estimate of 103 Mt for the lower installed PV capacity of 4 TWp in 2050.

If PV modules degrade in the field on average by ~0.5% yr^{-1} (ref. [27]), the Al demand will increase by 4.7% to 509 Mt by 2050 to accommodate the production of replacement modules (Supplementary Fig. 2). However, the demand is more sensitive to the fraction of rooftop capacity, due to our assumption that only rooftop PV installations use the lighter Al for their mountings. Decreasing the rooftop fraction to 30% by 2050 can decrease the cumulative demand from 486 to 444 Mt (Supplementary Fig. 3), but this reduced demand depends on the continued use of steel for non-rooftop PV, which may not be the case if large fractions of floating and building-integrated PV are included in the non-rooftop market segments.

Figure 2 shows that annual demand for Al will increase and reach 28.5 Mt by 2050. This annual demand is >40% of the 2020 global Al production (65 Mt) and more than half of all the Al produced by China in 2020 (37 Mt)[28]. Although Al is abundant in the Earth's crust and bauxite reserves are estimated to be 30 Gt (ref. [29]), Al production levels will need to be significantly increased over the next 30 years to meet the demand from PV manufacturing alone. This escalation in demand does not include the use of Al in other clean energy technologies, which is also expected to increase[13], or its continued use for transportation and building infrastructure. Consequently, it can be viewed as a lower limit on the actual demand. If the majority of PV manufacturing continues to be performed in China, supported by local producers, then this demand may need to be met by a mix of local Chinese and imported Al production.

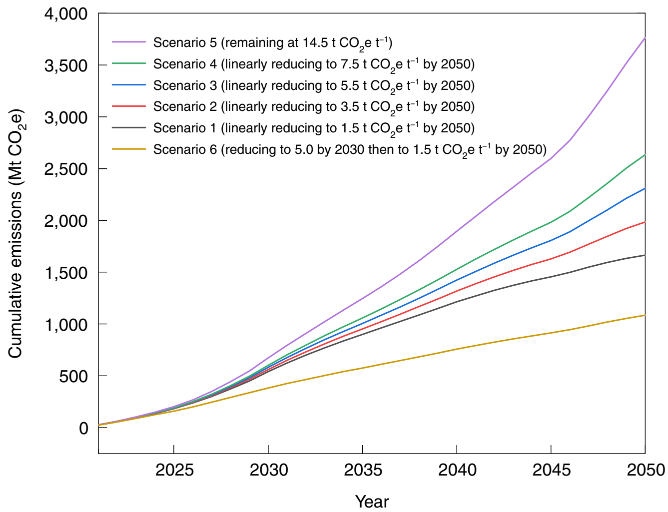

Fig. 3 | GWP of the estimated Al demand shown in Fig. 2 for different primary emissions reduction scenarios. All scenarios assumed that 33% of the forecast secondary Al pool for China (from Li et al.[21]) is available for the production of the new PV modules. All other parameters used for the modelling are as listed in Table 1. The GWP for each scenario is listed in Supplementary Table 3 and comparative GWP values assuming the IEA's NZE 2050 scenario are shown in Supplementary Fig. 6.

Table 1 | Parameters used in the estimation of the GWP of the calculated Al demand

Parameter	Value
Al material flows	
Forecast secondary pool	Forecast secondary Al pool increasing from ~6 Mt in 2020 to 35 Mt in 2050 from Li et al.[21]
Secondary pool used by PV	33.3%
Recycled content	34% in 2020[20], increasing to 75% in 2050
Regeneration coefficient	83% from Li et al.[21] (includes collection and recycling efficiency)
GWP	
Primary production emissions	14.5 t $CO_2e\,t^{-1}$ Al in 2020[30,31], reducing to the target of 1.5 t $CO_2e\,t^{-1}$ Al by 2050 (most ambitious scenario)
Secondary production emissions	0.65 t $CO_2e\,t^{-1}$ Al (4% of the emissions of world average primary production[18] in 2020) decreasing to 0.5 t $CO_2e\,t^{-1}$ Al in 2050 owing to efficiency improvements and low-carbon electricity

GWP of required Al production. The GWP of the projected Al demand shown in Fig. 2 was estimated using the parameters listed in Table 1 for different primary production emissions reduction scenarios (Fig. 3). All scenarios assumed that 33% of the projected secondary Al pool is available for the PV capacity additions and that the secondary Al emissions intensity linearly decreased from the current average value of 0.65 t $CO_2e\,t^{-1}$ (4% of the world average primary production emissions in 2020)[18] to 0.5 t $CO_2e\,t^{-1}$ in 2050 due to efficiency improvements and decarbonized electricity. In the base scenario (Scenario 1), we assumed that the primary production emissions intensity linearly reduced from current levels of ~14.5 t $CO_2e\,t^{-1}$ Al in 2020[30,31] to the ambitious target of 1.5 t $CO_2e\,t^{-1}$ Al by 2050, the latter being the value projected by the International Aluminium Institute as a requirement to limiting temperature increases to <2 °C (ref. [18]). This reduction in emissions intensity, which could reduce the GWP by 56% of what would be expected if no reduction in the primary emissions intensity occurs from the current value (Scenario 5), was assumed to initially occur primarily via the decarbonization of electricity and then later through process improvements that reduce direct emissions (see Discussion). However, Scenario 1 still results in a large GWP of 1,665 Mt CO_2e by 2050 and peak emissions of ~90 Mt CO_2e in 2030 (~0.8% of China's 2019 emissions).

A number of alternative slower emissions intensity reduction scenarios are also shown in Fig. 3 (see also Supplementary Table 3) and compared with a more optimistic scenario (Scenario 6) in which the primary production emissions intensity is rapidly reduced to ~5 t $CO_2e\,t^{-1}$ Al by 2030 through extensive decarbonization of electricity, and then more slowly decreased to the target of 1.5 t $CO_2e\,t^{-1}$ Al by 2050 through process improvements directed at reducing direct emissions. This scenario can decrease the GWP to 1,085 Mt CO_2e, which is ~29% of the emissions, and is feasible by 2050 if no significant change occurs in the primary emissions intensity from its current average value of 14.5 t $CO_2e\,t^{-1}$ Al. Annual and cumulative emissions are shown for each scenario and their corresponding primary and secondary production contributions are shown in Supplementary Fig. 4. Whereas Scenarios 1, 2 and 6 result in emissions peaks that are <1% of China's 2019 emissions in ~2030 (Supplementary Table 3), the remaining scenarios result in larger magnitude peaks at ~2050. These later emissions peaks may seriously impact China's ability to achieve their target of NZE by 2060[32]. The estimated GWP of the required Al production can also be compared with the emissions generated from Si PV modules. Si production is another energy intensive process, and although the emissions for module production have been steadily decreasing due to increased efficiencies in production (Supplementary Table 5), they still contribute significantly to the embodied energy of PV modules. If we assume that PV module emissions reduce to 50 t $CO_2e\,MW^{-1}$ by 2030, at that time, emissions associated with our most optimistic Scenario 6 will represent 60% of the predicted PV module emissions (Supplementary Table 6).

An indicative breakdown of emissions based on Scenario 6 into secondary and direct/indirect emissions for primary production (Supplementary Fig. 5) suggests that while the indirect emissions contribute significantly to the peak in emissions ~2030, they only contribute ~18% to the GWP, with direct emissions being responsible for ~69%. This initial analysis highlights the importance of addressing both the direct and indirect emissions intensities of primary production. However, low-carbon electricity can also provide opportunities to reduce direct emissions and decarbonizing electricity therefore remains a key objective for both Al and Si production.

Figure 4,a,b shows the predicted annual and cumulative emissions from primary and secondary Al production when 33% and 100%, respectively, of China's forecast secondary Al pool[21] is available for added PV capacity. Both projections assume that primary emissions reduce according to Scenario 6. However, the GWP is only reduced by ~9% if all of China's forecast secondary Al is available for the added PV capacity. Since the report by Li et al.[21], China has increased its volume of imported primary Al in an effort to curtail domestic emissions. This additional Al, which is not included in the analysis, will increase the secondary pool available for later PV capacity addition. However, this additional resource may not be available soon enough to reduce the peak in emissions that is expected to occur in the next 10 years. It will therefore be critical to develop efficient scrap collection and separation systems both for PV and other Al uses and to improve secondary Al production processes to maximize regeneration efficiency. Whereas Al

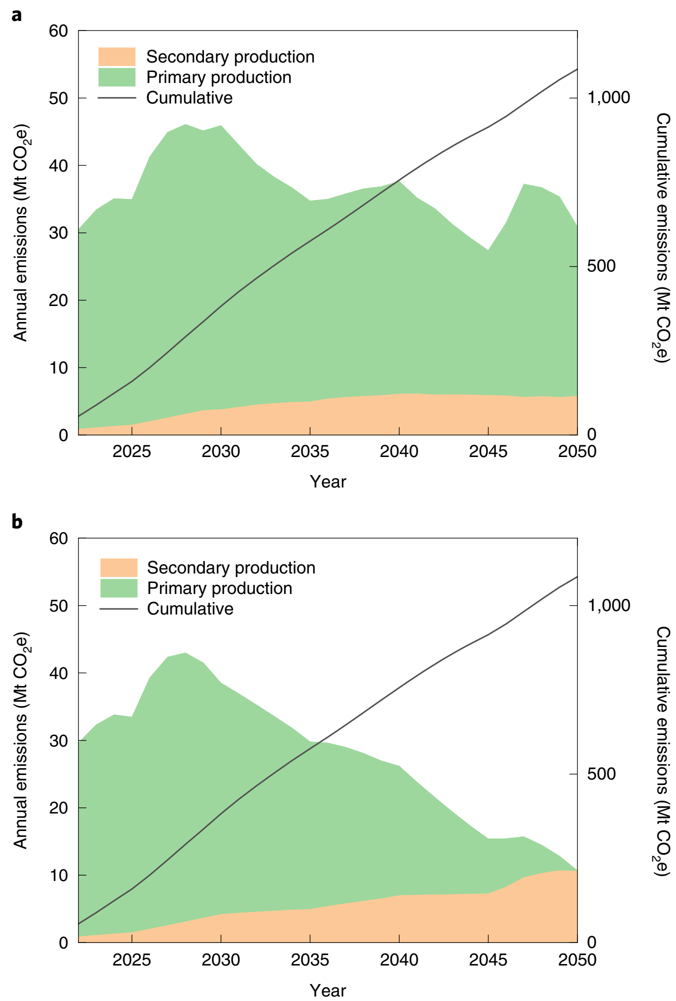

Fig. 4 | Annual and cumulative emissions from primary and secondary Al production in China. a,b, The emissions resulting from the estimated Al demand in Fig. 2 assuming that 33% (**a**) and 100% (**b**) of the forecast available pool of secondary Al in China[21] is available for new PV module production in China. Primary production emissions were assumed to reduce according to Scenario 6. All other parameters used for the modelling are as listed in Table 1.

in its purest form can be recycled indefinitely without any degradation or loss of property, the recycling of Al alloys can be more complicated[33]. Although most PV module frames use the Al 5754 alloy (AlMg3), the 6000 series (with Mg and Si) can also be used. Whilst it is straightforward to use end-of-life frames of both series to remanufacture 6000 series frames, the use of 6000 series material to manufacture 5000 series frames is more expensive and requires more complex separation and analysis technology[34].

The scenarios presented in Figs. 3 and 4 assume that the new module capacity added since 2020 will operate for 30 years in the field[35], holding their Al as an 'in-product' resource. However, if modules in the field are 'retired' earlier to take advantage of anticipated improvements in module efficiency, they can also release some of this Al into the secondary Al pool and reduce the amount of primary Al production that will be required. Yet Fig. 5 shows that the retirement of modules after 15 years in the field does not significantly reduce the peak that will occur in emissions within the next 10 years and, for the most optimistic primary production emissions scenario, only reduces the GWP by 8%. This highlights the global benefit of China (where the bulk of the Al and PV module manufacturing is expected to occur) increasing its Al imports now to support a greater fraction of local secondary Al production in the future.

Discussion

Although decreasing Al usage in PV systems can reduce the expected demand and its associated GWP, this strategy may only be effective if alternative materials used to replace the Al do not contribute additional emissions and do not diminish the product's longer-term value in terms of a circular economy. For example, replacing Al with steel in PV module frames can reduce PV module resistance to corrosion, and make modules heavier and more costly to transport. The predicted demand for Al can be reduced by larger increases in module efficiency and module area than those anticipated in our model. For example, increasing module area from 1.8 to 3.8 m^2 by using larger Si wafers could result in a 16% reduction in the mass of Al required for frames per watt of PV power. The Al demand of terawatt PV could also be reduced if carbon composite[36] or frameless modules[37] are adopted more rapidly than is predicted. These alternatives can reduce module embodied energy; however, for the GWP to reduce significantly, this transition would need to occur in the next 10 years. A faster adoption timeframe than that predicted by the ITRPV is challenging due to the durability required for long expected module lifetimes, manufacturing cost pressures and the reluctance of existing module production lines to make changes that have not been comprehensively verified in the field—all of which increase financial investment risk. The ITRPV actually reduced its predicted uptake of frameless modules in its 2021 report compared with previous years, suggesting a reduced confidence in the transition to frameless modules.

However, more promising routes for reducing the GWP of the required Al demand may be to: (1) use 'home-country' Al for mountings for PV systems (and possibly also frames) to reduce demand pressure on China's secondary Al pool; and (2) reduce the emissions intensity of primary production. The first option could reduce the potential GWP through accessing a larger secondary Al pool in the country of installation and the possible availability of lower-emissions primary Al where smelters already have access to low-carbon hydroelectricity (for example, in Norway and Russia).

The second option will require significant investment, both for existing Al smelters and for new Al production capacity, to meet the increased demand. Perhaps the easier task here is the new production capacity, which can be sited in renewable energy zones where 100% renewable power can be used and provisions are made to address intermittency (for example, storage). The average Al emissions intensity using low-carbon electricity at present is 5.5 t $CO_2e\,t^{-1}$ (Supplementary Table 2). A key advantage of establishing Al refineries and smelters within renewable energy zones is that they can absorb excess renewable energy generation and contribute to demand-side response by adjusting their operations (for example, load shedding when energy demand exceeds supply)[38]. However, much of the existing Al primary production relies on co-sited thermal coal as the power source, and decoupling of these energy sources is expected to be more complex. Since 2004, China has been the largest primary producer of Al, producing ~37 Mt in 2020 (~60% of the world's production)[28]. Most of this production uses thermal power from coal. Although electricity decarbonization may seem to be an obvious strategy, the scope of this transition needs to be recognized as increased PV production for decarbonized electricity can potentially place greater demands on Al primary production.

Reductions in direct emissions will also be required (Supplementary Fig. 5) if emissions intensities are to be reduced to 1.5 t $CO_2e\,t^{-1}$ Al by 2050. Over the past 20 years, large reductions in process-related emissions have been achieved, especially in regards to reducing emissions from perfluorocarbons[39]. In 1990, Al sector

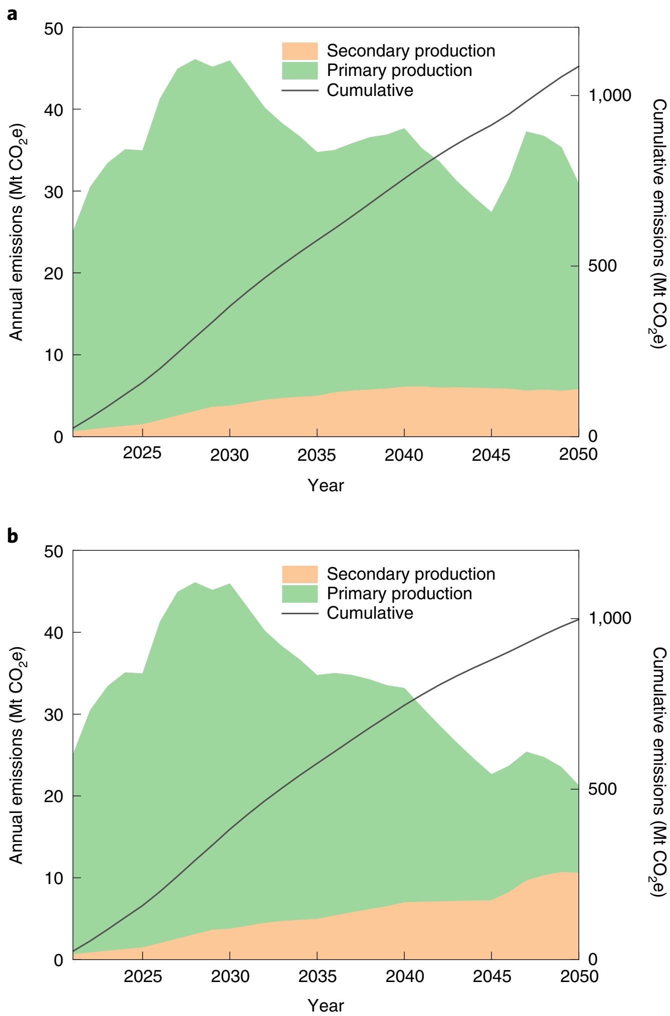

Fig. 5 | Annual and cumulative emissions of the estimated Al demand from primary and secondary Al production. a,**b**, The emissions resulting from the estimated Al demand in Fig. 2 assuming module lifetimes in the field of 30 years (**a**) and 15 years (**b**). The projections assume that the primary production emissions intensity reduces linearly from 14.5 to 5 t CO_2e t^{-1} Al by 2030 and then more slowly to 1.5 t CO_2e t^{-1} Al by 2050 (that is, Scenario 6 in Fig. 3). All other factors are as listed in Table 1.

emissions were ~300 Mt CO_2e, of which direct emissions contributed 200 Mt CO_2e (100 Mt CO_2e from perfluorocarbons). By 2018, the direct emissions share had been reduced from two-thirds to one-third of total emissions, largely due to reductions in perfluorocarbons emissions (down to 3% of the total) and efficiency improvements in the electrolytic smelting process[18].

New technologies can reduce emissions from the refining of bauxite to alumina, and many are directed at reducing emissions from the gas that is used to provide the thermal energy[40]. Electric boilers, which produce steam, are commercially available for low process temperatures. However there are limitations to this approach for the higher-temperature processes[40] and, used in the absence of low-emissions-factor electricity, potential advantages can be eroded[24]. Sources of both power and heat, such as concentrated solar thermal, can provide advantages in regions with rich solar resources[41]. Other options include: (1) biomass co-generation with hydrogen for process heat[40]; and (2) co-location of Al refineries and smelters, which can provide savings of up to 22 GJ t^{-1} by using the heat generated from electrolysis for the calcining step of the Bayer process[39].

The Hall–Héroult electrolysis process directly generates CO_2 at the anode of the electrolytic cell (Supplementary Equation (1)). This contributes 0.75 t CO_2e t^{-1} Al via stoichiometry alone. However, eliminating these direct emissions remains a challenge. Replacing currently used pre-baked carbon anodes with an inert anode can avoid these direct emissions by generating O_2 instead of CO_2. Consequently, considerable efforts have been directed towards identifying candidate materials for inert electrodes. However, this is a known challenge, as inert anodes require high electrical conductivity, resistance to fluoridation, high chemical stability towards oxygen at 1,050 °C, high resistance to thermal shock, low overvoltage for O_2 evolution and, preferably, should be amenable to retrofitting in current electrolysis cell designs[42]. Despite these challenges, a number of early commercialization activities are occurring[40]. Elysis (a joint venture between Rio Tinto and Alcoa) has begun constructing commercial-scale inert anode cells in Canada[43–45], and Rusal (Russia)[44] and Arctus Metals (Iceland) have reported the production of low-carbon Al using insert anode technologies[45].

Owing to its 'infinite' recyclability[18] Al can play a critical role in the rapid growth of PV to terawatt levels by 2050— growth that will be required to reduce emissions to net zero. Its light weight makes it amenable to rooftop PV installations; its resistance to corrosion is highly advantageous for PV modules, which are expected to operate in the field for 25 to 30 years; and its ability to be extruded as single, rather than welded, parts can facilitate low-cost PV installations. Although we show that resourcing the Al required to realize the ITRPV's broad electrification scenario presents an alarming GWP—due to the current insufficiency of secondary Al and the high average emissions intensity of primary Al production—we suggest that, rather than focus on reducing Al demand by replacing it with other metals, a more effective approach from the perspective of the circular economy would be to: (1) source Al components in the country of installation where possible (at least mountings); (2) incentivize reductions in the emissions intensity of Al primary production (for example, through carbon border taxes); and (3) introduce landfill penalties to increase recycling of PV modules and encourage collection and Al recyclables.

Methods

Estimation of Al demand. The global capacity and added annual capacity (shipments) were obtained from fig. 85 of the 2021 ITRPV report[4], which represents the ITRPV's broad electrification scenario and its path towards a NZE economy in 2050. Although this is the most ambitious of the four scenarios presented by the ITRPV, historical module shipments have tracked closely with the predictions of this scenario.

We assumed that the PV market comprises rooftop and utility-scale systems. Rooftop modules are constrained by area and weight and hence, for these modules, we follow the ITRPV's power and area trends predicted for (smaller) 120 half-cell (assuming M6 wafer sizes) modules. The efficiency of these modules is predicted to increase from 20.8% in 2020 to 22.4% in 2030[4], primarily due to increased adoption of higher efficiency Si heterojunction and tunnel-oxide passivated contact modules over the currently dominant passivated emitter and rear cell technology. Between 2030 and 2050, we assumed the same rate of module efficiency increase owing to a growing contribution from Si tandem technology. Since area/weight restrictions are not so critical for the utility scale, we assumed that utility-scale modules followed the ITRPV's power and area trends for 144 half-cell (M6 wafers) modules. Module efficiencies are likely to be lower, owing to the criticality of cost for large ground-mounted installations, and are predicted to increase from 20.5% in 2020 to 21.9% in 2030[4] with passivated emitter and rear cell technology being retained for longer in the technology share due to its expected lower cost per watt. As with rooftop modules, we assumed that the efficiency trend of utility-scale modules would continue at the same rate from 2030 to 2050. The resulting module power and efficiency for each module type are listed in Supplementary Table 1 for 2020, 2030 and 2050. With this approach, we made no assumptions with regards to cell technology shares and trends, as they can be contentious, whereas trends based on market needs can be more robust.

Si wafer sizes are also expected to increase over the next 30 years and will result in increased module areas. Although module area will increase in increments as larger wafers are adopted by manufacturers, modules produced each year will comprise a mix of module types. As such, the module area was modelled as linearly incrementing following the trends in module area for both rooftop and utility-scale solar predicted by the ITRPV 2021[4] report. The average module area will continue to be larger for utility-scale modules, increasing from values of 2.2 m^2 in 2020 to 2.5 m^2 in 2050[4]. However, additional increases may be limited by packing efficiency in shipping containers. The size of rooftop modules is limited by the need for manual handling and consequently is only expected to increase from 1.8 to 2.0 m^2. Smaller modules can be achieved by either reducing the number of partial cells or, to a lesser degree, by using smaller wafer sizes for the rooftop market segment.

Manufacturing data were used for the mass of Al used in frames, mountings and inverters. The assumptions used for the Al demand calculations are summarized in Supplementary Table 1 and justified in more detail in Supplementary Sections 1 and 2. Our base model assumes that PV systems (including inverters) that are installed following 2020 continue to operate in the field for 30 years without replacement and that any additional replacement systems, installed to account for expected performance degradation in the installed systems, are insignificant with respect to the new capacity.

A key assumption in our model was that only rooftop installations use Al in their mountings[46] due to the importance of weight for these installations. Even though Al can provide superior corrosion resistance compared with steel, steel is typically used in utility-scale installations because of its lower cost and greater strength (for example, in high wind regions). However, depending on the growth of new non-rooftop applications (such as floating and building-integrated PV) where light weight may be critical, Al usage may also be required in non-rooftop installations in the future. As such, our estimated demand should be considered as a lower-limit (conservative) scenario.

GWP analysis. Rather than analyse the GWP emerging from the entire module production (that is, from the emissions that correlate with individual components, using a life cycle assessment methodology as reported previously by Fthenakis and Kim[47], for example), the Al demand GWP required for the ITRPV's broad electrification scenario was estimated using a simplified material flow analysis for a number of different scenarios assumed to occur in China. This allowed a more detailed analysis of the Al demand and its associated GWp. China was selected for the study as it currently is, and is expected to remain, the dominant manufacturer of crystalline Si modules[48]. It was also the largest Al primary producer in 2020. Our analysis assumed that the Al required for PV module production was produced through a combination of primary and secondary production, with forecasted annual secondary Al production levels predicted by Li et al. for China[21]. These forecast values were based on known resources of in-product Al and predicted Al use, a 16-yr average service lifetime for Al parts and a regeneration coefficient of 83% (which includes collection of scrap Al).

For the analysis in Figs. 3–5, the percentage of recycled content in the Al used for the added capacity was assumed to linearly increase from 34% in 2020[20] to 75% in 2050. The total pool of secondary Al in China available for recycling was interpolated from fig. 6 of Li et al.[21]. Given that it is unrealistic to expect that all the available secondary Al is directed into PV manufacturing, the sensitivity of the GWP of Al demand to the used fraction of this pool was evaluated for 33% and 100% of scrap Al pool usage. For each year of the analysis, the annual Al demand for PV manufacturing comprised the available secondary Al (up to the expected recycled content mass) with any shortfall being provided by primary production.

We assumed a primary production emissions intensity of 14.5 t CO_2e t^{-1} Al (refs. [30,31]) for 2020 and then considered different primary production emissions reduction scenarios to determine how they affected the estimated Al demand GWP. These scenarios included linear reductions in the primary production emissions intensity to 2050 targets of 1.5 (base scenario), 3.5, 5.5 and 7.5 t CO_2e t^{-1} Al and compared the resulting GWP with the worst case scenario in which the emissions intensity is unchanged at 14.5 t CO_2e t^{-1} Al until 2050 and a best case scenario in which the emissions intensity rapidly reduces to 5 t CO_2e t^{-1} Al by 2030 (assuming rapid decarbonization of electricity) and then more gradually reduces to the target of 1.5 t CO_2e t^{-1} Al by 2050 via process improvements. The secondary production emissions intensity was assumed to reduce to a lesser extent from a value that is ~4% of the world's average primary production emissions[18] (0.65 t CO_2e t^{-1} Al) to 0.5 t CO_2e t^{-1} Al by 2050 (that is, 0.5% reduction per year) due to process improvements.

Reducing the primary production emissions intensity to just 1.5 t CO_2e t^{-1} Al is very challenging. It will require effective elimination of all indirect emissions through decarbonization of electricity, heat (for refining and smelting; see the Supplementary Information for details) and mining/extraction. It will also require innovations in the Hall–Héroult electrolysis process to reduce all sources of significant direct emissions. For this reason, we also compared more moderate emissions reduction scenarios with higher final emissions intensities. Since our analysis assumed that PV manufacturing, Al refining and smelting all occur primarily in China during the period of interest, any changes that China can make in terms of transitioning to use more hydroelectricity or building their Al refineries and smelters close to solar PV and wind farms will largely determine the emissions reduction scenario that is most relevant.

Linear reductions in emissions were assumed in our modelling due to the difficulty associated with accurately predicting these trends given the number of factors involved. For example, changing political environments are expected to affect the rate at which electricity decarbonization can occur, the effectiveness of end-of-life collection and recycling schemes and the extent of technological innovation directed at addressing key direct emissions concerns (for example, low-emissions anodes for Al smelters).

Data availability

Data used for the modelling are available in Supplementary Dataset 1.

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Author contributions

A.L. conceived the study, conducted the modelling and was the primary author of the manuscript. M.L. and P.R.D. contributed to the discussion of sustainability and recycling and B.H. to the discussion on projected PV technology trends. All authors contributed to the manuscript structure and proof reading.

Competing interests

The authors declare no competing interests.

Additional information

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