TITLE

What future for primary aluminium production in a decarbonizing economy?

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ABSTRACT

Aluminium is an energy intensive material with an environmental footprint strongly dependent on the electricity mix consumed by the smelting process. This study models prospective environmental impacts of primary aluminium production according to different integrated assessment modeling scenarios building on Shared Socioeconomic Pathways and their climate change mitigation scenarios. Results project a global average carbon intensity ranging between 8.6 and 18.0 kg CO_2 eq/kg in 2100, compared to 18.3 kg CO_2 eq/kg at present, that could be further reduced under mitigation scenarios. Co-benefits with other environmental indicators are observed. Scaling aluminium production impacts to the global demand shows total emission between 1250 and 1590 Gt CO_2 eq for baseline scenarios by 2050 while absolute decoupling is only achievable with stringent climate policy changing drastically the electricity mix. Achieving larger emission reductions will require circular strategies that go beyond primary material production itself and involve other stakeholders along the aluminium value chain.

KEYWORDS

- Primary aluminium production
- Carbon footprint
- Scenario modelling
- Shared Socioeconomic Pathways
- Life cycle assessment

1 INTRODUCTION

Aluminium is the second most used metal in our modern economy, mainly in transportation, packaging, and buildings (Cullen and Allwood, 2013). As the stock per inhabitant keeps growing and shows no sign of saturating yet (Müller, Liu and Bangs, 2013; Maung *et al.*, 2017), the demand for primary aluminium is expected to increase by 34% in the next two decades (IAI, 2020b). Aluminium is an energy-intensive material, with its smelting causing 8% of all worldwide industrial electricity use (Kermeli *et al.*, 2015).

Aluminium production starts with the mining of the bauxite ore, followed by its refining with the Bayer process. The resulting aluminium oxide goes through an electrolysis smelting process, the Hall-Heroult process, to produce liquid aluminium, which is finally cast into ingots.

The electricity mix consumed by the smelter is the most determinant factor explaining the differences between environmental profiles (Paraskevas, Kellens, *et al.*, 2016; Saevarsdottir, Kvande and Welch, 2020). The oxidation of the carbon anode during the Hall-Heroult process is responsible for the other major source of CO_2 emissions, as seen in equation (1).

$$2Al_2O_{3(solution)} + 3C_{(s)} \rightarrow 4Al_{(l)} + 3CO_{2(g)} \qquad (1)$$

In order to eliminate direct emission of CO_2 and mitigate global warming potential (GWP) (Kovács and Kiss, 2015), a novel reduction technology as equation (2) is developed by aluminium companies, with industrial-scale tests planned or ongoing (Elysis, 2020; RUSAL, 2020):

$$2Al_2O_{3(solution)} \rightarrow 2Al_{(l)} + 3/2O_{2(g)} \qquad (2)$$

This technology, called inert anode smelting, promises to eliminate all direct CO_2 emissions and to increase productivity(Elysis, 2020).

As aluminium is a material with growing demand - especially as a lightweight, corrosive-resistant material in renewable energy infrastructure (Månberger and Stenqvist, 2018) and next generation vehicles (Hatayama *et al.*, 2012) - it is important to anticipate how the carbon intensity of aluminium may evolve in the future. As nations worldwide pledge to decarbonize electricity production as part of decarbonizing their economies, this evolution will in turn influence the desirability (and comparative advantage/disadvantage) of aluminium use within climate change mitigation efforts. An understanding of the evolution of the global greenhouse gas (GHG) emissions of the aluminium industry as a whole is key to inform policy making, as nations ramp up their efforts to mitigate climate change. Even aluminium producers have started declaring their GHG goals for 2030 and 2050 to position their industry in the global climate change mitigation efforts (RUSAL, 2018; Alcoa, 2019; Rio Tinto, 2019) (see SI-1 for specific statements).

Research has been done on prospective modelling of the aluminium industry focusing on the question of its recycling and stock dynamics, without directly addressing the long-term influence of the evolution in electricity production mix (Bangs, 2011; Müller, Liu and Bangs, 2013; Bertram *et al.*, 2017). There is a need for an integrated scenario analysis, to expand the scope of analysis beyond the aluminium sector and explore its nexus with the evolving decarbonization of electricity generation.

This study aims to align the prospective modelling of environmental impacts of primary aluminium production with the state-of-the-art scenario development paradigms in energy and climate change mitigation analysis, leveraging the different Shared Socioeconomic Pathway narratives (SSPs) (Riahi *et al.*, 2017). SSPs describe plausible future challenges for mitigation and adaptation to climate change and serve as foundations to the IPCC Sixth Assessment report, as further detailed in Box 1.

We present here an open, top-down modelling framework for the evolution of the carbon intensity of aluminium production and its total carbon footprint. As the projected demand already accounts for the presence of recycling flows (Bertram *et al.*, 2017; IAI, 2020b), and as previous studies extensively describe their stock dynamics (Liu and Müller, 2013; Chen, 2017) and inter-alloy contamination issues (Hatayama *et al.*, 2007; Rombach, Modaresi and Müller, 2012), this article complements existing literature by focusing on primary production and its link with future electricity production and technology developments.

It should be recognized that scenarios presented in this study do not have the pretension of predicting the future. Rather, “scenarios are […] used as scientific tools to explore what futures we could foresee, and which decisions today could most robustly lead to desired outcomes” (Kriegler *et al.*, 2014). By aligning our scenarios with SSP perspective that is articulated in terms of geopolitical, economic and social parameters, the unpredictability is inherent contrary to scenarios based on more physical parameters.

Box 1

SSPs overview

The SSPs are a "scenario framework used by the climate change research community in order to facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation" (Riahi *et al.*, 2017). The SSPs are based on five narratives describing alternative socio-economic developments and use a set of Integrated Assessment Models (IAMs) to calculate the elaboration of the energy, land-use and the emissions trajectories of SSP-based scenarios (Riahi *et al.*, 2017).

Brief narrative descriptions

SSP1 - Taking the Green road - describes a world "*shifting gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries"* (O'Neill *et al.*, 2017). This implies a reduction of resource and energy intensity. High-income countries support developing countries in their development goals by providing access to human and financial resources and new technologies. This narrative describes a world with low challenges of mitigation and adaptation.

SSP2 - Middle of the road - is an evolution of the societies with no marked shift from historical trends. This narrative describes a world facing moderate challenges to mitigation and adaptation.

SSP3 - A rocky road - is characterized by regional rivalry and international fragmentation. This leads to little international cooperation and low investments in education and in technology for development. Environmental concerns are not prioritized, and consumption remains material intensive, causing high challenges to mitigation and adaptation.

SSP4 - A road divided - represents a world with "*highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, leading to increasing inequalities and stratification both across and within countries*" (O'Neill *et al.*, 2017). Technology development is rapid in high-tech economies while technology diffusion is slow in other regions. SSP4 represents a world with high adaptation challenges combined with low mitigation challenge.

SSP5 - Taking the highway - is "*driven by the economic success of industrialized and emerging economies, this world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development*" (O'Neill *et al.*, 2017). This techno-optimistic pathway leads to high energy and resource consumption, which in turn results in high challenge in mitigation but low challenge of adaptation.

Mitigation scenarios

Every SSP has a baseline scenario and mitigation scenarios based on the Representative Concentration Pathways (RCPs) (Moss *et al.*, 2010; van Vuuren *et al.*, 2011) representing radiative forcing levels of 1.9, 2.6, 3.4, 4.5 and 6.0 W/m^2 by 2100. Some combinations of SSPs and RCPs are not possible due to socio-economic conditions. For example, the lowest radiative forcing level that can be reached from SSP3 is 3.4 W/m^2.

Regional definition

The SSP regional aggregation is made into 5 regions: Asia, Latin America (LAM), Middle East and Africa (MAF), Organisation for Economic Co-operation and Development (OECD) in 1990 and EU member states and candidates, and reforming economies of eastern Europe and the former Soviet Union (REF). See (https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=10#regiondefs) for the exact regional definitions.

2 METHODS

2.1 PRISMAL FRAMEWORK

The PRospective Impacts Scenario for ALuminium (PRISMAL) framework underpins the development and analysis of five internally consistent scenarios for the prospective footprint assessment of primary aluminium production. The open-source Python software (Pedneault and Majeau-Bettez, 2021) integrates life cycle assessment inventories for the entire aluminium production chain and future demand projections (IAI, 2020b) with the SSP narratives (O'Neill *et al.*, 2017). Specifically, PRISMAL articulates distinct scenarios in terms of three key parameters: evolution in electricity mixes, energy intensity reductions of the smelting process and the market penetration of inert anode technology (**Error! Reference source not found.**). Thus, not only does the framework directly integrate the SSP1-5 scenarios and the related mitigation scenarios to determinate the electricity mix of the PRISMAL scenarios, but it also ensures that other factors are modelled consistently with these SSP narratives (O'Neill *et al.*, 2017), as detailed in Table 1 (further descriptions of parameter choices are available in the subsequent methods sections and the SI-2, SI-3 and SI-4). As such, recognizing the mutual influence between industrial and regional energy policies, our top-down model treats the aluminium smelting electricity mix as an integral part of each region's overall electricity mix, experiencing a common decarbonization trend over long-term projections (2050, 2100). The mitigation scenarios considered in this analysis are the one converging to a radiative forcing levels of 1.9 and 2.6 W/m^2, which correspond to the 1.5°C and 2°C targets articulated in article 2 of the Paris Agreement, respectively (Riahi *et al.*, 2017; Rogelj *et al.*, 2018). Results were obtained for all the mitigation scenario available (3.4 , 4.5 and 6.0 W/m^2) but are not presented and discussed in the article while they are in the range between 2°C and baseline scenarios

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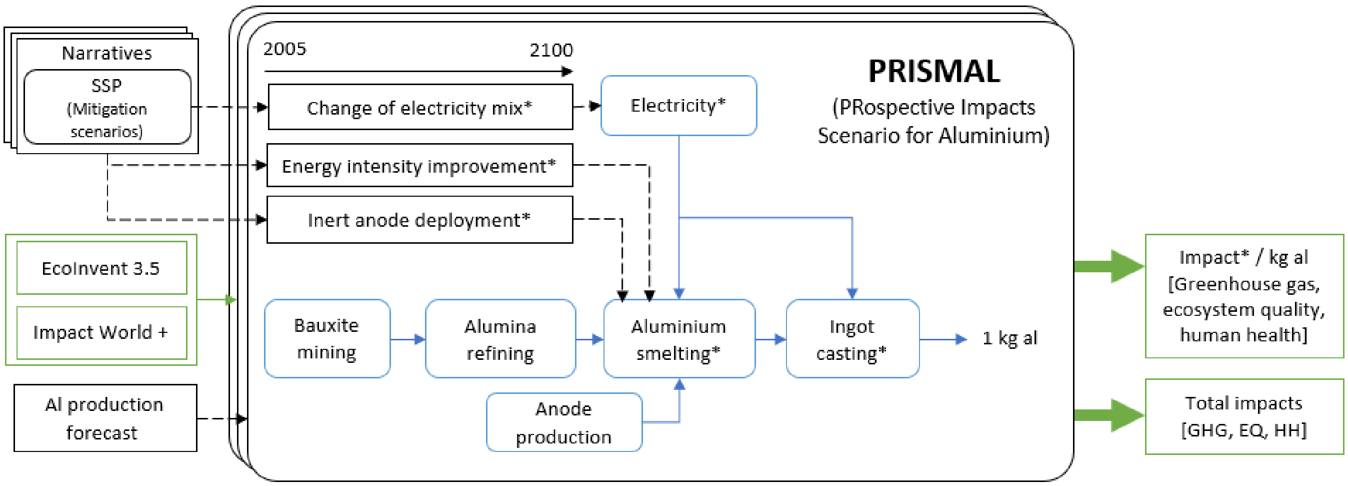

*Figure 1: General framework for prospective impacts scenarios modeling aluminium (PRISMAL). Boxes with * indicate that there is a geographical differentiation in the model (Asia, Latin America (LAM), Middle East and Africa (MAF), OECD and reforming economies of eastern Europe and the former Soviet Union (REF). Parameters influencing other life cycle stages such as bauxite mining and refining are assumed constant over time.*

*Table 1: Qualitative description of different scenarios. Quantitative model and justification are shown in SI. * indicate that there is a geographical differentiation in the model*

	Mitigation scenario	Electricity mix trends	Narratives	Smelting energy intensity	Inert anode	
					Deployment speed	Adoption level
PRISMAL1	1.5 °C	SSP1	"Taking the Green road"	Low	Quick	100%
	2.0°C					
	Baseline					
PRISMAL2	1.5 °C	SSP2	"Middle of the road"	Medium	Slow	75%
	2.0°C					
	Baseline					
PRISMAL3	1.5 °C	Not applicable				
	2.0°C	Not applicable				
	Baseline	SSP3	"A rocky road"	High	None	0%
PRISMAL4	1.5 °C	Not applicable				
	2.0°C	SSP4	"A road divided"	Medium*	Slow	75%*
	Baseline					
PRISMAL5	1.5 °C	SSP5	"Taking the highway"	Medium	Quick	100%
	2.0°C					
	Baseline					

2.2 SPACE AND TIME RESOLUTION

PRISMAL distinguishes between five different regions, identical to SSP framework (see box 1). A global aggregation is performed to obtain a global average based on the market share of aluminium production by region (Riahi *et al.*, 2017). We used historical data (IAI, 2020c) for 2005 and 2010 assessments, while 2019 market share (IAI, 2020c) has been used as a proxy for 2020. For subsequent years, constant market share based on 2019 data was assumed. A sensitivity analysis has been performed to test this latter assumption. As time resolution, PRISMAL covers a period from 2005 to 2100 with decennial resolution from starting at 2010.

2.3 DECARBONIZATION OF ELECTRICITY MIX

The electricity mix of aluminium smelters often differs significantly from that of their region (Koch and Harnisch, 2002). Consequently, the PRISMAL framework could not directly employ the regional electricity mixes forecasted by the different SSPs. Rather, the PRISMAL framework extracts the *trends* of these projected regional electricity mixes, and it uses these trends to update the smelter mixes. For example, if in a given scenario the market share of coal is projected to decrease by 65% between 2020 and 2030 in the electricity mix of Asia, then a similar percentage reduction is applied to the share of coal in smelter mix of that region.

We first compile the most recent aluminium smelter consumption mix (z_i^t, for i element of coal, hydro, etc.), along with historical mixes (2005, 2010) from IAI data (2020e). The 2019 data were used for 2020 since they were not available yet. In order to aggregate the different IAI regions into 5 regions, we calculated the weight average of electricity mix of North America, Europe and Oceania to have the electricity mix of OECD; Africa and Gulf and Middle East region for MAF region; China and “Asia except China” for Asia; and we supposed an equivalent European electricity mix for REF. No aggregation was needed for South America.

The future electricity mix trends from 2020 to 2100 for each of the 5 regions were extracted from SSP results (Bauer *et al.*, 2017; Riahi *et al.*, 2017) using their respective marker scenario. A marker scenario is the interpretation of one SSP by one specific selected IAM model (SSP1 – IMAGE, SSP2 – MESSAGE-GLOBIOM, SSP3 - AIM/CGE, SSP4 – GCAM4, SSP5 - REMIND-MAGPIE) (Riahi *et al.*, 2017). From the market share of each technology i at each time t (s_i^t) we calculate the positive ($d_i^{t\,+}$) and negative ($d_i^{t\,-}$) variations, following equations (3) and (4), respectively.

$$d_i^{t\,+} = \begin{cases} s_i^{t=1} - s_i^{t=0} & if\ s_i^{t=1} - s_i^{t=0} > 0 \\ 0 & otherwise \end{cases} \qquad (3)$$

$$d_i^{t\,-} = \begin{cases} s_i^{t=1} - s_i^{t=0} & if\ s_i^{t=1} - s_i^{t=0} < 0 \\ 0 & otherwise \end{cases} \qquad (4)$$

The decreases are then normalised by their initial market share, forming a relative decrease coefficient $\Delta_i^{t\,-}$ (equation (5)). The increases are also normalised $\Delta_i^{t\,+}$, but relative to the sum of all the increased (equation (6)), capturing each technology's relative share of new production capacity.

$$\Delta_i^{t\,-} = \begin{cases} \dfrac{d_i^-}{s_i^{t=0}} & if\ s_i^{t=1} \neq 0 \\ 0 & otherwise \end{cases} \qquad (5)$$

$$\Delta_i^{t\,+} = \frac{d_i^+}{\sum_j d_j^+} \quad \forall\ i \qquad (6)$$

These decreasing and increasing trends in the regional market shares of each technology are then applied to update the smelter mix. A vector $x_i^{t=1}$ containing the negative variation of the smelter market share is created with the product of smelter market share of aluminium smelter ($z_i^{t=0}$) and the normalised trends ($\Delta_i^{t\,-}$) as in equation (7). The vector with the positive variation ($y_i^{t=1}$), which displace the technologies that lost market shares in x, is calculated from the product of the sum of the negative vector (x) and the normalised increases ($\Delta_i^{t\,+}$) as in equation (8). Finally, the new market share of aluminium smelter $z_i^{t=1}$ is obtained by adding market share at previous time period and the positive and the negative variations. This calculation is repeated for every region and every time step between 2030 and 2100.

$$x_i^{t=1} = z_i^{t=0} * \Delta_i^- \quad \forall\, i \tag{7}$$

$$y_i^{t=1} = \left(-\sum_j x_j^{t=1}\right) * \Delta_i^+ \quad \forall\, i \tag{8}$$

$$z_i^{t=1} = z_i^{t=0} - x_i^{t=1} + y_i^{t=1} \tag{9}$$

An example of calculation and a comparison of the evolution of the calculated electricity mixes for PRISMAL scenarios and SSP electricity mixes is presented in SI-2. Environmental data and impact calculation are explained in section 2.6.

2.4 IMPROVEMENT OF THE ENERGY INTENSITY OF THE SMELTING PROCESS

Based on the conservation of energy law and thermodynamic calculations, the theoretical minimum energy requirement for the electrolysis process is 6.23 kWh/kg of aluminium (Obaidat *et al.*, 2018) while the world average in 2018 was 14.2 kWh/kg (IAI, 2020d). Part of the excess energy goes into a necessary heat loss to maintain the right amount of frozen electrolyte protecting the cell lining, and the rest is consumed to overcome resistance of the cell components (Obaidat *et al.*, 2018).

We formulated a techno-pessimistic, techno-optimistic, and middle-of-the-road scenario for the energy efficiency of smelting over time to account for technology evolution pathways that are consistent with the various SSPs. With current best practice, an energy intensity of 12.3 kWh/kg can be achieved (Hydro, 2020). In our most techno-pessimistic scenario, no further improvement is technically possible, and all efficiency gains come from a broader adoption of these currently known best practices across the entire industry by 2100. In this worst-case scenario, we therefore model a linear progression from the current average efficiency to 12.3 kWh/kg worldwide by 2100.

Ongoing research could pave the way to going beyond current practice by using Cu-inserted collector bar, developing wettable cathodes made of or coated with TiB_2 (Li *et al.*, 2008; Heidari, 2012), minimizing the distance between the anode and the cathode (Haraldsson and Johansson, 2018), designing slotted or perforated anodes to reduce bubble thickness under the anode (Tian *et al.*, 2013) and improving the overall operation of electrolysis cells with industry 4.0 technologies by optimising operation of the smelter due to the use of historical and real-time data, digital model and machine learning (Haraldsson and Johansson, 2018; Gupta and Basu, 2019).

Consequently, our techno-optimist scenario extrapolates historical trends in energy efficiency gains, as per equation (3),

$$\frac{a}{(t-h)} + 6.23 = Energy\ intensity \qquad (10)$$

where t represents the year, 6.23 is the minimum thermodynamic limit in kWh/kg Al. Fitting constants were determined by regression via the sum of least squares, giving an a = 1177 and h = 1862. The regression used historical data from 1890 to 1970 from McGeer et al.(1986) and from IAI for the period between 1980 and 2015 (IAI, 2020d). The extrapolation, with a R^2 of 0.992, leads to an average global smelting energy intensity of 12.5 kWh/kg of primary aluminium by 2050, and 11.2 kwh/kg by 2100 what we, and experts from the industry informally consulted, judge ambitious but achievable. The average of those two scenarios is then calculated to obtain an intermediate evolution pathway in smelting energy intensity.

For each PRISMAL scenario, we assigned a level of energy intensity (low, medium, or high) based on the SSP narratives to ensure consistency within each scenario. Consequently, the PRISMAL1 scenario is the least energy intensive because of the willingness to decrease global energy consumption inherent of the associated narrative. The energy intensity in the PRISMAL2 scenario is at a medium level, while PRISMAL3 and PRISMAL5 follow the upper threshold of energy intensity as neither of the associated narratives describe any willingness to improve energy use. The energy intensity of PRISMAL4 depends on the region; where OECD follows the lower limit, MAF the upper and LAM, Asia and REF the intermediate level of energy intensity. A graphical representation of the described extrapolations and numerical values for the energy intensities are available in SI-3.

2.5 INERT ANODE DEPLOYMENT

The deployment of the inert anode smelting technology depends on its competitiveness relative to current technology. Replacing carbon anode with an inert anode would eradicate the direct emissions of CO, CO_2, SO_2, fluorocarbon (PFC) and polycyclic aromatic hydrocarbon (PAH) generated by the traditional Hall-Heroult process (Andrey S., Sai Krishna and Peter V., 2018)

To model the deployment over time, a logistic curve has been used starting from 2020 (Foster, 1986). The market share of inert anode smelting technology over time ($D_{in,t}$) is described by equation (11)

$$D_{in,t} = \frac{A}{1 + e^{-k*(t-t_h)}} \qquad (11)$$

where *A* is the total amplitude possible of deployment over the examined time period (between 0 and 1); *k* is the steepness of the curve, and t_h is the year of the middle of the curve where the technology penetrated 50% of the market. We defined *A*, t_h, and *k* consistently with the five narratives to control the deployment the technologies for each PRISMAL scenario (see Table 1).

Narratives for SSP1 leads to "a rapid technological change is directed toward environmentally friendly processes" (O'Neill *et al.*, 2017). As inert anode development is driven by environmental considerations, we assumed a complete adoption over the century with a quick level of adoption from 2050. For PRISMAL2, an assumption of slow penetration rate and a maximum amplitude of 75% is made. For PRISMAL3, we assumed no deployment of inert anode technology because the narrative describes a world with a very slow technological development and no focus on clean technology. PRISMAL4 is split into three levels due to the assumed socioeconomic inequalities between regions. Deployment in OECD is slow but complete by the end of the century due to the wealth of the region. Asia, LAM and REF, the regions with an intermediate GDP also deploy the technology with a slow rate and a maximum amplitude of 75% but start after OECD. Finally, in MAF, the region with the lowest GDP, the adoption is also slow and delayed but the maximum amplitude is only 50%. For PRISMAL5, the relevant narrative states that "technological innovation is very high, with a focus on increasing labor productivity, fossil energy supply, and managing the natural environment" (O'Neill *et al.*, 2017). Because inert anode is considered as a green technology, the deployment is assumed quick and the amplitude is total, but it starts later than the one in PRISMAL1, as this techno-optimistic narrative does not adopt green technology in the first half of the century. The graphical evolution of the parameters with the numerical parameter values are shown in SI-4.

2.6 Environmental impacts

To assess environmental impact profiles of the five PRISMAL scenarios, a link between our modelling parameters and environmental impacts must be made. Life cycle inventory data related to the supply of material and energy flows are calculated with unit processes from *ecoinvent* (version 3.5, cut-off) (Wernet *et al.*, 2016). The environmental impacts potentially caused by these emissions and resource extractions were estimated with the IMPACTWorld+ life cycle impact assessment method (Bulle *et al.*, 2019) supported by the SimaPro v8.5.2.2 software. We generated an impact profile with three endpoint indicators: climate change (CC) [kg CO_2 eq], human health (HH) measured in disability-adjusted life years [DALY] and ecosystem quality (EQ) measured in potentially disappeared fraction of species over a square meter and during a year [PDF.m^2.yr]. The two latter indicators represent aggregated damage level indicators building on natural science modeling (Verones *et al.*, 2017). To avoid double counting and focusing on CC indicator, we removed CC midpoint indicator from HH and EQ endpoint indicators. HH takes into account ozone layer depletion, human toxicity cancer, human toxicity non-cancer, particulate matter formation, photochemical oxidant formation, ionizing radiations and water availability. The EQ includes marine acidification, freshwater acidification, terrestrial acidification, freshwater eutrophication, marine eutrophication, freshwater ecotoxicity, ionizing radiations, water availability, land transformation and land occupation. Only the short-term damage level indicators (i.e., within a time horizon of 100 years) have been included.

2.6.1 Impacts of electricity mix

The environmental profile of the electricity mix is calculated from the market share of each energy technology (biomass, coal, gas, hydro, nuclear, oil, solar and wind). The environmental profile of each electricity technology has been calculated by doing a weight average of the impact of different processes and region using production volume of ecoinvent. For example, for hydroelectricity, we calculated the CC, EQ, and HH per kWh of different technologies: reservoir non-alpine region, reservoir alpine region and run-of-river for different geography available on ecoinvent. A weight average based on the volume of all those technologies and geography is then made to have an average impact of hydro production.

As *ecoinvent* does not include carbon capture and sequestration (CCS) technologies, a reduction factor on GHG impact was used for these technologies in the electricity mixes. These factors were calculated as the ratio of median value for the life cycle carbon intensity of different electricity generation technologies with and without CCS as published in the IPCC Fifth Assessment Report on mitigation of climate change (Edenhofer *et al.*, 2014). The factor used for coal CCS is 27% and 35% for gas meaning that CC emissions are 27% and 35% of the original impact. No factor was applied on EQ and HH indicators. For the biomass CCS we directly apply the value of -0.776 kg CO_2 eq/kWh (Edenhofer *et al.*, 2014) and did not change the EQ and HH indicators either.

Tables with calculated values of CC impact per kWh for PRISMAL, mitigation scenarios and regions are available in SI-5.

2.6.2 Inert anode smelting modeling

Inert anode is a technology still in development for an industrial scale. Data is lacking and exact composition of the inert anode material is still confidential. Therefore, a screening LCA of inert anode technology has been made based on Lovács & Kiss (2015). We assumed an anode composition of 55% copper, 20% nickel and 25% of iron. We also assumed that the inert anode will have a lifetime thirty times longer than that of a prebaked anode (ELYSIS, 2019).

To model the smelting process with inert anode, we adapted the smelting process (Aluminium, primary, liquid {RoW}| aluminium production, primary, liquid, prebake) by removing direct emissions of CO, CO_2, SO_2, PFC and PAH. Emissions of HF (g) has been maintained because the fluoride-containing electrolyte will still generate those gases (Kovács and Kiss, 2015). *Ecoinvent* data (Wernet *et al.*, 2016) and calculated impacts of the technology are available at SI-6.

One of the biggest uncertainties concerning the inert anode smelting technology lies in the process energy consumption. The total theoretical energy requirement for the inert anode reaction is 9.184 kWh/kg of Al in comparison to 6.23 kWh/kg of Al for the traditional Hall-Heroult process (Obaidat *et al.*, 2018). The cost of electricity currently contributes 35% of the total cost of smelting (Allwood and Cullen, 2012); a technology with a higher energy intensity would not be economically viable for smelters. For that reason, we assumed an equal energy intensity for both the Hall-Heroult and inert anode process over the years. However, policy can also drive the deployment of the inert anode technology, even when it’s not economically competitive with a carbon anode, which means that an adoption of the technology could be done with a higher electricity consumption. To evaluate the consequence of such a context, a sensitivity analysis is done with an extra consumption of 3 kWh/kg for the inert anode which is the difference between the theoretical minimal energy requirement of the two reduction technologies.

2.6.3 Unit process

The cradle-to-gate or gate-to-gate impact profile of each process used by PRISMAL is pre-calculated with the Simapro life cycle assessment software. In order to get a single value impact, despite country-level specificity from ecoinvent, we take a weighted average of the member countries using the regional production volumes provided in ecoinvent. From the precalculated processes, we removed the physical input flows already accounted for in the PRISMAL model to avoid double counting. For example, the impact profile of the alumina production process does not account for impacts from bauxite mining. Similarly, the impact profile of the smelting process with a prebaked anode does not account for the impacts of the anode, the alumina and the electricity production supplying the process. Weighted averaged impact profiles of all the processes used for calculation in the PRISMAL model are available in SI-7. Those precalculated environmental data are used as an input of the PRISMAL program.

From the precalculated impacts, PRISMAL uses a technological matrix (with dimension 7 x 7 processes, see SI-8) to calculate the amount of each process needed to produce 1 kg of primary aluminium ingot. The electricity mix used for smelting and casting of liquid aluminium at the smelter is the same as these two processes always occur at the same location.

2.7 MAGNITUDE OF FUTURE PRODUCTION

The absolute environmental impacts of primary aluminium production are calculated by scaling the impact intensity to the global production of primary aluminium. The production volumes to 2050 were obtained from the IAI global alucycle (IAI, 2020a) based on a dynamic material flow model (Bertram *et al.*, 2017) according to their moderate Covid-19 demand impact scenario.

3 RESULTS

3.1 PROSPECTIVE ENVIRONMENTAL IMPACTS

The evolution of the environmental intensity indicators for global primary aluminium production depends on the PRISMAL scenarios and their associated mitigation scenarios (Figure 2). Results of all PRISMAL runs are available here.

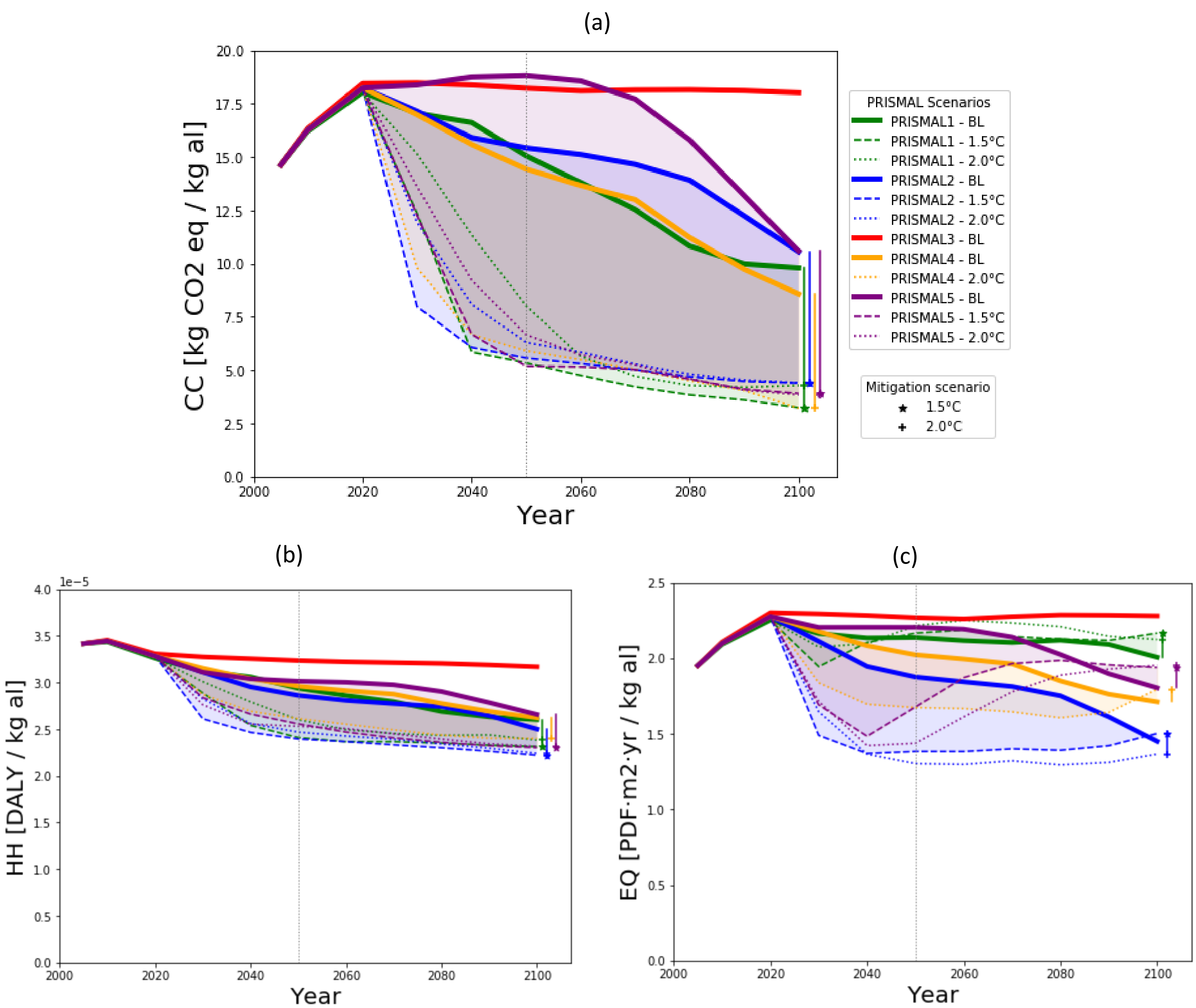

Figure 2: Average global GHG (a), HH (b) and EQ (c) impact per kilogram of primary aluminium for different PRISMAL scenarios. The dashed lines of every PRISMAL scenario represents the result with the electricity mix of the lowest mitigation scenarios possible with the associated SSP and the colored area represent the range between the baseline and the lowest mitigation scenario. Numerical values for the three indicators are presented in SI-9.1, SI-9.2 and SI-9.3.

Looking first at the baseline scenario mitigation, PRISMAL scenarios 1, 2 and 4 show a steady decrease in GHG emission intensity of aluminium production from 2020 to 2050, mainly due to reduced emissions intensity of electricity generation of the underlying SSP and the improvement of energy intensity of the smelting process. PRISMAL scenarios 3 and 5 show no emissions reductions to 2050 as a result of persistent high emissions intensity of electricity generation from SSPs 3 and 5 due to the increased challenges to mitigation in these narratives (see Box 1). In 2050, a decrease of 20% from 2020 level is expected for the best-case scenarios and more than 50% in 2100. Numerical values are available in SI-9.1, SI-9.2 and SI-9.3.

With the integration of the SSP mitigation scenarios in our analysis, a more drastic and rapid reduction of carbon intensity is observed. Naturally, the carbon intensity declines fastest in the 1.5°C (1.9 W/m^2) scenarios. However, with the exception of PRISMAL 3 scenario, in the long-term, the emission intensity of aluminium production converges to approximately the same levels under the 1.5 and 2.0°C targets, respectively (Figure 2 (a)). The Human health (HH) (Figure 2 (b)) indicator follows similar trends, thus showing an environmental co-benefits of low-carbon system (Hertwich *et al.*, 2015; Gibon, Arvesen and Hertwich, 2017).

For the HH indicator, all PRISMAL scenarios decrease in the future except PRISMAL3. Alumina refining is the main contributor of total HH impacts (due to chromium and arsenic emissions to water) followed by the electricity used (with the related emissions of SO_2, NO_X and PM from fossil-fuelled electricity plants). For the EQ indicator, PRISMAL2 represents the scenario with the lowest EQ impacts. Surprisingly, PRISMAL1 and scenarios with high mitigation do not display the lowest impact because of the larger market share of photovoltaic and biomass electricity. Those two technologies have a potentially higher impact on land transformation in comparison to other electricity technologies, increasing the EQ endpoint impacts indicator. The increased of EQ impacts observed in the mitigation scenario of PRISMAL1 , PRISMAL2 , PRISMAL4 and PRISMAL5 is due to a net increase in market share of photovoltaic and biomass. This potential trade-off between climate change and ecosystem quality indicators should be further studied.

With a focus on the PRISMAL2 scenario, Figure 3 shows a contribution analysis to GHG emissions of the global primary aluminium production (GLO) as well as the regional developments for five regions for the baseline. Similar graphics with 1.5°C target and 2.0°C target scenarios are available in SI-10. The role of three key factors in mitigation is depicted: (i) the change of electricity mix, (ii) the improvement of energy intensity of the smelting process and (iii) the progressive deployment of inert anode. The contribution of the improved energy intensity is obtained by the product between the impact of electricity set at the year 2020 (kg CO_2 eq/kWh) and the variation of energy intensity between two future periods of time (kWh/kg al). The improvement related to the changes of electricity mix is calculated as the variation of impact between the electricity mix between two time periods (kg CO_2 eq/kWh) multiplied by the electricity intensity of 2020. The improvement of inert anode deployment is the difference between the impact of prebaked anode and inert anode (direct emission and anode production). Emissions related to alumina refining and bauxite mining remain constant as assumed by our scenario evaluation.

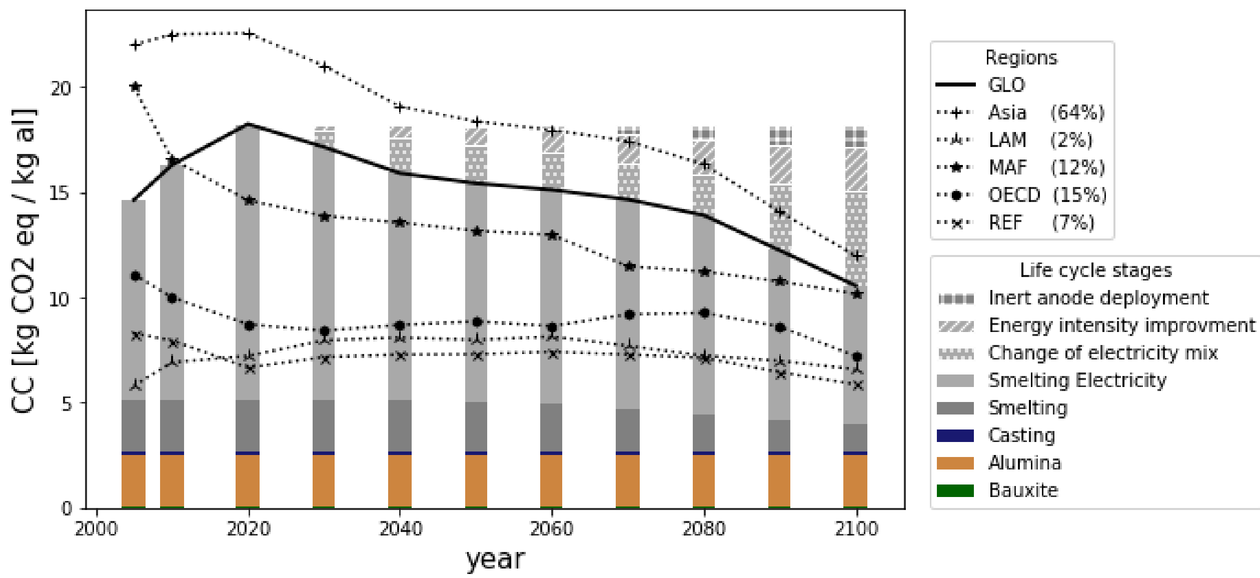

Figure 3: Contribution analysis of global (GLO) primary aluminium production for PRISMAL2 and evolution of carbon intensity per region with the baseline scenario. Hall-Heroult process and its direct emissions is grouped with the anode production into the smelting stage. The contribution analysis from life cycle stages is made for the GLO region. The percentage in parenthesis in the region's legend entry represents the market share of each regions used from 2020 to 2100.

The decarbonisation of the electricity mix has the biggest potential for reducing carbon intensity of aluminium production because of the wide range in carbon intensity within electricity production technologies. The gains are even higher and quicker with the 1.5°C and 2.0 °C mitigation scenarios. The improvement of operation of smelting plant to reduce the energy intensity of the electrolysis can also contribute to the overall reduction of the industry. Inert anode can reduce the carbon footprint of aluminium production up to 10% because direct emissions are not a major contributor of overall GHG emissions. However, with rapid decarbonization of electricity generation under the 1.5 and 2.0°C scenarios, smelting emissions and emissions from alumina production become a substantial share of remaining emissions, emphasizing the need to reduce those emissions as well. Under our default assumptions (copper-nickel-iron anode with a 30 times longer lifetime - see section 2.6.2 and SI-6 for more information), the environmental gains related to inert anode deployment would only become substantial after 2050. As shown by the sensitivity analysis (SI-11), a rebound effect could be observed if the energy intensity of the inert anode is 3 kWh/kg higher than the one of the Hall-Heroult process assumed in our baseline scenario and if the electricity mix supply has a high carbon intensity. For the mitigation scenarios with a low carbon electricity mix, no rebound effect is observed and inert anode technology lead to environmental gains even with an extra electricity consumption.

The prospective GHG intensity over time is also provided for five regions of the globe, with Asia currently having the highest market share (64%) and also showing largest improvement potential to 2050, mainly due to the decarbonization potential of a still heavily fossil-based electricity mix. A convergence across regions is observed. The other PRISMAL scenarios follow similar trends, though with a lesser degree of convergence, except PRISMAL3, which, in accordance with the SSP3 narrative, shows almost no regional convergence at all (see SI-12).

The expected convergence ensures that uncertainties of future regional market shares do not heavily influence our future weighted global average. The consideration of SSP mitigation scenarios emphasize this convergence because the electricity mix becomes more uniform in order to achieve a specific radiative forcing level. Moreover, a sensitivity analysis on different geographical allocation comparing extreme and conservative schemes for new future aluminium production capacity shows no major changes in global results because of this convergence of electricity mix and limited addition of new capacity in comparison of already existing infrastructure (see SI-13).

3.2 TOTAL PRODUCTION

A scaling of the impact intensity results for total primary aluminium production projection (Bertram *et al.*, 2017; IAI, 2020b) has been made in order to quantify absolute impacts of industry as a whole. Figure 4 shows total GHG emissions of the aluminium production worldwide according to each scenario to 2050 and the underlying annual aluminium production (See SI-14 for values). By looking at the baseline scenarios, we observe that the improved impact intensity of aluminium production is not sufficient to offset the increase in production volume. According to the model, the total impact of the aluminium industry will increase between 18% (PRISMAL1) and 40% (PRISMAL3) from 2020 to 2050, while the production increases by 42% during the same period. A relative decoupling is observed for PRISMAL1, PRISMAL2 and PRISMAL4 meaning that the production growth rate is higher than pollution growth rate. The objective of absolute decoupling, a net stabilisation or reduction of impacts with a concurrent increase in production, is not reached. Thus, the absolute decoupling from 2020 levels could be observed with 1.5 and 2.0°C mitigation scenarios as shown by the blue area and the vertical lines of each PRISMAL scenarios.

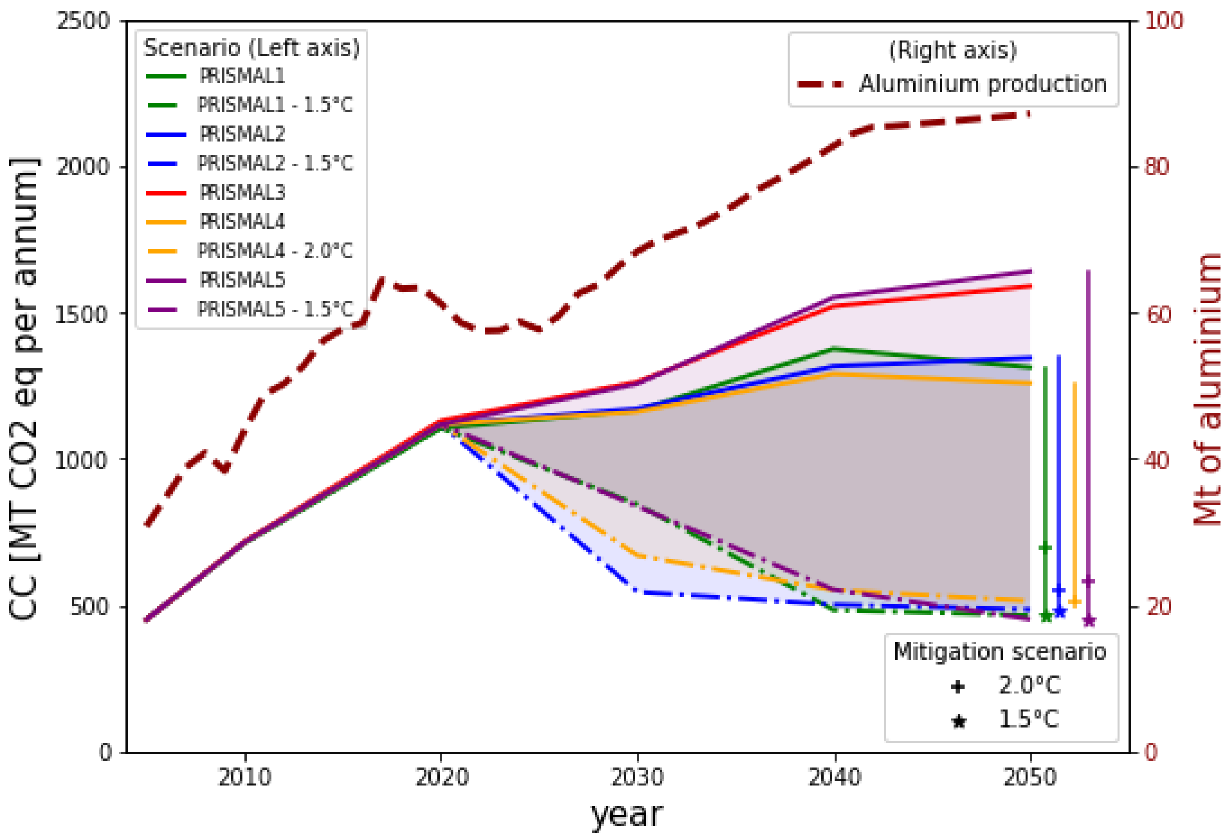

Figure 4: Total GHG emissions of the aluminium production according different PRISMAL scenarios and annual production of primary aluminium. The blue area represents the range between the baseline mitigation scenario and the 1.5°C mitigation scenario of PRISMAL2. The vertical lines represent the range between baseline scenario and lower possible mitigation scenario results.

4 DISCUSSION

4.1 STRATEGIC IMPLICATION

Globally, the different PRISMAL scenario runs demonstrate that major improvements in the carbon intensity of aluminium can realistically be achieved before 2050, and even more so extending toward 2100. These improvements, however, mostly depend on aggressive climate mitigation policies that extend beyond the aluminium sector and into the decarbonization of electricity production chains. Thus, the different mitigation scenarios robustly converge to reductions of 55-70% from 2020 level in 2050 and to reductions between 75 and 80% in 2100. When taking the projected increase of aluminium production, the PRISMAL2 scenario with 1.5°C policies (RCP 1.9) shows a reduction of 632 Mt of CO_2 eq compared to the baseline of 1117 Mt of CO_2 eq in 2050.

This unusual importance of electricity in the aluminium production chain hints at a strategically significant virtuous cycle: just as aluminium is expected to play a major role in climate mitigation efforts (renewable energy infrastructure with battery production (Månberger and Stenqvist, 2018) and mounting structures and frames for photovoltaic panels (Maurice Bödeker and Bauer Martin Pehnt Heidelberg, 2010), lightweighting of transport (Bertram, Buxmann and Furrer, 2009), etc.), these mitigation efforts are expected to play a major role in the reduction of this metal's environmental and carbon footprint.

Consequently, when prospectively assessing the future environmental impacts of green technologies, the aluminium contribution to their lifecycle impact is likely to be disproportionally overestimated if current aluminium production data is employed, as any scenario that involves a massive use of these green technologies likely also involves a particularly important decarbonization of the aluminium value chains.

As our projections show, the future decarbonization of aluminium production depends mostly on a factor that is not within the direct control of the industry actors: the availability of affordable and reliable low-carbon electricity sources. Decarbonized energy sources either grow increasingly constrained (limited hydropower potential, land use competition for bioenergy (Chen and Önal, 2016; Ryberg, Robinius and Stolten, 2018), material constraints (Moreau, Dos Reis and Vuille, 2019)) or require buffer capacity, integrated grid networks (Worighi *et al.*, 2019), or extensive sequestration activities (Bui *et al.*, 2018) in order to perform. These constraints and extensive value chains lead to the involvement of multiple actors, even in the case of vertically integrated energy production. A system's perspective and coordinated efforts will therefore be required for aluminium to serve as a strategic material in the global climate mitigation efforts.

The aluminium industry has a more direct influence on the other two parameters of this study: gains in energy efficiency and deployment of inert anodes. Though of lesser relative importance than the decarbonization of the electricity mix, efforts to increase energy efficiency are nonetheless expected to lead to major cumulative environmental impact reductions (between 48 and 135 Mt CO_2 eq by 2050), especially since cost reductions through efficiency gains will likely stimulate these efforts.

Conversely, the short-term cost effectiveness and feasibility of inert anode technology remains to be demonstrated. It is unclear whether it would prove feasible to retrofit existing installations. Our scenarios present a level of technological penetration that is limited by technological readiness and the stock turnover of aluminium smelters, and consequently we anticipate substantial industry-wide decarbonization benefits from inert anodes only after 2050. Inert anodes can thus be seen as a long-term strategic investment, especially if the more aggressive electricity decarbonization scenarios come to pass and direct smelting emissions represent a more important share of the total lifecycle impacts (e.g., direct emissions representing 25% of emissions by 2050 in the PRISMAL2 scenario with 2.0°C policies without inert anodes). As any new technology, a life-cycle perspective should be taken as more data on inert anode production and use become available, in order to avoid burden shifts and unintended consequences.

According to baseline scenarios, we can expect a relative decoupling between environmental impacts and primary aluminium production for baseline scenarios in the next three decades, except for PRISMAL 3 and PRISMAL5 scenarios which are based on a narrative with high social-economic challenges for mitigation. While aluminium producers have started to set environmental goals for the next decades (see SI-1), our analysis shows that an absolute reduction of emissions by 2050 for this sector would require a drastic change in electricity mix consistent with an aggressive climate change mitigation policy. Carbon capture would still be necessary in the most optimistic scenarios to capture the remaining emission of 500 Mt CO_2 eq per annum.

Beyond improving the environmental intensity of primary production, which has been the focus of this analysis, reduction of the overall material demand can contribute to the achievement of a low carbon economy (Material Economics, 2016) and an absolute decoupling of the aluminium sector. This could be achieved by the adoption of circular economy strategies that go beyond primary material production itself and involve other stakeholders along the aluminium value chain, namely: bauxite mining, alumina refining, material recirculation, product material efficiency and circular business models (Material Economics, 2016). Such circular economy strategies seem necessary to overcome alloy intercontamination issues in recycling (Rombach, Modaresi and Müller, 2012) and to reduce of transformation and fabrication losses (Cullen and Allwood, 2013). In a report made by Material Economics (2016) on potential future gains of circular economy, a possible CO_2 emission reduction of 300 Mt (-24% in comparison of their baseline scenario) by 2050 was calculated considering different circular initiatives within the aluminium sector.

Material substitution strategies can further contribute to GHG mitigation potential. Aluminium can displace other materials with overall life cycle benefits in respect to the targeted function achieving reduction that are not taken into account here and would compensate some of the emissions reductions potentials as shown in Figure 4. For instance, substituting steel by aluminium reduces use-phase emissions due to light-weighting (Bertram, Buxmann and Furrer, 2009).

While the mentioned circular economy and substitution strategies were not assessed by the present study, they should be considered as a means to reach absolute decoupling and meet more ambitious net-zero targets for the 2050 time horizon or beyond and thus mitigate reputational risks of the aluminium industry and help nations to achieve their pledges in international climate agreements.

4.2 VALIDATION AND LIMITATIONS

The global and regionalized lifecycle GHG relative impacts of PRISMAL are within ranges of previous studies (McMillan and Keoleian, 2009; Paraskevas, Van de Voorde, *et al.*, 2016), as further discussed and illustrated in SI-15. The scaled-up global emissions slightly exceed the 1 billion tons of CO_2 eq of GHG emissions estimated by the IAI in 2018 for the whole industry (Vatne, 2019).

Our prospective scenario analysis focuses on the evolution of the electrolysis process, which accounts for 70% of the cradle-to-gate GHG emissions of primary aluminium production. Since bauxite and alumina refining contribute less than 30% GHG impact for all baseline scenarios, this focus is not expected to alter our conclusions. Nevertheless, further research could explore impact reduction potential in both of these upstream life cycle stages.

While we did not specifically analyse the impact evolution of the alumina refining, few elements deserved to be discussed. Almost 60% of the CC impact of alumina refining comes from the heat consumed by the process (Nunez and Jones, 2016). The decarbonization of the industrial heat sector and improvement in the energy efficiency of the processes has the potential to reduce aluminium cradle to gate impacts. An estimation of 31% reduction of energy use in alumina refining by 2050 is forecasted (Kermeli *et al.*, 2015). The electrification of industry could also be a possible pathway to reduce environmental impacts and improve productivity, but operating costs in general are much higher than fossil fuel-based heating (Wei, McMillan and de la Rue du Can, 2019). Indirect electrification using hydrogen produced by electrolysis as an energy carrier and feedstock can also play a key role in industry decarbonization (Wei, McMillan and de la Rue du Can, 2019) but ambitious, targeted and near-term action is needed to further overcome barriers and reduce costs of hydrogen deployment (IEA, 2019). Future research should be addressed to quantify more precisely the future impact of alumina refining and identify the appropriate lever of action to reduce the impacts.

In the scenario development, the adoption of inert anode technology shows the potential to reduce environmental impacts of aluminium production only after 2050. The scenarios assume that inert anode process will become available at a larger scale. In addition, we assumed that this process does not incur an increase in energy intensity based on economic and competitiveness reasoning. The combination of inert anode and wettable cathode seems to be a promising opportunity to achieve this goal (Haraldsson and Johansson, 2018; Gupta and Basu, 2019) but those technologies are not commercialized yet.

The upscaling to total global emissions has been made using an exogenous aluminum demand projection that is not influenced by the SSP narratives. Linking material consumption to SSPs framework is relevant because material use has important consequences for environmental pressures and socio-economic activities (Schandl *et al.*, 2020). On one hand, greener scenario could lead to a higher level of dematerialization and material efficiency but on the other hand, aluminium can substitute other materials and be used for novel applications leading to an increase of consumption. For example, due to a substantial increase of aluminium in transport for light weighting vehicles, aluminium demand could increase in sustainable scenarios. While future projections of material consumption are out of the scope of this study, further research should explore the links between future demand, recycling dynamics and regional market share to these narratives.

Despite the limitations, the prospective results generated by the PRISMAL framework provide significant indications of environmental improvement potentials of the aluminium industry.

4.3 Conclusion

Prospective life cycle impacts of aluminum production sector were modelled up to 2050 and 2100 based on the Share Socioeconomic Pathways. The narratives were leveraged to model technology penetration and grid mix evolution. Results project a global average carbon intensity ranging between 8.6 and 18.0 kg CO_2 eq/kg in 2100 for baseline scenarios compared to 18.3 kg CO_2 eq/kg at present level. Further reduction, under 5.0 kg CO_2 eq/kg, is realistic with aggressive policy efforts in the energy sector. The evolution of other environmental indicators showed environmental co-benefits of a decarbonized future. Changes in smelting technology (improvement of energy intensity and adoption of inert anode process) are not enough the decouple GHG emissions to aluminium production. The impacts of the electricity are the main lever for improvement.

The anchoring of this work in the SSP framework and results ensure consistency within scenario modeling and within the scientific community. While, the study mainly focusses on the primary production of the aluminium, future research could integrate PRISMAL results, the SSP narratives and the stock dynamics of the whole aluminium value chain.

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