TECHNICAL APPENDIX

MISSION POSSIBLE PARTNERSHIP

MAKING NET-ZERO ALUMINIUM POSSIBLE

An industry-backed, 1.5°C-aligned transition strategy

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1. Emissions scope

Overview of emissions included in scope

The International Aluminium Institute's (IAI) cradle-to-gate emissions scope for the aluminium sector includes all direct and indirect emissions from primary production steps (including mining, refining, anode production, smelting, and casting), and secondary production and downstream processes (including recycling, semis production and remelting). For alumina production, the IAI only includes metallurgical grade alumina and excludes the emissions associated with chemical grade alumina. The STS similarly follows this scope boundary, only accounting for alumina refineries producing metallurgical grade product.

The IAI's sectoral emissions have been broken down into two buckets for the purpose of the STS modelling and analysis (Exhibit TA.1.1):

1. All asset-level direct emissions and indirect emissions (only from electricity) at refineries and smelters. These are included directly in the STS modelling and scenarios.
2. All other remaining emissions sources projected at the global level.

IAI – Aluminium Sector Emissions (million tonnes of CO_2e in 2018)

	Electricity - Indirect	PFC - Direct	Process CO_2 - Direct	Ancillary Materials[1] - Indirect	Thermal Energy - Direct/Indirect	Transport[3] - Indirect	Total
Mining	0.6	-	-	-	2.6	-	**3.2**
Refining	16.9	-	-	14.8	124.3[2]	15.4	**171.4**
Anode Production	-	-	6.4	19.3	6.4[2]	-	**32.1**
Electrolysis	670.2	35.4	92.6	6.4	-	18.7	**823.3**
Casting	-	-	-	-	6.4	-	**6.4**
Primary Total	**687.7**	**35.4**	**99.0**	**40.5**	**139.7**	**34.1**	**1036.4**
Recycling[4]	3.1	-	-	-	15.6	-	**18.7**
Semis Production[5]	9.5	-	-	-	19.0	-	**28.5**
Remelting[6]	2.5	-	-	-	8.4	-	**10.9**

% of Total Emissions		
	86%	Detailed decarbonisation pathway (i.e. asset-level granularity) with cost-optimisation technology selection
	14%	Projected decarbonisation pathway based on IAI's GHG pathways modelling

Notes:
[1] Ancillary materials cover any chemicals or materials that are used in the process, which include the GHG impacts associated with the production of caustic soda, lime, aluminium fluoride, pitch, and coke production. IAI utilizes life cycle databases (e.g., GaBI) to compile the emissions data.
[2] Direct emissions from thermal energy requirements in refining and anode production (~85% of total) are included in the detailed decarbonisation pathway scope.
[3] Note transport emissions are not modelled in detail, e.g., shipping or trucking, as these are included in other MPP sectoral scopes.
[4] Recycling of post-consumer scrap (i.e., old scrap) and remelting of pre-consumer scrap from part-manufacturers (i.e., new scrap), including sorting and casting emissions.
[5] Fabrication of all primary/secondary aluminium.
[6] Remelting of pre-consumer scrap from the fabricator (also known as fabricator scrap, internal or run-around scrap).
Source: International Aluminium Institute (IAI), 2018

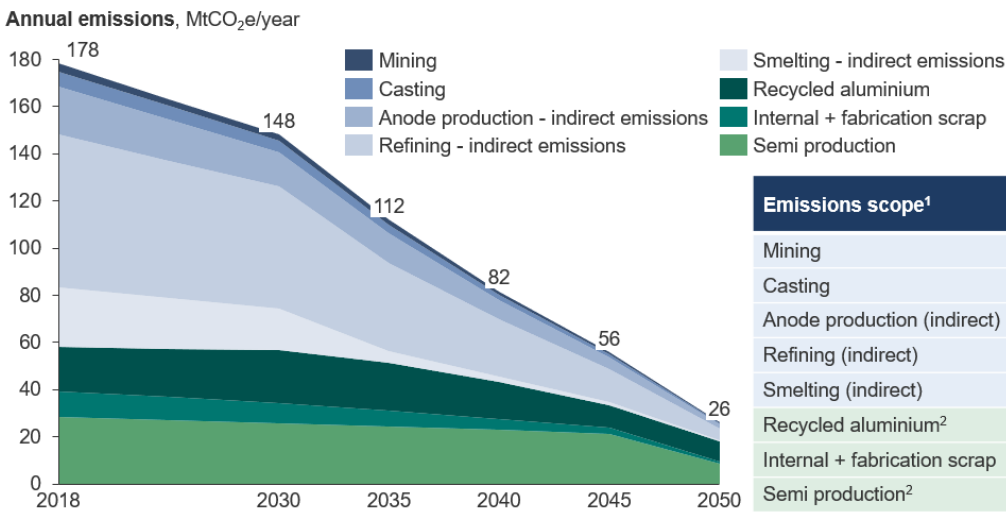
Exhibit TA.1.1: Scope of emissions considered in the aluminium STS

Asset-level emissions sources in the STS

The table above (Exhibit TA1.1) shows which emissions sources were incorporated into the asset-level modelling for the STS. This includes: (1) all indirect emissions from electricity consumption at refineries and smelters, (2) direct PFC and process CO_2 emissions from the smelting and anode production processes[i], and (3) direct emissions from the consumption of fossil fuels for thermal energy within refining and anode production. Taken together, these three emissions categories represent over 85% of the total aluminium sector's global emissions.

Explanation of how other emissions categories were considered in the STS

For the remaining emissions sources not modelled at the asset-level in the STS, analysis of their decarbonisation trajectory is taken from the IAI's 1.5°C scenario as shown in Exhibit TA1.2 below. In primary production, this includes emissions related to mining bauxite and casting aluminium into ingots, as well as indirect emissions associated with anode production, refining and smelting (excluding indirect emissions associated with electricity production, as previously discussed these are included in the STS scope boundary). The trajectory below also shows emissions reductions for recycling, internal and fabrication scrap processing, and semis production.



Emissions scope[1]	% reduction 2018 to 2050
Mining	91%
Casting	91%
Anode production (indirect)	91%
Refining (indirect)	92%
Smelting (indirect)	98%
Recycled aluminium[2]	55%
Internal + fabrication scrap	89%
Semi production[2]	71%

Notes:
[1] Indirect emissions for smelting exclude emissions associated with electricity generation, which are captured in the core STS modelling. Indirect emissions for refining excludes emissions associated with electrified digestion/calcination processes, but include emissions associated with electricity used for auxiliary plant equipment.
[2] Reduction in emissions intensity (tCO_2e/t) of recycled and semi production between 2018 and 2050 are 82% and 81%, respectively. However, total emissions $MtCO_2e$ do not decrease at same rate as a result of total secondary production increasing in the 1.5-degree scenario.
Source: IAI 1.5 Degrees Scenario (2021)

Exhibit TA1.2: Decarbonisation trajectory for aluminium value chain outside of the STS core modelling scope

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[i] While anode production emissions were assessed at the asset-level in the STS model, this is not the case in reality. Although a majority of smelters have anode production on-site, an estimated 40-50% of global capacity of carbon anodes are produced off-site and purchased on a merchant market. For simplicity, the STS associates direct emissions from upstream anode production to each individual smelter, irrespective of whether it does or does not have an anode production facility on-site.

2. STS modelling

2.1 Overview of model logic

The Aluminium Sector Transition Strategy Model (AL-STSM) calculates pathways to net-zero emissions by 2050 for the aluminium sector.

The model does this by assessing the business case for switching a given plant to a new technology archetype. 30 technology archetypes for refineries and 24 technology archetypes for smelters are considered in the model. Business cases for each of these archetypes consider feedstock, fuel, and energy consumption, associated emissions, and operating and capital expenditures from publicly available data sources.

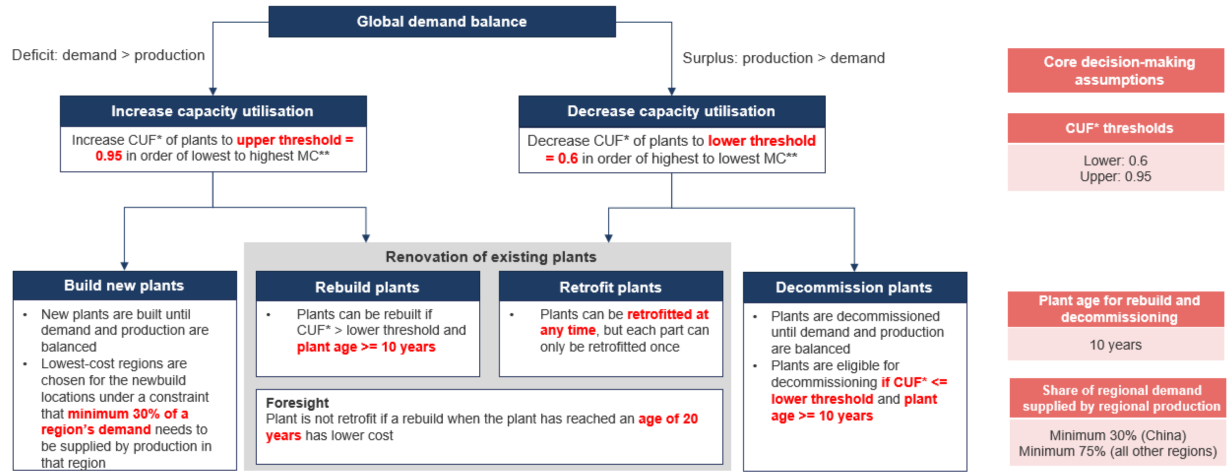
We calculate the business case for every possible technology switch combination, for every year between 2020 to 2050, considering the lifetime of assets and regional weighted average cost of capital (WACC). Based on these inputs, we derive total cost of ownership (TCO), capital expenditure (CAPEX) and levelized costs per ton of output product. Four types of switches are considered: decommissioning, retrofits (where only a part of the asset is changed), brownfield new build (where an existing plant is decommissioned and a new one with a different technology is built in its place) and greenfield (where a new plant is built from scratch).

The business cases for possible technology switch combinations are then fed into a Python-based bottom-up decision making model to optimize technology choices. The model calculates a production pathway to meet the two demand scenarios we use in our analysis: a BAU scenario where primary aluminium demand grows in line with GDP and population growth and a 1.5°C compliant scenario where we maximize circularity levers for material efficiency and recycling.

The model assesses the technological, economic, and carbon emissions implications of 95 alumina refineries and 181 primary smelters in 11 geopolitical regions transitioning to net-zero production. The model solves for a global demand of alumina and aluminium, while meeting a local production constraint of 30% of the local alumina and aluminium demand within China, and 75% for all other regions.

The simulation takes a step-by-step approach (Exhibit TA2.1). For every year, the model calculates the global demand balance. Where there is a deficit or surplus in total production from all modelled assets, the model adjusts the assets' Capacity Utilization Factors (CUF) to try to meet the demand. Once the CUF having been adjusted, the model re-calculates the global demand balance. On the one hand, if a deficit in production remains, the model builds new plants, picking the best technology based on the business case (e.g. technology with lowest cost, least carbon intensive technology). On the other hand, if production still exceeds demand, the model decommissions plants starting with the ones that have the lowest CUF. After the model has adjusted the CUF and made related decommissioning and building decisions, it starts considering possible retrofits to existing assets. In this phase, the model picks the best possible transition (e.g. staying with the same technology, rebuilding the plant or retrofitting the plant), and looks for possible plants to undergo such a transition. These steps are repeated every year during the entire simulation period.

The model is intended to be a flexible tool for interested parties to (1) determine the milestones necessary for the aluminium sector to decarbonise, and (2) initiate concrete action, considering different net-zero scenarios. The model is based on predefined scenarios but can be customized at a granular level via custom parameter settings.



*CUF: Capacity Utilisation Factor. **MC: marginal cost of production (in USD/tonne produced).

Exhibit TA2.1: Capacity utilisation and plant investment decisions are optimised year-by-year

2.2 **Overview of scenarios**

In the modelling exercise, we run a series of scenarios which illustrate different aspects of the transition and sensitivity analyses on selected input prices. These are detailed in the table below (Exhibit TA2.2):

	Business-As-Usual Scenario (BAU)	1.5-Degree Aligned Scenario (1.5DS)	Alternative Scenarios
Primary Alum. Demand[1] *(% increase in demand, 2020-50)*	**High growth:** aligned with IAI reference scenario – 32%	**Moderate growth:** aligned with IAI 1.5 degree scenario – 4%	**High Substitution:** aligned with IAI high substitution scenario – 57%
Recycling *(% increase, 2020-50)*	275% growth in secondary production	245% growth in secondary production	
Resource & Material Efficiency	No further efficiency gains	Resource and material efficiency limiting growth in total aluminium demand to 50%	
Power Grid *(variation between regions)*	Electricity price in 2035: $35 to 125 /MWh Carbon intensity in 2035: 5 to 550 g/kWh	Electricity price in 2035: $35 to 90 /MWh Carbon intensity in 2035: 2 to 380 g/kWh	**Rapid Grid Decarbonisation**: low carbon power available through the grid by 2035
Decision Making	Selection of lowest cost technology of meeting demand	Selection of lowest cost technology to meet the 1.5 degree budget	**Fastest Abatement:** firms can only choose low carbon options
Remaining emissions *(Mt CO_2e emissions in 2050)*	Aligned with IAI reference scenario (250 Mt CO_2e)	Aligned closely to IAI 1.5 degree scenario (84 Mt CO_2e)	
Other key assumptions			**Carbon Cost:** adds an increasing carbon cost to TCO decision making **No CCS:** CCS is unavailable for meeting smelter power needs

Notes: 1) Total aluminium demand growth (primary and secondary aluminium) in each scenario: BAU (81%), 1.5DS (50%) and High Substitution (94%).
Sources: Aluminium Sector Transition Strategy Model (2022), IAI Material Flow Model (2021)

Exhibit TA2.2: Summary of scenarios modelled

2.3 Overview of demand model

The STS has been constructed with an existing set of primary aluminium demand projections from the IAI's work. The IAI's demand projections are based on a detailed regional material flow analysis that has been published academically and informed by data and discussions with regional aluminium associations and producers. The model quantifies regional stocks and flows of rolled, extruded, and casting alloys across space and over time. The model calculates regional domestic scrap availability and metal demand of the same alloy group and differentiates new and old scrap in each group at a given point in time. This is based on primary metal production, semi-fabricated products shipment, and trade data from 1950s to 2014. Nine regions are covered: China, Europe, Japan, Middle East, North America, Other Asia, Other Producing Countries, South America, and Rest of World.

For more details on methodology, please refer to the published academic paper: "A regionally-linked, dynamic material flow modelling tool for rolled, extruded and cast aluminium products" by M. Bertram et al. A publicly accessible version of the material flow model 'Alucycle' with interactive features can be found on the IAI's website: https://alucycle.international-aluminium.org/

3. Techno-economic assumptions on refining and smelting technologies

3.1 Refining

Low-temperature (100°C–320°C) coal, gas or oil boilers are currently used by the industry to generate steam for digestion. The STS considers four low-carbon alternatives: electric boilers, hydrogen boilers, mechanical vapour recompression (MVR), and concentrated solar thermal (CST). Similarly, conventional calciners rely on gas or oil combustion to produce heat at temperatures ranging from 1000°C to 1300°C. Hydrogen- or electricity-based calcination are the two most promising avenues explored by the industry to abate emissions from this process step. The STS outputs are based on the following techno-economic input assumptions (Exhibits TA3.1 and TA3.2), which are derived from public sources, and which have been refined and validated through stakeholder engagement:

Digestion	Gas Boiler	Oil Boiler	Coal Boiler	Electric Boiler	Hydrogen Boiler	MVR	CST[ii]
TRL	9	9	9	9	8	7	7
Market availability	2020	2020	2020	2020	2027[1]	2027[1]	2027[1]
Lifetime	25 y.[2]	25 y.[2]	25 y. [2]	25 y. [2]	25 y.[3]	25 y. [2]	25 y.[4]
2020 Efficiency	92 %[2]	94 %[2]	89 %[2]	99 %[2]	90 %[3]	300 %[1]	n.a.
2050 Efficiency	94 %[2]	96 %[2]	91 %[2]	99 %[2]	90 %[3]	300 %[1]	n.a.
Thermal energy intensity	6.75 GJ/t Aa[iii] (Note: this varies by region in the model)						
CAPEX	**16 $/t Aa** 65 $/kW[2]	**16 $/t Aa** 65 $/kW[2]	**149 $/t Aa** 592 $/kW[2]	**24 $/t Aa** 95 $/kW[1]	**42 $/t Aa** 166 $/kW[3]	**230 $/t Aa** 924 $/kW[4]	**517 $/t Aa** 2,070 $/kW[4]
Fixed OPEX	**0.6 $/t Aa** 2.4 $/kW[2]	**0.5 $/t Aa** 2.1 $/kW[2]	**10 $/t Aa** 40 $/kW[2]	**0.3 $/t Aa** 1.3 $/kW[2]	**1 $/t Aa**[3]	**0.6 $/t Aa** 2.4 $/kW[1]	**9.2 $/tAa** 37 $/kW[4,5,iv]
Variable OPEX (excl. fuel)	**2.4 $/t Aa** 1.2 $/MWh[2]	**2.1 $/t Aa** 1.1 $/MWh[2]	**2.6 $/t Aa** 1.3 $/MWh[2]	**1.2 $/t Aa** 0.6 $/MWh[2]	**4.2 $/t Aa**[3]	**4.3 $/t Aa** 2.1 $/MWh[1]	**1 $/tAa** 0.5 $/MWh[4]
Total OPEX (excl. fuel)	**3 $/t Aa**	**2.6 $/t Aa**	**12.6 $/t Aa**	**1.5 $/t Aa**	**5.2 $/t Aa**	**4.9 $/t Aa**	**10.2 $/t Aa**

Exhibit TA3.1: Alumina refining steam production (digestion) technical parameters

[ii] Assumptions for a 392 MWth CST tower plant with 14 hours of thermal energy storage (TES) capacity.

[iii] Assuming 69% of thermal energy required in refineries is used for digestion, amounting to ~7.3 GJ/t alumina based on the IAI 2020 global average.

[iv] CST tower plant's fixed OPEX is assumed to account for 90% of total OPEX. Source: Assessment of Technology Options for Development of Concentrating Solar Power in South Africa (Fichtner, 2010)

Calcination	Fossil Calciner[v]	Hydrogen Calciner[vi]	Electric Calciner[vii]
TRL	9	4-5	4-5
Market availability	2020	2030[1]	2030[1]
Lifetime	25 y.[1]	25 y. [1]	25 y.[1]
2020 Efficiency	Gas/Oil - 88%[6]	92%[7]	95%[7]
2050 Efficiency	Gas/Oil - 88%[6]	92%[7]	95%[7]
Thermal energy intensity	3 GJ/t Aa[viii] (Note: this varies by region in the model)		
CAPEX	**75 $/t Aa[8]**	**111 $/t Aa** 985 $/kW[7]	**156 $/t Aa** 1,376 $/kW[7]
Fixed OPEX	**0.4 $/t Aa**	**0.4 $/t Aa** 3.2 $/kW[7]	**0.3 $/t Aa** 2.4 $/kW[7]
Variable OPEX (excl. fuel)	**0.4 $/t Aa**	**0.4 $/t Aa** 0.4 $/MWh[7]	**0.2 $/t Aa** 0.3 $/MWh[7]
Total OPEX (excl. fuel)	**0.8 $/t Aa[ix]**	**0.8 $/t Aa**	**0.5 $/t Aa**

Exhibit TA3.2: Alumina refining calcination technical parameters

Market availability designates the year in which a technology becomes available for adoption in our modelling. Asset lifetime is the approximate number of years during which an asset can be used before it has to be replaced. Efficiency factors and regional thermal energy intensities are used to calculate fuel consumption per tonne of alumina and technology.

CAPEX values vary by region, in line with regional thermal energy intensities, and over time. CAPEX projections until 2050 are based on the following three principles: (1) CAPEX for conventional (i.e., fossil-fuel based) technologies is assumed constant; (2) CAPEX for high TRL low-carbon alternatives is assumed to progressively decline until it becomes level with the relevant conventional equivalent; (3) CAPEX for low TRL low-carbon alternatives is assumed to gradually decline by 15% between 2020 and 2050. OPEX values also vary based on regional thermal energy intensities. Fuel costs are added to TCO calculations in line with regional fuel prices. Both CAPEX and OPEX estimates derived from sources published prior to 2020 have been adjusted for inflation using an aggregate OECD producer price index (PPI).

Biomass boilers were considered but excluded from our analysis to align with MPP's cross-sectoral biomass allocation model. The availability of biomass being constrained, its supply is

[v] Assumptions based on a circulating fluidized bed (CFB) calciner.

[vi] Assumptions based on a direct-firing hydrogen heater proxy; tested and validated during stakeholder engagement.

[vii] Assumptions based on a large-scale electric ceramic tunnel kiln proxy; tested and validated during stakeholder engagement.

[viii] Assuming 31% of thermal energy required in refineries is used for calcination, amounting to ~3.3 GJ/t alumina based on the IAI 2020 global average.

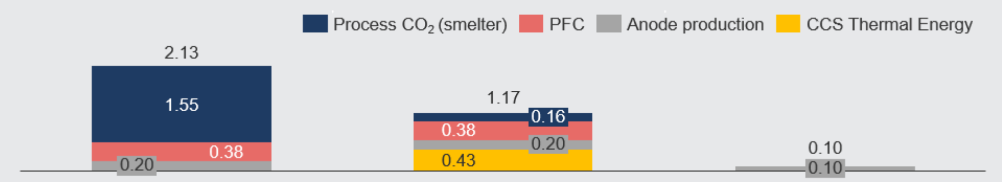
[ix] Based on assumption that total OPEX amount to 1% of CAPEX; tested and validated during stakeholder engagement.

prioritised for sectors which do not have viable alternatives to reach net-zero emissions by mid-century (e.g., aviation's reliance on sustainable aviation fuels). Given the availability of alternatives in aluminium, no biomass supply was allocated to the sector. However, while switching to biomass is not permitted in the STS modelling, existing refineries running on biomass are not required to switch to an alternative low-carbon fuel.

Likewise, consideration was given to retrofitting fossil-fuel based calciners with CCS, but this option was not retained in our modelling. This is because (1) there is no known industrial example exploring CCS retrofits to calciners, and (2) the scale of carbon capture on a calciner is likely to be too small for the technology to be economically viable.

3.2 Smelting

Aluminium is produced from alumina through electrolysis. The process (known as the Hall-Héroult process) results in CO_2 and PFC emissions, which are respectively caused by the reaction of the oxygen freed from the alumina with the carbon anode, and by the occurrence of anode effects[x]. The STS studies the possible role of two technologies with the potential to abate direct emissions from smelting: carbon capture and storage (CCS) and inert anodes. Our modelling is based on the following techno-economic input assumptions, which are derived from public sources, and which have been refined and validated through stakeholder engagement.

	Hall-Héroult (HH)	HH+CCS	Inert anodes
TRL	9	3-4	7
Market availability	2020	2030	2030
Alumina consumption kg/t aluminium	1,935[9]		
Electricity consumption MWh/t aluminium	13.5-17.2[10]	13.5-17.2 (+0.2)[xi]	13.5-17.2[xii]
Direct emissions tCO_2e/t aluminium[9,11]			
Details	• Representative average process CO_2 and PFC emissions assumed • Anode production emissions include process CO_2 and thermal energy	• 90% capture of smelter process CO_2, not PFCs or anode production emissions • CCS requires additional thermal energy (assumed natural gas)	• Emissions from thermal energy required to produce anodes
New build CAPEX Greenfield (brownfield) USD/t aluminium	6,000 (4,851)[xiii,12]	6,285 (5,136)[xiv,13]	6,000 (4,851)[1]

[x] Anode effects describe rapid voltage increases that occur when the alumina content in the electrolytic bath decrease below required levels. These voltage increases cause carbon from the anode to react with the fluorine found in the molten cryolite bath, which generates PFCs.

[xi] (+0.2) corresponds to the increase in electricity consumption from operating the CCS plant.

[xii] Inert anodes assumed to require the same amount of electricity consumption as carbon anodes; assumption developed and validated during stakeholder engagement.

[xiii] Representative average smelter. Excludes capital costs for a captive power plant, an anode baking furnace, or an anode raw material plant.

[xiv] Assuming CO_2 concentration of 1.2% in smelter flue gases.

Retrofit CAPEX USD/t aluminium	-	285[xiii,13]	3,000[xv,14]
Total OPEX USD/t aluminium	**1,764**	**1,849**	**1,595**
Alumina[xvi]	*756*	*756*	*756*
Electricity[xv]	*512*	*512*	*512*
Anode[15]	*250*	*250*	*100*[xviii]
Labour[16]	*95*	*95*	*80*[xix]
Other costs[xvii,16]	*151*	*151*	*147*
CCS plant O&M costs	*-*	*39*	*-*
CCS plant fuel costs	*-*	*46*	*-*

Exhibit TA3.3: Smelter technology technical parameters

As for digestion and calcination technologies, market availability designates the year in which a technology becomes available for adoption in our modelling. Alumina consumption is standardised across technologies, region and time and is used to calculate the cost of alumina in each technology archetype's TCO. Electricity consumption varies regionally based on IAI data and is fixed over time (i.e., we do not model possible improvements in smelters' energy efficiency). It is used to calculate the cost of electricity as well as scope 2 emissions per tonne of aluminium. Direct emissions are assumed constant across regions and time.

CAPEX does not vary regionally. Our model assumes that CAPEX for the incumbent Hall-Héroult archetype is constant until 2050, while CAPEX for CCS and inert anodes progressively decreases by 15%. OPEX varies by region in line with local alumina and electricity prices. Both CAPEX and OPEX estimates derived from sources published prior to 2020 have been adjusted for inflation using an aggregate OECD producer price index (PPI).

The STS does not consider carbochlorination with CO regeneration as a low-carbon alternative to conventional smelting. However it is in development by a number of aluminium producers and other technology developers. Future development of aluminium modelling could consider this provided there is available cost and performance data.

[xv] Assuming a smelter with 500 cells and 250kt capacity with a retrofit cost of $1.5M USD per cell; assumption tested and validated during stakeholder engagement.

[xvi] Representative value only, model takes into account regional alumina and electricity prices.

[xvii] Other costs include AlF, cell rebuild, maintenance, and other G&A costs.

[xviii] Approximated assuming longer lifetime of inert anodes (1 year) versus carbon anodes (1 month), but also 6x material cost for inert anodes. Source: expert interviews, 2022.

[xix] Conservative assumption based on labour productivity gains and increased anode lifetime. Source: expert interviews, 2022.

4. Techno-economic assumptions on power supply and energy prices

4.1 Power decarbonisation technologies

The bulk of emissions in the aluminium sector comes from electricity consumption in the smelting process. To decarbonise smelters' power supply, several options exist. Techno-economic assumptions that underlie our modelling can be found for each of these in Exhibit TA4.1 below. These assumptions are derived from public sources and have been refined and validated through stakeholder engagement:

	Coal+CCS	Gas+CCS	Hydro	PPA + Grid	Nuclear SMR	Grid
TRL	9	8	9	9	4-5	9
Emissions (tCO_2e/MWhe)	0.11	0.05	-	-	-	-
CAPEX – New Build ($ mil /MW)	4.5	2.6	1.3 – 1.5	1.1	5.0 – 6.0	1.1
CAPEX – Retrofit ($ mil /MW)	0.6 – 2.7	0.7 – 3.1	-	-	-	-
OPEX ($ k /MW)	252	70 – 130	7-31	-	513	-
Capacity Factor (%)	90%	90%	80%	100%	90%	100%
2030 LCOE (USD/MWh)	~60-82	~34-70	~26-28	50-107	*Not available until 2035*	~65

Exhibit TA4.1: Smelter power supply technical assumptions

Cost values for the power supply options above vary by region, over time, and, in some instances, by scenario. For grid (and PPA+grid) power sources related CAPEX, it covers costs associated with building a connection from the smelter to the grid. The approaches for technology costs are as follows:

1) For CAPEX, non-fuel OPEX, capacity factors, and grid mixes:
    a. For North America, these are based on a decarbonized version of the Williams et al. (2021) paper with the 2050 mix being reached in 2040 and extrapolated into net-zero onwards
    b. For EU, the calculation uses the Fit for 55 scenario to 2030 and then scaled from 2030 to 2050 in line with REF scenario with net-zero by 2050 set as the ultimate goal (i.e. all unabated fossil fuels phased out by 2050).
    c. Rest of World, including China and India: based on a mix of BP energy statistics the IEA World Energy Outlook 2021 Net-zero Scenario - adjusted so net-zero is reached by 2050

2) For CAPEX and OPEX of coal+CCS and natural gas+CCS, the costs are calculated from the IPCC Special Report on Carbon Dioxide Capture and Storage, which is being used as the base for the regional extrapolation.
3) It is assumed that there will be no dedicated hydro facilities built for a smelter. The vast majority of newbuild hydro facilities are in China and these are connected to the grid as opposed to captive power for a smelter.

4.2 Energy prices

Fossil fuel prices

2020 prices for natural gas, thermal coal and crude oil are taken from regional spot market indices. Price projections until 2050 are calculated based on the IEA's World Energy Outlook[17]. These projections are made for two scenarios: a business-as-usual (BAU) scenario based on the IEA's Stated Policies scenario, and a Decarbonized World scenario based on the IEA's NZE scenario. In our modelling, BAU prices underpin our BAU scenario, while Decarbonized World prices are used for all other net-zero scenarios. To account for near term spikes in fossil fuel prices, pricing for 2021 and 2022 is based on the World Bank's Commodity Markets Outlook[18]. Following 2022, prices are assumed to decline back to original IEA estimates by 2025. Price projections until 2050 are calculated by applying implied growth rates from the IEA scenarios to 2025 regional estimates.

Grid and PPA prices

Grid and PPA prices are sourced from the MPP's Power Pricing Model. Levelized costs of energy (LCOEs) are calculated for each power supply technology based on their respective CAPEX, OPEX, fuel costs, capacity factors, and WACC. All input assumptions are taken from open-source data, which is mainly obtained from the IEA, Bloomberg New Energy Finance (BNEF), and the European Commission's Joint Research Centre (JRC).

Grid prices are calculated by:
(1) Weighing the LCOE of each technology by its share in the regional grid mix.
(2) Adding transmission and distribution costs as well as taxes, which are both region specific where possible.

PPA prices are calculated by:
(1) Taking starting point PPA prices for 2020 from LevelTen Energy's PPA Price Index and from Pexapark's Pexa Euro Composite Index.
(2) Indexing these starting points in line with the growth in grid prices.

The outputs are modelled deeply across four different key regions: US, EU, China, and India. Outputs for other regions are proxied based on these key regions.

Hydrogen prices

Hydrogen prices are sourced from the MPP's Hydrogen Pricing Model. Levelized costs of green hydrogen (LCGH) are calculated from 2020 to 2050 based on two key cost components:

(1) Generation costs, derived from power prices[xx], load factors[xx] as well as electrolyser CAPEX[xx], OPEX, and efficiency[19,20].
(2) Non-generation costs, comprised of storage costs, transport costs, and taxes and margins.

Current electrolyser CAPEX as well as storage and transport costs are taken from the Energy Transitions Commission's work, while future electrolyser CAPEX is estimated based on expected learning rates and future GW capacity demand[21,22].

The outputs are modelled deeply across four different key regions: US, EU, China, and India. Outputs for other regions are proxied based on these key regions.

[xx] Input varies by region.

5. Levelised cost

The levelised cost of a aluminium or alumina production technology is the ratio of the total costs of a generic plant to the total amount of alumina or aluminium expected to be generated over the plant's lifetime (Exhibit TA5.1).

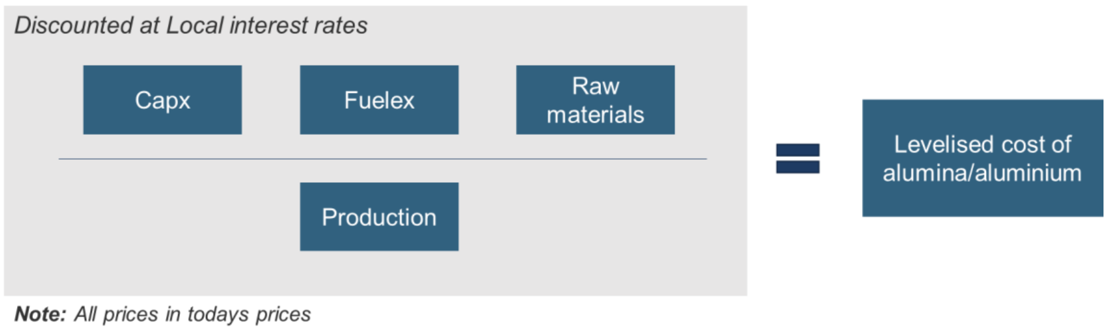


Exhibit TA5.1: Simplified schematic of levelised cost

The levelised cost can be the average levelised cost (including any existing capex), or the marginal levelised cost (the additional levelised cost, so not including any existing capex).

The average levelised costs of existing assets is calculated by looking at the levelised cost of a new asset

How to use levelised costs

Levelised costs outlined in this report are one metric for looking at costs of production and give an indication of the relative difference in cost between technological options. They are created using generic costs and financing assumptions and will not take account of the other aspects a producer may consider (for example structure of financing).

The forthcoming MPP report on financing low carbon aluminium looks more closely at how different levers can cover the cost gap. It also provides an open source investment model for projects to look at how to address the cost gap with real world policy and financing interventions, allowing investors to input site specific assessments into an investment calculation.

6. Asset-level assumptions

Our model is based on a bottom-up approach to simulate net-zero pathways for the aluminium industry, solving for optimal decarbonisation transitions at the asset level. Asset-level data is thus one of the key building blocks of the STS. To enable an open and transparent debate on what is needed to achieve decarbonisation in the sector, MPP is committed to grounding its analysis and conclusions on open-source data. In the absence of a public database on aluminium assets, we have collected data on the global pool of alumina refineries and aluminium smelters. The following figure (Exhibit TA6.1) outlines the different data points gathered for each asset:

Asset identification

Plant name	Parent company	Country	Coordinates	Status	Start of operation (y.)
				Operating Idle	

Production & Energy

Nameplate capacity (Tons product / Year)	Operating rate (%)	Electricity supply source	Electricity supply fuel (for direct or PPA)	Captive plant capacity (MW)	Thermal energy fuel - Digestion	Thermal energy fuel - Calcination
		Direct Generation Grid PPA+Grid				

Dark blue — For refineries & smelters; Green — For refineries only (Thermal energy fuel - Digestion, Thermal energy fuel - Calcination)

Exhibit TA6.1: Template for gathering plant data

Our data collection approach differed for assets located outside of and in China. For assets outside of China, data points were collected from a range of public sources, including company annual reports, presentations, and websites as well as trade journal articles. For assets in China, data was obtained from a third-party provider because of the absence of publicly available information.

In total, data was collected on 95 alumina refineries (79 in operation, 16 idle) and 181 aluminium smelters (171 in operation, 10 idle). The following tables (Exhibit TA6.2 and TA6.3) provide an overview of these assets:

Region	# of refineries	Average age of refineries (y.)	Average nameplate capacity (tAa/year)	Fuel used for digestion (% of plants using fuel)	Fuel used for calcination (% of plants using fuel)
US	2	65	860,000	Coal (0%), Gas (100%), Oil (0%)	Gas (100%), Oil (0%)
Canada	1	86	1,560,000	Coal (0%), Gas (100%), Oil (0%)	Gas (100%), Oil (0%)
South America	9	52	1,955,189	Coal (17%), Gas (17%), Oil (50%)	Gas (50%), Oil (50%)
Russia	3	71	1,003,000	Coal (67%), Gas (33%), Oil (0%)	Gas (67%), Oil (33%)
Rest of Europe	8	46	1,169,875	Coal (0%), Gas (100%), Oil (0%)	Gas (100%), Oil (0%)
Middle East	5	33	946,000	Coal (0%), Gas (75%), Oil (25%)	Gas (100%), Oil (0%)
Africa	1	23	650,000	Coal (0%), Gas (0%), Oil (100%)	Gas (0%), Oil (100%)
China	48	15	1,833,750	Coal (100%), Gas (0%), Oil (0%)	Gas (100%), Oil (0%)
Rest of Asia	12	32	1,042,500	Coal (100%), Gas (0%), Oil (0%)	Gas (44%), Oil (56%)
Oceania	6	43	3,454,833	Coal (50%), Gas (50%), Oil (0%)	Gas (100%), Oil (0%)

Exhibit TA6.1: Summary of alumina refinery data gathered and input into model

Region	# of smelters	Average age of smelters (y.)	Average nameplate capacity (tAl/year)	Electricity supply (% of plants per type of supply)
US	7	63	234,286	Direct Generation (17%), Grid (0%), PPA+Grid (83%)
Canada	10	43	331,200	Direct Generation (60%), Grid (0%), PPA+Grid (40%)
South America	6	42	413,667	Direct Generation (50%), Grid (0%), PPA+Grid (50%)
Scandinavia	8	73	197,625	Direct Generation (63%), Grid (13%), PPA+Grid (25%)
Russia	11	48	404,636	Direct Generation (70%), Grid (10%), PPA+Grid (20%)
Rest of Europe	19	48	193,730	Direct Generation (18%), Grid (47%), PPA+Grid (35%)
Middle East	14	27	546,929	Direct Generation (57%), Grid (14%), PPA+Grid (29%)
Africa	5	33	358,600	Direct Generation (20%), Grid (0%), PPA+Grid (80%)
China	84	18	504,896	Direct Generation (45%), Grid (39%), PPA+Grid (16%)
Rest of Asia	12	23	530,417	Direct Generation (75%), Grid (0%), PPA+Grid (25%)
Oceania	5	47	420,200	Direct Generation (0%), Grid (20%), PPA+Grid (80%)

Exhibit TA6.2: Summary of aluminium smelter data gathered and input into model

7. Aluminium's 1.5°C aligned carbon budget

The International Aluminium Institute (IAI)'s 1.5 degree scenario (1.5DS) carbon budget was used to underpin the STS modelling. Between 2020 to 2050, the IAI 1.5DS carbon budget is estimated to be 15.9 Gt CO_2e (for scope 1,2 and 3 category 1-5,7,8)[23]. Given the variety of different methodologies to allocate a global carbon budget to individual sectors and the inherent uncertainty around the global carbon budget itself, the 15.9 Gt CO_2e should be understood as an indicative point of reference, not as a precise single truth.

To develop the 1.5DS, the IAI used a mixture of internal and external IEA data, breaking down emissions into separate buckets based on the available data at the time:

- **Direct CO_2 emissions covered by the IEA**, which includes process emissions from anode production and electrolysis and thermal energy emissions derived from refining, anode production, casting, recycling, semis production, and internal scrap. Direct emissions reductions follow the IEA's Beyond 2°C (B2DS) scenario (ETP 2017[24]), which are then reduced by the same percentage published for steel in B2DS compared to the steel data in the IEA's Net Zero Emissions (NZE) by 2050 scenario[25].
- **CO_2e emissions associated with electricity used for electrolysis**. Using IAI 1.5DS primary production data[26], IAI electricity consumption per tonne of primary aluminium (all reduced to 12,700 kWh/tonne), IEA regional emissions intensity data (CO_2e/kWh), IEA transmissions losses, and estimates for upstream emissions. B2DS IEA regional emissions intensity data has been reduced to match global reductions required for the IEA's Net Zero Emissions (NZE) by 2050 scenario[27]. It is assumed that 33% of all fossil fuel using smelters are connected to or work at a level of an NZE grid by 2030 and 100% by 2035.
- **Other CO_2e emissions**, which includes electricity consumption across the value chain (excluding electrolysis), direct PFC emissions, ancillary materials indirect emissions, mining thermal energy emissions, and transport emissions. These emissions are not covered by the IEA and were assumed to achieve reductions at the same rate as direct emissions.

8. The cost of inaction

Carbon emissions cause an economic damage that is currently not internalized in the use of fossil fuels. The so-called social cost of carbon (SCC) quantifies this economic damage. In a 2018 study, the SCC has been estimated to be $417 (177-805) per tonne of CO_2.[76]

However, there is mounting scientific evidence that inaction on climate change will be even more expensive than decarbonising our economies, with a new 2021 study suggesting social costs of carbon of over $3,000 per tonne of CO2.[77,78] Large uncertainties exist around the impact of climate change on long-term economic growth "and how far societies can adapt to reduce these damages; depending on how much growth is affected, the economic costs of warming this century could be up to 51% of global GDP."[77]

Using the SCC estimates above, the cumulative investments of $1 trillion required for transitioning the aluminium sector to net-zero compare to a social cost of carbon of $15 (4–30) trillion[xxi] if the sector were to be unmitigated until 2050. This is based upon the SCC values of the 2018 study. Using the 2021 study's estimates, this number could be as high as $110 trillion.

From a socio-economic perspective, the upsides of the transition outweigh its cost; decarbonising aviation would have a net-positive financial impact on the global economy. Despite all uncertainties inherent to such estimates, this comparison indicates that inaction is not an option: regarding climate change, in terms of long-term economic growth[78] as well as with regards to pollution and human health[79]. Human well-being will benefit from decisive action in terms of all these aspects.

[xxi] Assuming 37 $GtCO_2e$ in the BAU scenario.

9. Limitations

With any modelling there are significant limitations, this is particularly true in a industry such as aluminium, where local conditions and wider systems are critical to understanding the possibilities for decarbonisation. There are several key limitations in approach which are important to consider highlighted below in Exhibit TA9.1.

Limitation	Description
Existing plant arrangements	The analysis conducted uses assumptions and publicly available information to understand the current state of the refinery and smelter asset base. Key assumptions such as individual assets' power price & arrangements are commercially sensitive so not available for use in this open-source model.
Trade patterns	The analysis conducted makes simple assumptions about supply and demand patterns for the aluminium sector. These assumptions broadly mean that it is highly unlikely that significant changes in geographic distribution of assets will occur.
Supply-demand modelling of the sector	The modelling is focused on the underlying production costs of the supply of alumina and aluminium. It does not attempt to model the interaction of supply and demand for aluminium via trade flows. It is likely that decarbonizing the sector will result in changes to the supply of alumina and aluminium and how that interacts with demand as some customers might move faster on low carbon alumina than others.
Non-energy economic decision-making factors	The modelling conducted looks at the levelized cost and total operating cost of alumina and aluminium production. It does not model changes in other parts of the cost structure of aluminium production and particularly does not model geo-political trends and decisions. For example, countries deciding to impose export restrictions on key parts of the aluminium value chain or border carbon adjustments.
Power modelling	The approach to power sector modelling used is deliberately simple using annual averages focusing on broad economics. To fully understand particularly smelters' interaction with the electricity system and how it might combine with variable low carbon generation, significantly more detailed local and finely tuned time period modelling would be required. This modelling would be able to capture how smelters would be able to interact with renewables, storage and demand side response options and could reveal additional cost-effective options for smelters to decarbonize.
Technology development	New technology has a key role in decarbonizing the sector, with new low-carbon heating technology and anode technology as well as emerging power technology all playing critical roles in the sector's decarbonization. The costs, performance and availability are highly uncertainty, given many technologies are not commercialized yet. In addition, other technologies might emerge that offer additional benefits or transformational step changes. Finally, the roll out of technology across the sector is inherently uncertain. This analysis assumes that roll out can occur across the whole sector and does not directly consider proprietary technology etc. This is proxied through growth rate limits for new technologies.

Exhibit TA9.1: Aluminium STS modelling limitations

These uncertainties are inherent in any modelling of a complex sector, particularly given aluminium's significant interactions with trade, the global and local markets for aluminium products and interactions with wider energy systems, however the modelling represents the best available view. Many of these limitations can be addressed when actual projects are designed and will be part of the investment decision making process.

In addition, the open-source nature of the modelling allows others to base their own analysis on the broad approach and evidence collected by MPP. These additional insights that others generate about the sector are key to mapping out how the aluminium sector can deliver a 1.5°C consistent trajectory.

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