The Aluminium Demand Risk of Terawatt Photovoltaics for Net Zero Emissions by 2050

Supporting Information

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S1. Aluminium Use in PV Modules

Mountings

The mountings that support PV modules can be constructed using steel or aluminium. Aluminium alloys have similar structural properties to steel, but their weight is ~ 30% of that of steel. Although aluminium is more expensive than steel, aluminium alloys allow for cheaper transportation due to their lesser weight resulting in lower fuel costs[1]. The light weight of aluminium frames is also important for rooftop PV installations with modules already weighing approximately 20 kg, close to the point at which two people are required to carry the modules onto the roof. Additionally, welding is not required as complex, as aluminium alloy shapes can be extruded as a single part. Aluminium also has higher corrosion resistance than steel in outdoor environments due to its thin surface layer of aluminium oxide. This oxide provides protection over pH values ranging between 4.5 and 8.5[1] and so, provided that the aluminium mountings are constructed on concrete pads, corrosion can be prevented over an installation's 25+ year operation.

There are also arguments for using extruded aluminium for mounting structures for ground-mount utility scale PV although, in most cases, lower cost galvanised steel has been used, especially where the strength of steel is required (e.g., high wind areas). Although aluminium is more expensive on a per kg basis, the overall cost per MW installed can be less due to lower installation and shipping costs. However, this depends on local economics.

Connecting aluminium frames to steel mountings can introduce problems associated with galvanic corrosion if connections between the two metals involve a large steel (cathode) area in contact with the aluminium frame. For routine installations, this potential issue can be managed using appropriate connectors and materials, however for new module assembly concepts and installations located in marine environments, galvanic corrosion between either mounting components or between modules and frames can reduce system lifetime. This concern is particular pertinent for floating PV, where the salty humid environment can rapidly promote galvanic corrosion. In these installations, aluminium may be required for both its light weight and resistance to galvanic corrosion. However, because the floating PV market is relatively new and localised (e.g., to countries like Japan and Singapore), it was difficult to obtain accurate data on aluminium usage and projected capacity to 2050. Consequently, in our model, all non-rooftop PV systems were classified as utility scale and it was assumed that all utility scale systems use steel mountings for their lower cost.

Utility scale PV is predicted to grow to account for ~60% of global capacity in 2050, with a combination of off-grid, residential, commercial and industrial rooftop accounting for 40%[2]. If it is assumed that: (i) rooftop-based installations continue to use lighter aluminium racks and mounting structures; and (ii) ground-mounted utility scale installations use largely steel mountings with some aluminium fixtures for low cost, then the projected aluminium demand for mountings to support installed PV can be estimated accordingly. The IEA estimated that 2.84 kg/m^2 of module area of aluminium was required for European rooftop PV mounting systems on a slanted roof installation[3]. However, it is anticipated that this usage will decrease with new mounting designs and as new methods of integrating PV modules into roofing materials[4-6] become adopted to a larger extent. This decreased use was modelled as 0.5% reduction per year, leading to a usage of ~ 2.4 kg/m^2 in 2050.

As a result of our assumption that utility scale continues to use steel mountings, our model is sensitive to the fraction of total annual added capacity that is utility scale. This fraction is expected to depend on government policies and incentives, and so, is difficult to forecast. For this reason, we consider utility scale percentages of 60 and 70% as indicative scenarios.

Inverters

The casings of inverters are typically made from aluminium alloys due to their corrosion resistance. Older inverters used larger fractions of steel for the casing, but in more recent inverters (post 2016), steel has been largely replaced by aluminium to reduce the weight of units. A 2016 European life cycle assessment reported that 5.0 kg and 20.5 kg aluminium was required for a 2.5 kW and 20 kW inverter, respectively[7]. This is ~ 1 kg/kW for an inverter which was estimated to have an average lifetime of ~ 15 years. A more recent report by Stamford and Azapagic assumed the aluminium content of a 3 kW inverter to be 1.43 kg (i.e., 0.48 kg/kW)[8]. In our modelling we have assumed the lower value of 0.48 kg/kW

Central and string inverters that are used for utility scale systems typically have a lifetimes of 10-25 years[9], however the warranties for most rooftop system inverters are closer to 5 years. This would mean, that inverters for both utility scale and rooftop systems would most likely require replacement during the period between 2020 and 2050. However, because it was difficult to obtain reliable data on the lifetime of inverters in the field as lifetime often is highlygh sensitive to field conditions, we elected not to include inverter replacement in our model. Consequently, our estimates of the mass of aluminium required for the inverters for PV systems are conservative

Module Frames

Aluminium alloys are typically used for PV module frames. The aluminium 5754 alloy, also called AlMg3 and containing 94.2-97.4% aluminium and 2.6-3.6% magnesium, is commonly used for crystalline silicon module frames [10] due to its light weight and excellent corrosion resistance. In 2021, typical modules required on average 0.5 kg aluminium per m of module perimeter (2021 PV manufacturing data; average of three manufacturers). This is ~1.2 kg/m^2 for a 600 W Trina Vertex module (TSM-DEG20C.20; module dimensions 2.172 m $\times$ 1.303 m) which corresponds to 5.8 Mt of aluminium per TW of PV and almost half that reported for modules in 2016[3]. This reduction in the aluminium usage for module frames has been largely due to increases in module efficiency and area (see below) and adoption of lighter weight frames. Our model of aluminium demand includes the effect of increased module area and efficiency as predicted by the 2021 ITRPV[11].

Although it was expected that aluminium frames would be gradually replaced by plastic frames in the ITRPV 2014 report, this transition has not occurred to any significant extent and the ITRPV 2021 report predicts that 80% of crystalline silicon modules will continue to use aluminium frames in 2030. However, longer range analyses suggest the current challenges presented by frameless and plastic frames may be resolved and by 2050, the use of aluminium in frames is expected to be significantly reduced[12]. In our model we have assumed that the frameless rate will increase from current values of 7% in 2020 to be ~ 50% in 2050.

It is possible that the introduction of carbon border taxes act to incentivise the manufacture of frameless PV modules or modules with alternative frame materials, if reducing the emissions associated with producing the aluminium for frames cannot be achieved in sufficient time. The effects of an introduced carbon border tax are not included in our model, however there would be scope in the future to consider this impact on the production of both modules and mountings.

Cells

Aluminium is used for the full surface of the rear electrode of aluminium back surface field (BSF) and monofacial passivated emitter rear cell (PERC). This usage was estimated at 800 mg per M6 PERC cell (or ~138 mg/W for a 21% efficient PERC cell) in 2021 reducing gradually to 700 mg by 2030. Bifacial cells require considerably less aluminium (~ 200 mg/M6 cell or ~35 mg/W for a 22% efficient bifacial cell) and bifaciality is expected to increase from 28% to ~ 78% by 2030[11]. If this trend to increasing bifaciality continues to 2050 then practically all c-Si PV modules by 2050 would be bifacial. A further trend that will affect the amount of aluminium used at the cell level is the gradual reduction in the PERC market share from 85 to 70% as increasing production capacities of thermal oxide passivated contact (TOPCon) and Si heterojunction (SHJ) technologies, which use even less Al[11], are introduced. However, even in 2021 when 28% cells were bifacial, a 72 M6 cell module would only use ~ 50 g of aluminium at the cell level, which is insignificant compared to the amount of aluminium required for collectively for the frames, mountings and associated electronics.

S2. Expected Changes in Module Area and Power

The average module efficiency was assumed to be 20.8% for 120 half-M6 cells rooftop modules and 20.4% for 144 half-M6 cell utility scale modules in 2020[11]. Approximately 80% of these modules use p-type PERC cells. Over the next 30 years, modules are expected to use higher efficiency n-type TOPCon and HJT cells, with the ITRPV predicting average module efficiencies of 23.3% and 22.9%, respectively, for rooftop and utility scale modules in 2030. We assume that the same trend in average module efficiency continues to 2050, with Si tandem modules (of efficiency ~ 26%) contributing a larger fraction of the share in 2050.

Wafer sizes are also expected to increase over the 30 years considered in our model resulting in increased module areas. Although module area will increase in increments as larger wafers are adopted by manufacturers, modules produced in each year will comprise a mix of module types and so the module area was modelled as linearly incrementing following the trend in module area for both rooftop and utility scale solar.

Module areas will continue to be larger for utility scale increasing from values of 2.2 m^2 in 2020 to 2.5 m^2 in 2050[11]. Rooftop module size is limited by the need for manual handling and consequently are only expected to increase in size from 1.8 to 2.0 m^2. The smaller module can be achieved by either a reduced number of partial cells and, to a lesser degree, by use of smaller wafer sizes for the rooftop market segment.

S3. Aluminium Demand Scenario Results

Figure S1 and Figure S2 show: (i) the annual and cumulative aluminium demand for the cases of 0.5% annual average module degradation; and (ii) the lower rooftop PV fraction of 30% by 2050, respectively. All other parameters are as shown in Table 1.

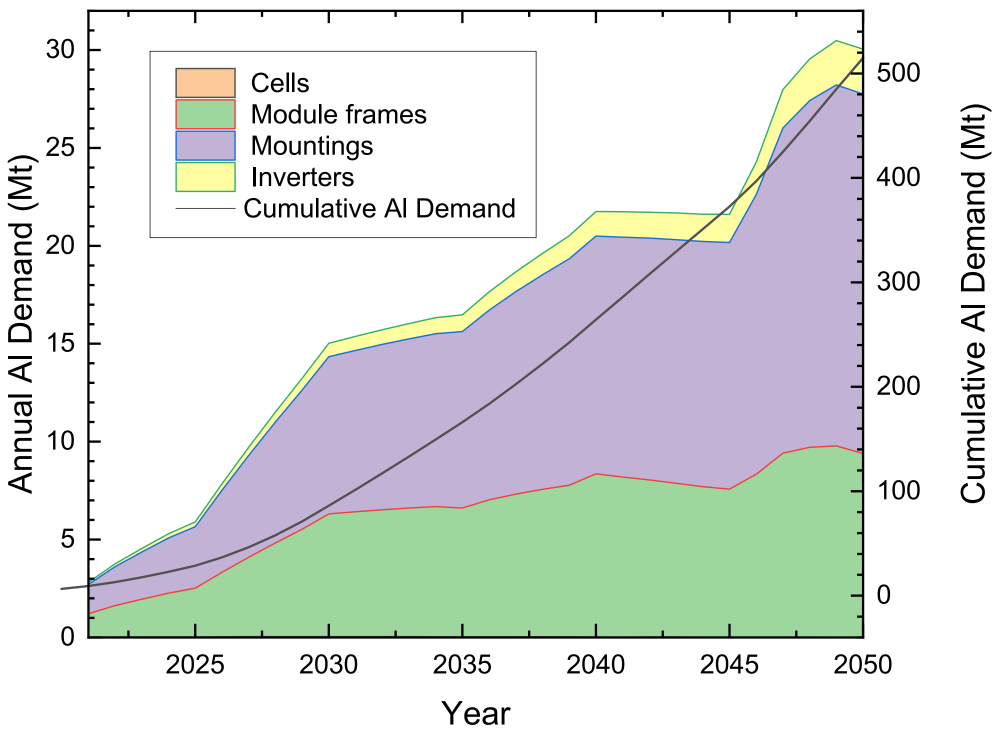

Figure S1. Annual (left) and cumulative (right) aluminium demand for the ITRPV broad electrification scenario from 2021-2050 for the base case of 40% rooftop modules by 2050 and assuming 0.5% average module degradation in the field.

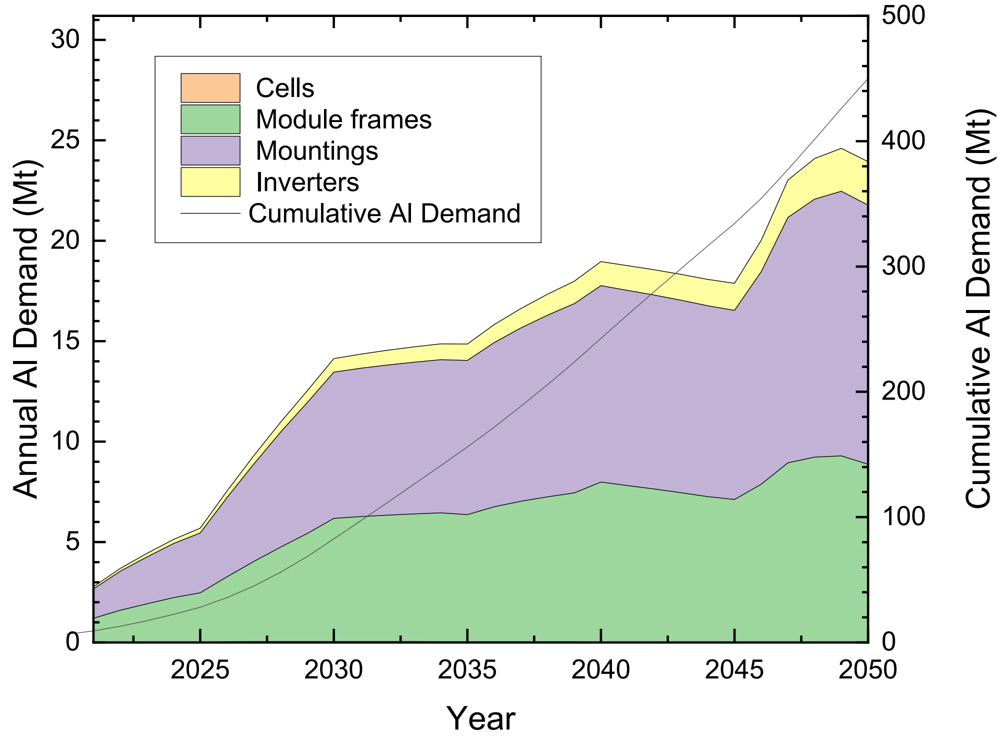

Figure S2. Annual (left) and cumulative (right) aluminium demand for the ITRPV broad electrification scenario from 2021-2050 for the case of just 30% rooftop modules by 2050 and assuming minimal module degradation in the field.

S4. Aluminium Production and its Global Warming Potential

A combination of secondary and primary aluminium production will be required to resource the aluminium demand presented by the capacity additions required to achieve the 2021 ITRPV broad electrification scenario. It is shown that reduction of the primary emissions intensity will be critical to reduce the GWP. We provide more detail below of the primary production process.

Primary Production

The Bayer process produces smelter-grade alumina which comprises ~99.5% Al_2O_3, starting from bauxite that contains just 30% to 60% Al_2O_3. The bauxite is washed in a hot solution of NaOH at 250 °C, which dissolves the $Al(OH)_3$. The other components of bauxite do not dissolve and can be filtered out as solid impurities. On cooling, the $Al(OH)_3$ precipitates and can then be converted to Al_2O_3 by calcining at temperatures of 1050 °C[13]. The average energy consumption of this process is 12 GJ/t and ranges between 7.2 and 21.9 GJ/t depending on the process[14]. Most of this energy is required as thermal energy, with a much smaller fraction (~ 3-4%[15]) being supplied as electricity.

The Hall-Héroult electrolysis process has been in use for more than a century. In this process Al_2O_3 is dissolved in molten cryolite (Na_3AlF_6) at 960 °C where it decomposes to oxygen and liquid Al. As aluminium is denser than the molten cryolite, it deposits at the bottom of the cathode and the oxygen reacts with a pre-baked C anode to form $CO_2(g)$ according to:

$$2Al_2O_3(solution) + 3C(s) \rightarrow 4Al(l) + 3CO_2(g) \qquad \text{Eq. S1}$$

The carbon anodes are a fuel which is consumed at a rate of 450 kg per tonne of aluminium produced[16] and the CO_2 generated contributes direct emissions to the process. Liquid aluminium, from the electrolysis process, is then transferred to the cast house, which is usually an integrated part of the smelter. In the cast, alloy element ingots are added to the melt to produce the desired alloys. The energy required for the electrolysis process is ~ 55 GJ/t of aluminium[15], which is provided as electricity. About half of this energy is converted to heat in the process. The IEA reported a combined refining and smelting energy intensity of 62.6 GJ / t aluminium.[17]

Table S1 compares world average energy intensities and emissions intensities for aluminium, copper and steel. Variations exist in values reported due to different processing practices and ore quality (see, for example, for copper); however, the values provided can provide a comparative guide. For electricity intensive processes, such as aluminium primary production, average emissions intensities are quoted for low and high carbon electricity grids as a guide.

Table S1. World average energy and emission intensities of primary production for selected metals required for clean energy technologies in 2020.

Metal	Average energy intensity (GJ / t metal)	Average emissions intensity (t CO_2e / t metal)
Aluminium	11.5 (refining)[17] 51.1 (smelting)[17] 62.6 (combined)[17]	21 (high carbon electricity 2018)[18] World average (2018)[18] 5.5 (low carbon electricity 2018)[18] 14.5 (China, 2017)[19,20]
Copper	28-36 (concentrate)[21] 20-29 (heap leaching)[21]	4.7 (high C electricity)[21] 1.4 (low C electricity)[21]
Steel	19[22]	1.2 – 2.2[22]

S5. Global Warming Scenario Results

Figure S3 shows the annual and cumulative emissions that would result with the different aluminium primary emission reduction scenarios shown in Figure 3. Aluminium demand is calculated for the base case of 60% utility scale PV by 2050 and parameters as detailed in Table 1.

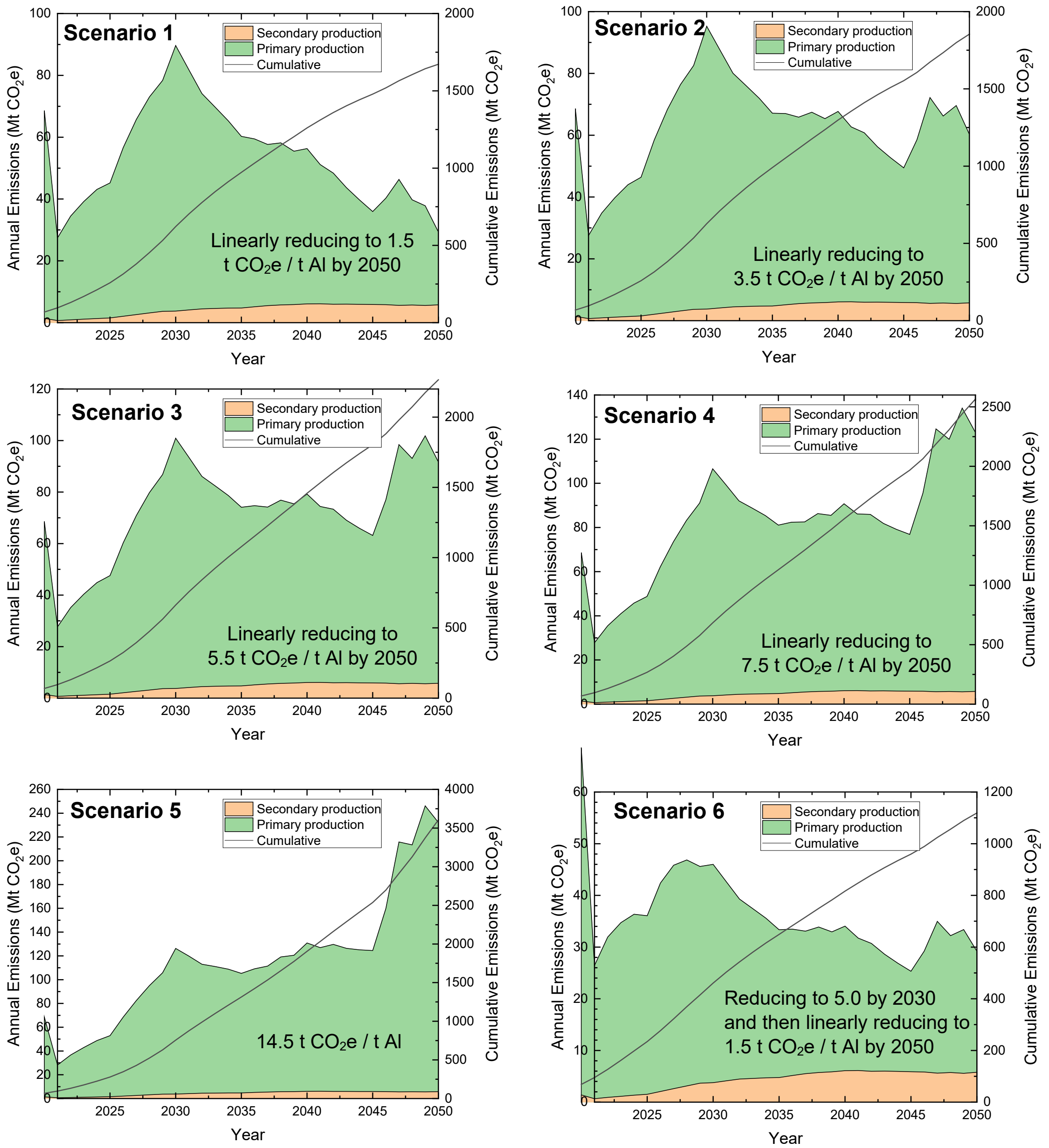

Figure S3. Annual (left y-axis) and cumulative (right y-axis) emissions from primary and secondary aluminium production in China required for the aluminium demand shown in Figure 2 under the different aluminium primary emissions reduction scenarios shown in Figure 3. All scenarios assume a primary production emissions intensity of 14.5 t CO_2e / t aluminium for 2021.

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