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“Decarbonising the Aluminium Industry: KPIs for financial institutions”

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A Nonno Graziano,
che purtroppo da un po' ci ha lasciati per una dannatissima tedesca.

Voglio ricordarti come ti ricorda la me più piccola,
seduta al tavolo del salone a imparare le divisioni a due cifre,
a scrivere la L maiuscola in corsivo, che per qualche motivo mi veniva specchiata,
aspettando di finire i compiti per potersi affacciare alla vetrata di casa e con il dito puntato verso il "coccoleone" (nome canzonatorio che mi avevi insegnato – da bravo direttore Enel – per il cane a sei zampe di Eni).

Questa tesi è per te, è per il bene che ti voglio e che non so come farti arrivare.

Per sempre,
Tua nipote

PS: la tedesca, purtroppo, non si chiama Erika, né Klara, ma Alzheimer.

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Chapter 1 – *Introduction*

« Aluminium has been called the sustainability nutrient of the world, and for good reason. Consider that 75% of all the aluminium made since 1886 is still in use – big time. »

– William J. O'Rourke,

Former Head of Alcoa Russia and Director of Duquesne's Business School[1]

1 Context and Relevance

As early as 1893, The Spectator[2] wrote, "As the world has seen its age of stone, its age of bronze, and its age of iron, so it may before long have embarked on a new and even more prosperous era – the age of aluminium".

A century and a half later, this quote remains timely, as the importance of aluminium has only grown. We need aluminium for circuits, for devices, for our vehicles (whether on they move on land, on water or by flight); our food comes in aluminium packaging, our energy travels through aluminium lines, and our bridges are made of aluminium beams held by aluminium cables. Aluminium is required in order to electrify global economy, to enhance production of more efficient batteries, and to capture sunlight, heat, water, and air and turn them into energy.

Yet, while aluminium has become indispensable to the functioning of modern economies and their transition to low-carbon ones, its availability – particularly as a raw material – is increasingly constrained. Demand for aluminium is expected to increase 50% by 2050[3], driven by the role this material plays in strategic sectors like renewable energy, electric vehicles, and digital technologies.

At the same time, access to affordable and secure supplies is narrowing. The 2022 Energy Crisis, triggered by the geopolitical fallout of Russia's invasion of Ukraine[4], led to a wave of aluminium smelter shutdowns across Europe, with energy-intensive producers

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[1] *Alcoa Co-Founder Charles Hall Smelt Success*. (2016, February 18). Investors.com. https://www.investors.com/news/management/leaders-and-success/charles-hall-unlocked-the-secret-of-aluminium/.

[2] The Future of Aluminium. (1893). *The Spectator*, 76–77.

[3] European Aluminium. (2022b, October 22). *Our vision 2050 for the aluminium industry: A vision for circular, low carbon, and competitive aluminium*. https://european-aluminium.eu/blog/vision2050/; International Energy Agency. (2023, July 11). *Aluminium*. IEA.org. https://www.iea.org/energy-system/industry/aluminium.

[4] International Energy Agency. (n.d.). *Global Energy Crisis*. https://www.iea.org/topics/global-energy-crisis.

halting operations due to unsustainable electricity prices[5]. More recently, at the beginning of June 2025, President of the United States Donald Trump announced a doubling of tariffs imposed on aluminium imports from 25% to 50%; « this decision adds further uncertainty to the global economy and increases costs for consumers and businesses on both sides of the Atlantic," responded the European Commission[6]. Almost 60% of total aluminium production is under Chinese control[7], leaving the EU wedged between two increasingly protectionist powers – reliant on imports from one, and exposed to trade retaliation from the other.

At the same time, while it is the most abundant metal on Earth, not even all the aluminium our planet has to offer would be enough for the future to be sustainable at current rates – where "sustainable" is to be read first and foremost as "economically feasible", since the aluminium value chain still relies on a mainly take-make-use-dispose model[8].

This is the fragile context in which the European aluminium industry operates, where the importance of this metal grows while its primary production becomes economically and geopolitically more volatile.

This essentiality, paired with vulnerability, makes the aluminium sector a compelling subject of analysis for this dissertation. On the one hand, aluminium is labelled as a *hard-to-abat*e[9] sector: it depends upon the use (thus exposed to fluctuations) of fossil fuels, invasive raw material extraction, and linear consumption patterns – where the situation is worsened by trade wars, strategic dependencies, and limited resource availability. On the other, the very

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[5] Hotter, A. (2025, January 6). *EU metals producers eye Ukraine's end to Russian gas imports*. Fastmarkets. https://www.fastmarkets.com/insights/eu-metals-producers-eye-ukraines-end-to-russian-gas-imports-andrea-hotter/; European Aluminium. (2024). ENVIRONMENTAL PROFILE REPORT FOR THE EUROPEAN ALUMINIUM INDUSTRY: Life Cycle Inventory (LCI) data for aluminium production and transformation processes in Europe - Executive Summary. In *European-Aluminium.eu*. https://european-aluminium.eu/wp-content/uploads/2024/11/2024-11-07-European-Aluminium-EPR-2024-Executive-Summary.pdf.

[6] Barbati, G. (2025, May 31). EU "strongly regrets" Trump's announcement to double steel and aluminium tariffs to 50%. *Euronews*. https://www.euronews.com/2025/05/31/trump-announces-50-increase-on-steel-and-aluminium-tariffs; Gambino, L., & Mackey, R. (2025, May 31). Trump announces 50% steel tariffs and hails 'blockbuster' deal with Japan. *The Guardian*. https://www.theguardian.com/us-news/2025/may/30/trump-tariffs-steel-japan.

[7] *10 largest aluminum producing countries in the world*. (2024, October 10). Harbor Aluminum. https://www.harboraluminum.com/en/top-aluminum-producing-countries.

[8] Elisha, O. D. (2020). Moving Beyond Take-Make-Dispose to Take-Make-Use for Sustainable Economy. *Research Gate*. https://www.researchgate.net/publication/349964391_Moving_Beyond_Take-Make-Dispose_to_Take-Make-Use_for_Sustainable_Economy; Smith, A. (2024, December 10). Aluminum can recycling remains below 30-year average. *Resource Recycling News*. https://resource-recycling.com/recycling/2024/12/10/aluminum-can-recycling-remains-below-30-year-average/; DePesa, R. (2025, April 25). Declining Aluminum Recycling Rates. *3BL*. https://www.3blmedia.com/news/declining-aluminum-recycling-rates?; *Declining aluminum recycling rates*. (n.d.). https://www.csrwire.com/press_releases/820591-declining-aluminum-recycling-rates.

[9] *Emissions Fall in Hard-to-Abate Sectors But Still Off Track to Reach 2050 Net-Zero Targets*. (2024, December 12). World Economic Forum. https://www.weforum.org/press/2024/12/emissions-fall-in-hard-to-abate-sectors-but-still-off-track-to-reach-2050-net-zero-targets/.

need to find alternative, less resource-intensive value chain creates a unique opportunity to accelerate the sector's shift toward circularity – where scrap recovery, closed-loop production, and material recirculation may offer not only environmental gains but also strategic resilience and economic viability.

Still, for this shift to take place, significant flows of capital need to be mobilised and allocated efficiently – and, most importantly, to both companies already aligned with climate goals and those that have yet to do so.

2 Research Question

Given all that is argued above, how can the introduction of KPI help direct the aluminium sector in ways that reconcile environmental integrity with operational resilience?
Are traditional metrics – such as financed emissions – appropriate metrics to manage transition risks? And if not, which KPIs could ensure that credit decisions account for deeper, structural vulnerabilities embedded in each producer's technological profile, regulatory exposure, and readiness to adapt?

These are the core questions this thesis seeks to address.

3 Methodology and Literature Review

To understand how the financial sector can meaningfully contribute to the transition of the aluminium industry, it is necessary to first clarify what transitional alignment means and how it is currently defined and measured.

This thesis first looks at legal, policy and voluntary frameworks that inform what companies are expected to do, to what extent, and why, from a sustainability perspective.

It started by looking at the legal framework, specifically the international and European one. Subsequently, given the lack of quantitative constraints for aluminium manufacturers to abide by, it explores voluntary initiatives and best practices, focusing on reporting schemes, industry alliances, coalition frameworks and benchmarks.

3.1 Legal Review

Seeking to understand if the boundary of compliance is defined by any quantitative indicator, this research started by looking at the legal framework, specifically the international and European one.

3.1.1 The International Context

The idea of sustainable development has gained a lot of traction in recent decades due to growing concerns about climate change and its alarming effects. This shared perspective has led to the ratification of several international treaties. Although this thesis is primarily focused on the European context, some international initiatives are worthy of mention, since they set what later became the EU's agenda.

Four international instruments have proven particularly influential:

1) The Basel Convention, 1989[10] – setting early rules for hazardous waste management, trade, recycling and responsible disposal.
2) The United Nations Framework Convention on Climate Change (UNFCCC)[11], 1992 – establishing the principle of *Common But Differentiated Responsibilities* and framing the two main approaches to climate action: mitigation and adaptation, still foundational to transition planning today.
3) The 2030 Agenda for Sustainable Development, 2015[12] – introducing the 17 sustainable development goals (SDGs), which attempts at mainstreaming sustainability in business practices.
4) The Paris Agreement, 2015[13] – officialising the global temperature thresholds (+1.5°C and + 2°C).

These instruments, especially the last one, constitute the cornerstone around which all climate action builds upon.

3.1.2 The European Context

Within the European Union, the legal framework for climate action has progressively evolved from aspirational and voluntary objectives to binding obligations. In fact, early environmental initiatives – such as the Common Agricultural Policy[14] and the First Environmental Action

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[10] UNEP. (1989). Base Convention: On the control of transboundary movements of hazardous wastes and their disposal. In *UNEP*. https://www.basel.int/portals/4/basel%20convention/docs/text/baselconventiontext-e.pdf.
[11] Kyoto Protocol to the United Nations Framework Convention on Climate Change. (2018). In *Cambridge University Press eBooks*(pp. 491–508). https://doi.org/10.1017/9781316577226.067.
[12] Martin. (2018, June 20). *United Nations sustainable development agenda*. United Nations Sustainable Development. https://www.un.org/sustainabledevelopment/development-agenda-retired/#:~:text=%E2%97%8F,future%20for%20people%20and%20planet.
[13] *The Paris Agreement*. (2015). United Nations Climate Change. https://unfccc.int/process-and-meetings/the-paris-agreement.
[14] *CAP at a glance*. (2025, May 27). Agriculture and Rural Development. https://agriculture.ec.europa.eu/common-agricultural-policy/cap-overview/cap-glance_en.

Program[15] – were entirely deliberate under soft law principles. The first binding piece of law ever passed on sustainability was the Birds Directive[16], whose legal basis laid in former Article 235 of the European Economic Community (EEC) – now Article 352 of the TFEU – which allowed any necessary action to protect the internal market, thus justifying biodiversity conservation given its role in agriculture[17]. According to the same line of reasoning, sustainability became a top priority for the EU, which in 2019 transposed the objectives set by the Treaty of Paris into its European Climate Law and European Green Deal[18], officially setting the target of achieving climate neutrality (Net Zero[19]) by 2050.

However, despite the aluminium sector's strategic importance, no EU directive directly targets its value chain. Nonetheless, this sector falls under broader sustainability laws designed for high-impact industries, including: the Corporate Sustainability Reporting Directive (CSRD)[20], the Corporate Sustainability Due Diligence Directive (CSDDD)[21], the European Taxonomy[22], the EU Emission Trading System (ETS)[23] and the Carbon Border Adjustment Mechanism (CBAM)[24]. Despite the stringent limits imposed by these pieces of law, recent geopolitical concerns and private sector pressures led to a loosening of these provisions through the Omnibus Package of 2025[25].

At last, from the analysis conducted, legal compliance turns out to be insufficiently stringent and overly superficial, especially for the aluminium sector, whose impact extends well

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[15] *EEA: 25 years of growing knowledge to support European environment policies*. (n.d.). European Environment Agency. https://www.eea.europa.eu/articles/eea-25-years-of-growing.

[16] *The Birds directive*. (2025, May 21). Environment. https://environment.ec.europa.eu/topics/nature-and-biodiversity/birds-directive_en.

[17] European Commission. (n.d.). The Role of the "Flexibility" Clause: Article 352: The Commission's Contribution to the Leaders' Agenda Monetary Union as an objective of European in. In *Commission.Europa.Eu*. https://commission.europa.eu/document/download/2f216d25-a1fe-4a1a-b451-51f653bf349e_en?filename=role-flexibility-clause_en.pdf.

[18] *Il Green Deal europeo*. (n.d.). Commissione Europea. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_it.

[19] *Net zero FAQs | EGA*. (n.d.). https://www.ega.ae/en/sustainability/net-zero/net-zero-faqs.

[20] *Corporate sustainability reporting*. (n.d.). Finance. https://finance.ec.europa.eu/capital-markets-union-and-financial-markets/company-reporting-and-auditing/company-reporting/corporate-sustainability-reporting_en.

[21] *Corporate sustainability due diligence*. (n.d.). European Commission. https://commission.europa.eu/business-economy-euro/doing-business-eu/sustainability-due-diligence-responsible-business/corporate-sustainability-due-diligence_en.

[22] *EU taxonomy for sustainable activities*. (n.d.-b). Finance. https://finance.ec.europa.eu/sustainable-finance/tools-and-standards/eu-taxonomy-sustainable-activities_en.

[23] *EU Emissions Trading System (EU ETS)*. (n.d.-b). Climate Action. https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en.

[24] *Carbon Border Adjustment Mechanism*. (n.d.). Taxation and Customs Union. https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en?.

[25] *Directive - 2019/2161 - EN - omnibus directive - EUR-Lex*. (n.d.). https://eur-lex.europa.eu/eli/dir/2019/2161/oj/eng; European Commission. (2025, February 26). *Questions and answers on simplification omnibus I and II*. https://ec.europa.eu/commission/presscorner/detail/bg/qanda_25_615.

beyond CO_2 emissions alone: aluminium manufacturing comprises the release of greenhouse gases (GHGs) with a *global warming potential* (GWP)[26] up to 12,6500 times greater than CO_2[27], intensive water consumption, and the generation of several hazardous physical waste streams which – despite their significant environmental footprint – are often landfilled rather than properly managed or recovered.

For this reason, a second layer of analysis led to the consultation of voluntary sustainability frameworks, such as ESG principles[28], international reporting standards (specifically, ISOs[29]) and climate-aligned target validating methodologies (SBTi[30]).

3.2 Voluntary Initiatives and Best Practices Review

As anticipated just above, given the lack of clearly defined quantitative limits set by law, a second review was conducted within the field of voluntary initiatives and best practices.

This Section starts by looking at widely-applicable target validation frameworks – specifically, the Science-Based Targets initiative (SBTi[31]) – to then move towards more industry-specific resources, including aluminium alliances and coalition frameworks – namely, the European Aluminium Alliance[32], the Aluminium Stewardship Initiative[33], and the Net Zero Industry Tracker[34]. In its third and last section, this chapter focuses – instead – on benchmarking, and the windows this practice opens on plausible futures. Below are the most relevant findings from this second review.

3.2.1 Sustainability at the Corporate Level: SBTis

Within the context of sustainability at the corporate level, the only initiative analyses is the Science-Based Target initiative. That is, because – in some sense – to look at SBTi is to look

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26 *Understanding global warming potentials | US EPA*. (2025, January 16). US EPA. https://www.epa.gov/ghgemissions/understanding-global-warming-potentials?.
27 *Understanding global warming potentials | US EPA*. (2025, January 16). US EPA. https://www.epa.gov/ghgemissions/understanding-global-warming-potentials?.
28 Bellini, M. (2025, January 7). ESG: tutto quello che c'è da sapere per orientarsi su Environmental, Social, Governance. *ESG360*. https://www.esg360.it/environmental/esg-tutto-quello-che-ce-da-sapere-per-orientarsi-su-environmental-social-governance/.
29 *ISO - Standards*. (n.d.). ISO. https://www.iso.org/standards.html.
30 *How it works - Science Based Targets*. (n.d.). Science Based Targets Initiative. https://sciencebasedtargets.org/how-it-works.
31 *Ambitious corporate climate action*. (n.d.). Science Based Targets Initiative. https://sciencebasedtargets.org/.
32 *European Aluminium: ALUMINIUM, THE BASE METAL FOR THE GREEN TRANSITION*. (2025). European Aluminium. https://european-aluminium.eu.
33 Aluminium Stewardship Initiative. (2022b, December 6). *ASI Home | Aluminium Stewardship Initiative*. https://aluminium-stewardship.org/.
34 *The Net Zero Industry Tracker*. (2005). World Economic Forum. https://www.weforum.org/publications/net-zero-industry-tracker-2024/.

at all corporate reporting frameworks, since it is the latter than validates the former. More simply, performances shared by companies are evaluated and certified by SBTi based on how aligned they are with their targeted climate ambition.

In detail, SBTi helps companies and financial institutions set greenhouse gas reduction targets aligned with the latest climate science and the goals of the Paris Agreement (hence the below 2°C or 1.5°C temperature thresholds). Through its methodologies and tools – specifically, its Sectoral Decarbonization Approach (SDA) – it ensures credibility, comparability, and effectiveness of targets set.

However, while SBTi's meticulous approach rightly emphasizes emission targets – widely recognised as the primary strategy to meet climate goals – once translated into financial assessments by banks, these metrics become financed emissions: these digits alone fail to capture the full spectrum of risks tied to sector-specific production impacts – such as those of the aluminium industry (as explained in Chapter 4). Accordingly, despite the value of SBTi and emission targets in general, a more granular and tailor-made approach is needed to capture the full extent of this sectors' impact – which goes far beyond emissions.

For this reason, the following Sections of Chapter 3 look at aluminium industry - specific best practices, certification schemes and promising technologies, searching for a framework capable of delivering the full materiality of this sector.

3.2.2 Industry-Specific Standards and Best Practices: European Aluminium, Aluminium Stewardship Initiative, The Net Zero Industry Tracker

Given the limited findings of the first two reviews for the scope of this thesis, a third layer of inquiry was added: best practices and collation frameworks developed specifically for the aluminium industry were examined. We specifically examined the European Aluminium Alliance, the Aluminium Stewardship Initiative, and the Net Zero Industry tracker.

Key findings from this section lie in the reports these alliances publish, which – finally – provide projections, reports, market data, aluminium- specific certification schemes, and promising technologies, all of which suggest practical actions aluminium producers can adopt to align with climate targets. However, quantitative evaluation of a company's transition plan requires comparison. To this end, the following and last section of Chapter 3 focuses on benchmarks that represent the "ideal pathway" for each of the internationally set climate targets (1.5°C, below 2°C, NDCs, or Paris pledges). These benchmarks enable companies' actions to be assessed according to how closely they align with these transition pathways.

3.2.3 Benchmarking

More in detail, three different benchmark methodologies were analysed, respectively: the First Movers Coalition[35], the Materials and Embodied Carbon Leaders' Alliance[36] and the Transition Pathway Initiative[37], and – at last – the Network of Central Banks and Supervisors for Greening the Financial System (NGFS[38])'s scenarios.

Each of these initiatives shows and defines a reference pathway, whether it be via the development of low-carbon sourcing, different climate targets, or how each of these provides for different projections about possible systemic responses to the degrees of urgency and coordination in undergoing the transition; all of them ultimately remain focused on the same element – that is, decarbonisation.

However – while decarbonisation most certainly remains the primary strategy for limiting temperature rise within established thresholds – it is not the only aspect that should be monitored in highly impactful industries such as aluminium.

The multi-layered review conducted shows that – while they indeed are interesting to enquire about in search for a window on the future of the aluminium industry – the breadth of these initiatives too remains largely confined to emissions-based indicators, offering limited insights into the full scope of the sector's impact on the environment.

4 Analysis

From this comprehensive analysis of all the regulatory instruments currently available to the aluminium sector – both mandatory and voluntary – a consistent gap emerges since none of them offers a fully delineated and quantitative mapping of the material impact of the industry: despite existing and enforced frameworks, all frameworks presented heavily rely on carbon emissions, and when they go beyond, they only do so through qualitative assessments that still fail to grasp crucial dimensions such as waste generation, water use, and site-specific resource intensity. Such a narrow focus overlooks many critical aspects of the aluminium value chain –

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[35] *Commitments | First Movers Coalition*. (n.d.). https://initiatives.weforum.org/first-movers-coalition/commitments; First Movers Coalition & World Economic Forum. (2022). First Movers Coalition – Aluminium Commitment. In *World Economic Forum*. World Economic Forum. https://www3.weforum.org/docs/WEF_Aluminum_one_pager_2022.pdf.

[36] MECLA. (2024b, July 24). *Home - mecla.org.au*. mecla.org.au. https://mecla.org.au/.

[37] *Transition Pathway Initiative*. (2025a). Transition Pathway Initiative (TPI). https://www.transitionpathwayinitiative.org.

[38] *NGFS Scenarios Portal*. (n.d.-a). NGFS Scenarios Portal. https://www.ngfs.net/ngfs-scenarios-portal/.

particularly in its primary segment – where the environmental impact extends far beyond carbon accounting: in fact, many producers of primary aluminium operate in resource-constrained regions, with supply chains that delocalise the most polluting phases of production (such as bauxite mining and refining) in the Global South. In these contexts, material indicators such as water consumption or waste management gain even more relevance, given the structural scarcity of local resources and the fragility of surrounding ecosystems.

Yet, none of the major environmental performance frameworks systematically accounts for this type of context-specific materiality.

For this reason, a materiality assessment of the aluminium industry was conducted in Chapter 4 – *Overview of the Aluminium Industry* – for both the primary and secondary production routes – to finally capture and quantify the full extent of the environmental pressures generated along the value chain, from extraction to waste.

4.1 Materiality Review

As anticipated just above, an analysis of the material flow associated to the aluminium manufacturing industry was conducted.

Findings of the materiality assessment are shown in Chart 1 (see below). In addition to this, Chapter 5 delved into existing literature on scientific processes to decarbonise and improve the efficiency and circularity of the aluminium industry; major findings are to be attributed to the paper by Zore L. and the European Joint Research Centre on *Decarbonization Options for the Aluminium Industry*[39]. More specifically, three dimensions emerged as fundamental to drawing conclusions on how to align—and to what extent—the aluminium industry with climate targets, and they are:

1) Reduction of emissions – however, not only in absolute terms or as percentages (both targeted and achieved) but as their decoupling from the volumes produced: in a world where aluminium demand shows consistent growth, operational efficiency must be achieved by reversing the aluminium-to-emissions ratio in favour of greater sustainability.

[39] Zore, L. (2024). Decarbonisation options for the aluminium industry. In J. A. Moya (Ed.), *European Commission's Joint Research Centre (JRC)*. European Commission's Joint Research Centre (JRC). https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://publications.jrc.ec.europa.eu/repository/bitstream/JRC136525/JRC136525_01.pdf&ved=2ahUKEwjm7dicnISMAxXD3QIHHVRnCAUQFnoECBwQAQ&usg=AOvVaw1wy2cCymISvMjc41qqIRZC.

2) Circularity – aluminium is, in principle, infinitely recyclable[40], and from the second production cycle onwards, it requires 95% less energy to be processed[41]. Given this, a growing demand for aluminium, plus its outstanding recyclability and energy efficiency, leads to only one conclusion: increased reuse – until primary production becomes obsolete.
3) Resource efficiency is crucial because the aluminium sector is highly resource-intensive, affecting both its consumption and the waste it generates.

Given how these strategic findings remain unaddressed by currently available instruments, ten KPIs were designed in Chapter 7 to capture each of these dimensions and declinate them into ready-for-use indicators.

4.2 Thesis Statement

Given the findings of the previous sections, the development of ten KPIs was conducted to respond to the need of capturing the three dimensions emerged above; specifically, these indicators were designed to offer a more complete lens to quantify the aluminium sector's material impact, their full relevance emerges when they are operationalised within financial institutions' risk governance frameworks.

In fact, the proposed KPIs aim to measure the transition, not to initiate it. To enable change, finance must first understand its nature, assess its relevance for creditworthiness, exposure, and portfolio-level risk. The overarching goal is to create an evaluation scheme where precise, measurable, and comparable indicators address real-economy transition risks in the aluminium sector; only in this way can capital allocation decisions contribute to the transition, closing the gap between environmental and financial value.

In fact, current state-of-the-art practices, with their limited specificity, expose the entire system (companies, their lenders – whether it be banks or investors – and all their stakeholders) to several systemic risks, including:

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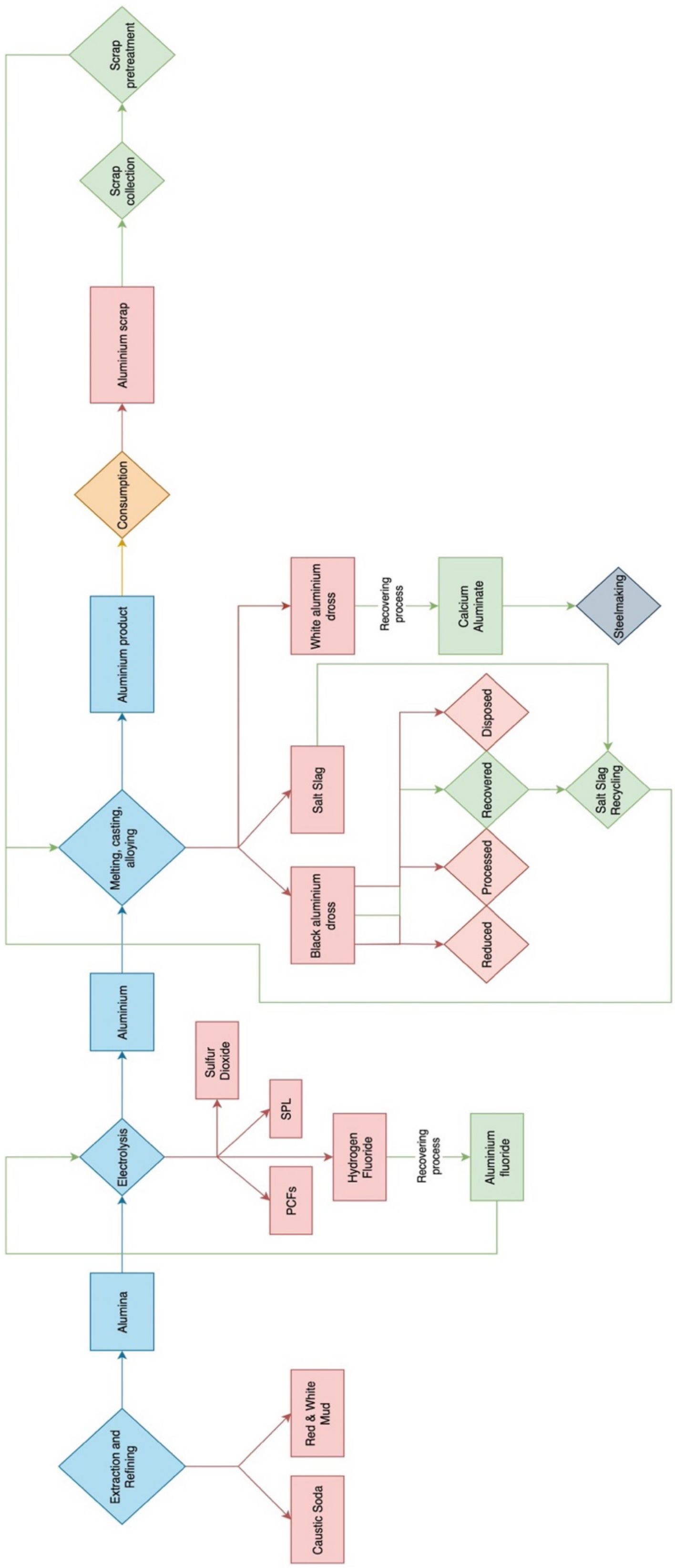
[40] International Aluminium Institute. (2024c, October 28). *Aluminium is infinitely recyclable - International Aluminium Institute*. https://international-aluminium.org/landing/aluminium-is-infinitely-recyclable/#:~:text=International%20Aluminium%20Institute-,Aluminium%20is%20infinitely%20recyclable,without%20changing%20its%20fundamental%20properties.

[41] International Aluminium Institute. (2024d, October 28). *Aluminium recycling saves 95% of the energy needed for primary aluminium production - International Aluminium Institute*. https://international-aluminium.org/landing/aluminium-recycling-saves-95-of-the-energy-needed-for-primary-aluminium-production/.

Chart 1: Primary (in blue) and Secondary Aluminium Production, with physical waste (in red) and recycling processes (in green)



- Litigation risks
- Capital depreciation, impaired and stranded assets
- Loss of market share
- Supply chain disruptions and potential operational shutdowns

According to this logic, having established the KPIs, this thesis translated them into financial implications, linking each one of them to the transmission channels of the transition risk it represents – including the ones mentioned above – and defining their corresponding risk thresholds. In addition, the ten KPIs were applied to ten of the most relevant aluminium producers worldwide: this practical application was conducted to ground the thresholds advanced in Chapter 9 within the boundaries of feasibility and operational efficiency: that is because, the sources that inspired them, were on the one hand too permissive (legal baseline), and on the other too optimistic (best available technologies and scientific literature). The results of this step are shown in Appendix 2.

5 Findings & Conclusions

Drawing some conclusions, the analysis conducted showed that, despite the growing number of tools and frameworks designed to assess the environmental impact of manufacturing industries – including the aluminium sector – each of these approaches presents significant limitations in terms of transformative potential.

Most of these instruments provide a static snapshot of the current business practices that, even if conducted granularly, still lacks any real guidance on how to improve over time. For example, traditional ESG metrics are backward-looking and often lack comparability across companies and sectors, while environmental product declarations (EPDs), while technically detailed and accurate at the product and process level, fail to a standard definition for sustainable aluminium; unlike other high-impact sectors – such as agriculture, where recognised benchmarks exist (i.e., organic products) – the aluminium industry still lacks a clear and universally accepted framework to define what constitutes “green”.

It is within this context that the development of the ten proposed KPIs can play a strategic role: they are in fact designed as practical tools not only for measuring impact but also for guiding continuous improvement and enhancing comparability across industry actors.

This gap in reliable, sector-specific indicators is felt not only by companies themselves but also by their financial institutions, which currently lack the tools capable of capturing and quantifying the real risk profile of the aluminium industry.

At last, the goal of this contribution was that of equipping financial institutions with aluminium sector-specific instruments that reflect the capacity to transform of a company, its resilience in doing so, and how the risks associated with the process impact both the company (client) and the bank (its lender). In doing so, environmental data becomes decision-relevant – not as a separate sustainability layer, but as a core component of credit evaluation and strategic capital allocation.

Chapter 2 – *Legal Context*

Introduction

Between 2021 and 2024, the European manufacturing industry has emitted around 200 million tons of CO2 per yearly quarter, constituting the smallest decrease in emissions among the sectors shown (see Chart 2).

However, the impact of the manufacturing industry goes far beyond the amount of GHGs it emits. It is responsible for resource depletion, environmental pollution and contamination, habitat destruction, and, ultimately, generates substantial amounts of waste.

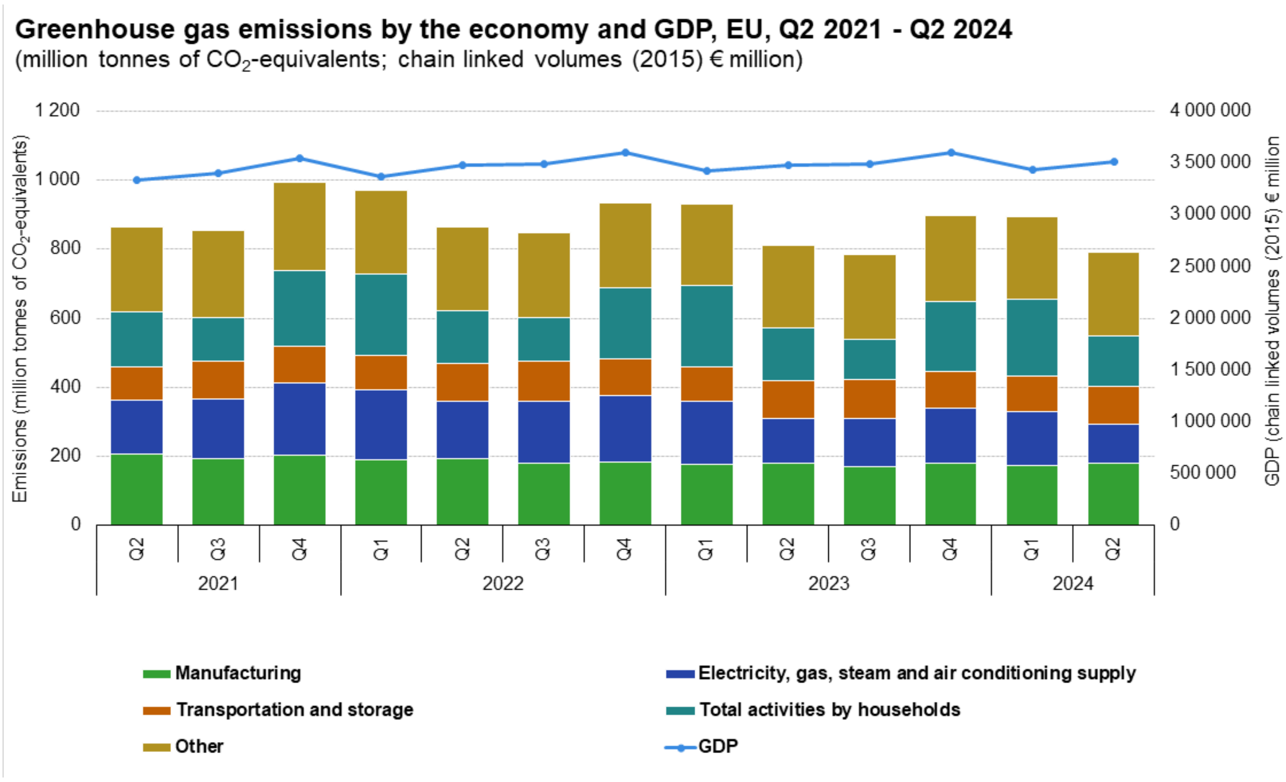


Chart 1: Greenhouse gas emissions by the economy and GDP, EU, Q2 2021 - Q2 2024[42]

Any industrial activity, given its highly polluting potential, operates within the context of abundant – yet fragmented – international, European, and industry-specific regulations, recommendations, and standards.

[42] Greenhouse gas emissions by the economy and GDP, EU, Q2 2021 - Q2 2024 (million tons of CO2 equivalents, chain linked volumes (2015) € million). (2025). In *Eurostat*. Eurostat. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Quarterly_greenhouse_gas_emissions_in_the_EU

The following review examines the legal context surrounding aluminium manufacturing, with an emphasis on the growing sustainability efforts.

We will structure the review: Section 1 will deal with the most relevant international agreements, responsible for setting the overall agenda on "what is necessary to combat climate change"; Section 2 will be focused on the European level, looking at how the EU "inherited" the international targets, declining them into European plans; Section 3 will present findings from this chapter and explain the rationale for the subsequent chapter.

1 The International Context

Over the last few decades, the concept of sustainable development has gained significant momentum, driven by growing concerns about climate change and its increasingly concerning impacts. The shared perspective on the urgency of action has led to the crystallization of several international agreements. Despite the scope of this thesis being primarily centered on the EU context, it is beyond necessary to discuss supra-European efforts, for they are the ones setting the agenda for the European Union as well.

1.1 The Basel Convention

The Basel Convention on the Control of Transboundary Movement of Hazardous Wastes and Their Disposal is an international treaty adopted in 1989 and enforced in 1992[43]. This treaty is pertinent as it addresses the transfer of hazardous waste between countries, especially from developed to developing nations.

This convention has four primary objectives, namely:

a) Classification of hazardous waste and definition of its handling, transport and disposal
b) Prior Informed Consent (PIC) ensuring countries are allowed to ship waste
c) Minimization and Recycling as strategies to avoid landfilling
d) Illegal Trafficking Provisions to prevent illegal waste movements

Economic disparities undermine the effectiveness of the Basel Convention, despite its noble intentions.

[43] UNEP. (1989). Base Convention: On the control of transboundary movements of hazardous wastes and their disposal. In *UNEP*. https://www.basel.int/portals/4/basel%20convention/docs/text/baselconventiontext-e.pdf

Unfortunately, it is common for governments or other entities struggling with poverty to accept hazardous waste in exchange for financial incentives – even at the expense of public health.

There have been many cases of fraudulent dumping of hazardous waste in, especially in Africa. Among them, the most infamous ones are the Trafigura toxic waste scandal of 2006 in Abidjan, Côte d'Ivoire[44], the toxic waste incident of 1988 in Koko, Nigeria[45], and the overall recent trend of dumping of clothes on the coasts of Ghana[46].

1.2 The United Nations Framework Convention on Climate Change (UNFCCC)

Adopted in 1992 following the Earth Summit in Rio de Janeiro, the UNFCCC is an international agreement laying down the foundational framework for global efforts in combating climate change. It was, in fact, this almost unanimously adopted agreement defining the concept of Common But Differentiated Responsibilities (CBDR-RC)[47]: this principle acknowledges the major responsibility of developed countries in causing most emissions, and that, as such, it is their role serve as leaders in sustainability efforts to "earn time" for those that are still not developed.

Furthermore, incorporating the findings of the 1990s Intergovernmental Panel on Climate Change (IPCC), the UNFCCC defined the main two strategies to combat climate change: *mitigation* and *adaptation*. *Mitigation* is defined as « an anthropogenic intervention to reduce the sources or enhance the sinks of GHG », while *adaptation* refers to « an adjustment in natural or human systems in response to actual or expected climate stimuli or their effects, which moderates harm or exploits beneficial opportunities »[48]. In other words, *mitigation* addresses the causes of climate change (the "illness"), while *adaptation* works on its effects

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[44] Amnesty International. (2021, August 16). *Trafigura: A Toxic Journey*. https://www.amnesty.org/en/latest/news/2016/04/trafigura-a-toxic-journey/

[45] *The contribution of cartoonists to environmental debates in Nigeria: the Koko Toxic-Waste-Dumping incident*. (2017, October 18). Environment & Society Portal https://www.environmentandsociety.org/perspectives/2013/1/article/contribution-cartoonists-environmental-debates-nigeria-koko-toxic-waste

[46] Johnson, S. (2024, February 8). 'It's like a death pit': how Ghana became fast fashion's dumping ground. *The Guardian*. https://www.theguardian.com/global-development/2023/jun/05/yvette-yaa-konadu-tetteh-how-ghana-became-fast-fashions-dumping-ground

[47] Hey, E. & United Nations. (n.d.). THE PRINCIPLE OF COMMON BUT DIFFERENTIATED RESPONSIBILITIES. In *LegalUn.org*. United Nations. https://legal.un.org/avl/pdf/ls/Hey_outline%20EL.pdf.

[48] Klein, R. J. T., Huq, S., Denton, F., Downing, T. E., Richels, R. G., Robinson, J. B., & Toth, F. L. (2007). Inter-relationships between adaptation and mitigation. In *Climate Change: Impacts, Adaptation and Vulnerability* (pp. 745–777). CambridgeUniversityPress. https://www.ipcc.ch/site/assets/uploads/2018/02/ar4-wg2-chapter18-1.pdf.

(the "symptoms"). Subsequent international agreements[49] will rely on these notions, stressing the need to have a positive synergy between the two to put in place a *resilient*[50] response to the climate crisis.

1.3 The Agenda 2030

With a harmless, colourful façade, the Agenda 2030 (Chart 3) was the first "toolkit" instrument, bringing much-needed attention to sustainability beyond the buzzword.

Defining *sustainable development* as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs"[51], the Agenda unpacks said concept into 17 *sustainable development goals* (SDGs). Despite its intent to provide policy guidance, the Agenda has demonstrated – upon pragmatic analysis – limited practical effectiveness: it is conceivable that due to the lack of specificity of the goals, which sometimes lent themselves to more formal than substantive corporate adherence, an overall underestimation of 2030 Agenda developed, indirectly encouraging the emergence of [52].

1.4 The Paris Agreement

With considerably more serious premises, the Paris Agreement of December 2015 goes beyond the 2030 Agenda, incorporating previous international agreements and strengthening the whole debate with an analysis of the climate context we are to face. Based on said

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[49] Including the Kyoto Protocol of the United Nations Framework Convention on Climate Change (2018), which one could define as the father of the Paris Agreement. In *Cambridge University Press eBooks* (pp. 491-508). https://doi.org/10.1017/9781316577226.067.

[50] Resilience « is described as a combination of: (i) shock absorbing and coping; (ii) evolving and adapting; and (iii) transforming. [Accordingly], coping is the first and ideal strategy for managing risk. However, when societies exceed their ability to cope, they should be able to adapt to the adverse changes they face: this is sometimes described as incremental adaptation [...]. If the adaptative action is not adequate to overcome the disaster risk, societies will need to transform ». *What is the difference between adaptation and mitigation?* (2024, August 20). European Environment Agency's Home Page. https://www.eea.europa.eu/en/about/contact-us/faqs/what-is-the-difference-between-adaptation-and-mitigation#:~:text=In%20essence%2C%20adaptation%20can%20be,of%20climate%20change%20less%20severe.

[51] Martin. (2018, June 20). *United Nations sustainable development agenda*. United Nations Sustainable Development. https://www.un.org/sustainabledevelopment/development-agenda-retired/#:~:text=%E2%97%8F,future%20for%20people%20and%20planet.

[52] United Nations claims that « by misleading the public to believe that a company or other entity is doing more to protect the environment than it is, greenwashing promotes false solutions to the climate crisis that distract from and delay concrete and credible action ». Businesses found it very easy to claim they were contributing to the 17 goals because of their lack of measurability and enforcement, which ultimately resulted in a greenwashing tendency when it came to the agenda. United Nations. (2025). *Greenwashing – the deceptive tactics behind environmental claims | United Nations*. https://www.un.org/en/climatechange/science/climate-issues/greenwashing

scenario(s), the Paris Agreement sets the temperature limits that ought to regulate any human activity from 2015 onwards: to hold the increase in the global average temperature to well below +2°C, and to pursue efforts to limit the temperature increase to +1.5° (United Nations, 2015)[53].

These milestones, especially the last one, would, from 2015 onwards, unleash a potential revolution in what *business as usual* should have to become by 2030 and 2050: to reduce the temperature increase is to cut GHG emissions, and to cut emissions is to start a *decarbonization* path. Following legal (both hard law and soft law) instruments, voluntary initiatives and standards will be anchored to these temperatures as the reference point for the development of any realistic transition plan.

Chart 2: The 17 Sustainable Development Goals[54]

[53] Both temperature limits referring to "pre-industrial levels" intended as the average temperature between the years 1850 – 1900. *Why 1.5°C?* (2023, December 11). Met Office. https://www.metoffice.gov.uk/blog/2023/why-1-5c.
[54] *THE 17 GOALS | Sustainable Development*. (n.d.). https://sdgs.un.org/goals.

2 The European Context

Inheriting what has been established by the international context, the European Union made the cause of sustainability its own, becoming one of the world's leaders in the achievement of climate goals. However, aside from the internationally binding agreements, the European debate on sustainability began long before the 90s.

2.1 Early EU sustainability efforts: *united before the union*

Before the birth of the EU as we conceive it today, formally established by the Treaty of Maastricht[55], the Union could not legislate, much less enforce. Nonetheless, its predecessor, the European Economic Community (EEC), engaged in preliminary environmental and sustainability actions through soft law, primarily relying on countries' voluntary bases. These efforts included action programs, collaborative conventions, and international commitments (see Table 1): the targeted areas comprised pollution control, waste management, environmental protection, and mitigation of industrial activities. Subsequent actions introduced the *polluter-pays-principle* [56] and the concept of *preventive action*.

Table 1: Early sustainability policy before the formalization of the EU

<table>
<tr><th>Policy</th><th>Year(s)</th><th>Specific Focus</th><th>Objectives</th><th>Enforcement</th></tr>
<tr><td>Common Agricultural Policy (CAP)</td><td>1962</td><td colspan="2">Ensuring a stable and safe food supply, providing a fair standard of living for farmers, stabilizing markets, and maintaining reasonable prices for consumers</td><td>Hard law</td></tr>
<tr><td>Stockholm Conference</td><td>1972</td><td>1st global discussion on environmental protection</td><td>Established 26 principles to guide sustainable development and market the birth of the (UNEP)</td><td>Soft law</td></tr>
<tr><td>First Environmental Action Program (EAP)</td><td>1973 – 1976</td><td colspan="2">Marked the inception of a coordinated environmental policy within the EEC to establish a framework for integrating environmental considerations into economic policies</td><td>Soft law</td></tr>
</table>

[55] The Treaty of Maastricht established the EU with its three-pillar structure (the European Communities, the Common Foreign and Security Policy and Cooperation in the field of Justice and Home Affairs) along with the Eurozone. From 1992 onwards the EU acquired supranational powers, allowing it to legislate on its competences. Jones, E., Menon, A., & Weatherill, S. (2012). *The Oxford Handbook of the European Union*. Oxford University Press.

[56] First introduced by the Organization for Economic Cooperation and Development (OECD) in 1972, the polluter pays principle was later on enshrined in the Article 191(2) of the TFEU, along with the precautionary principle and the concept of preventive action. Khan, M. (2015). Polluter-Pays-Principle: the cardinal instrument for addressing climate change. *Laws*, *4*(3), 638–653. https://doi.org/10.3390/laws4030638.

Birds Directive[57]	1979	To protect wild bird species and their habitats	Required MS to designate Special Protection Areas (SPAs)	Hard law
Early Waste Directives	1975	Directive on Waste (75/442/EEC)	Set the 1st legal framework for EU waste management	Hard law
	1985	Hazardous Waste Directive (84/631/EEC)	Introduced strict controls on the disposal and transportation of hazardous waste	Hard law
Single Europea Act (SEA)	1987	Integrated environmental protection into European Community treaties		Hard law

2.2 EU sustainability efforts

Table 2 displays a detailed timeline of significant European sustainability-oriented policies that shaped the EU, especially with regards to the aluminium manufacturing industries. Among the policies displayed in Table 2, the most relevant ones for the examined sectors are further detailed in Table 2 into their objectives, targets, and enforcement measures. Special attention should be paid to the New Circular Economy Action Plan (from now on referred to as CEAP) of 2020[58], which substituted the one of 2015[59] with more ambitious and specific targets and established new sustainability requirements for products, including eco-

[57] This policy was the first officially binding instrument on environmental protection, targeting biodiversity conservation. The Birds Directive was in fact an exception, as sustainability-related policies entered EU law only in 1987 with the Single European Act (SEA). Its legal basis lay in Article 235 of the EEC (now Article 325 TFEU), allowing the adoption of measures aligned with EEC objectives – even in the absence of explicit treaty competencies. Bird conservation was tied to economic interests, based on the ecological role of birds in protecting agricultural crops from pests. This early legislation may have been influenced by the lessons of Mao Zedong's Four Pests Campaign (1958–1962), part of the Great Leap Forward. Seeking to increase crop yields, the CCP targeted rats, mosquitoes, flies, and sparrows. The latter were nearly eradicated through mass mobilization, but their absence led to a locust infestation that contributed to the Great Chinese Famine (1959 – 1961), which caused up to 45 million deaths. Long story short, this disaster was acknowledged and verified between 1977 and 1978, and in 1979 the EU found its first legal quibble to make sure birds were safe and sound. *The Birds directive*. (2025, May 21). Environment. https://environment.ec.europa.eu/topics/nature-and-biodiversity/birds-directive_en; Platt, J. R. (2025, April 14). *Six lessons from the world's deadliest environmental disaster*. The Revelator. https://therevelator.org/china-sparrow-campaign/

[58] Policies activated under CEAP 2020 can be observed in

Appendix 1: Policies activated under the Circular Economy Action Plan; those that despite being inscribed within the same legal framework, have not yet been activated (not even as proposals) can be found, along with those all the others, in CEAP's Annex (at the last pages of the document). *EUR-LEX - 52020DC0098 - EN - EUR-LEX*. (n.d.). https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN

[59] *First circular economy action plan*. (n.d.). Environment. https://environment.ec.europa.eu/topics/circular-economy/first-circular-economy-action-plan_en.

design, right to repair, and consumer empowerment, to increase producers' liability along with product durability, repairability, and circularity.

Table 2: Most impactful sustainability policy after the formalization of the EU

Policy	Year	Objective	Targets	Enforcement
End-of-Life Vehicles (ELV) Directive	2000	Sets increasing percentages of vehicle weight to be reused, recycled and recovered[60].	By 1st Jan 2006: a) increase reuse & recycling to 80% b) increase reuse and recovery to 85% By 1st Jan 2015: a) increase reuse & recycling to 85% b) increase reuse & recovery to 95%	Hard law
Gothenburg EU Council Strategy	2001	Introduced sustainable development as an EU priority	Decoupling economic growth from resource depletion and environmental degradation	Soft law
Emission Trading System Directive	2005	Establishment of the carbon market	To reduce GHGs from key sectors by setting a cap on emissions and creating a market for trading emission allowances	Hard law
Waste Framework	2008	Established EU waste hierarchy (prevention, reuse, recycling)		Hard law
Industrial Emission Directive (IED)	2010	Sets emission limits based on Best Available Techniques (BAT) and forces installations to work under permits issued by national authorities		Hard law
End-of-Waste Criteria for Scrap Metal	2011	Defined the criteria under which scrap metal ceases being considered waste		Hard law
CEAP	2015	Initiated the evolution of the EU's economic model into a circular one, focused on reducing waste, increasing recycling, and promoting sustainable product design (sustainability as the norm).		Soft law
Revised Waste Framework	2018	Updated the 2008 Waste Framework aligning it with the CEAP		Hard law
EU Green Deal	2019	Planned Europe to become the first climate-neutral continent by 2050 by reducing GHGs, promoting circularity, and ensuring sustainable growth while maintaining competitiveness.	a) Climate Neutrality by 2050 b) Reduction in GHGs ≥ 55% by 2030 c) Decarbonization of industries d) Reduction of 50% reduction in residual municipal waste by 2030 e) Zero-pollution ambition	Soft law

[60] Reuse & Recycling refers to the percentage of a vehicle's mass that is reused as parts or recycled into new materials; Reuse & Recovery refers to the percentage of a vehicle's mass that encompasses the above but also includes other forms of recovery such as energy recovered from waste. Re-use, recycling and recovery of vehicle parts and materials | EUR-Lex. (n.d.). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=legissum:n26102

EU Taxonomy	2020	Set a classification system designed to define "environmentally sustainable economic activities"	a) Contribution to ≥ 1/6 targets of the Taxonomy b) DNSH any of the other objectives c) meet minimum social safeguards	Hard law
New CEAP	2020	Amends the 2015 CEAP expanding it to the entire product life cycle, focusing on resource efficiency and innovative business models (see Table 2)		Soft law
CRR3 (Capital Requirements Regulation III)	2021	Integrate ESG risks into prudential regulation for banks[61]	a) Include climate-related and ESG risks in ICAAP and Pillar 3 disclosures b) Align capital requirements with sustainability risk[62]	Hard law
CRD VI (Capital Requirements Directive VI)	2021	Strengthen supervision of climate-related risks	a) ESG risks explicitly considered in supervisory review (SREP) b) Supervisors gain power to assess banks' climate alignment[63]	Hard law
Carbon Border Adjustment Mechanism (CBAM)	2023	Addresses *carbon leakage*[64] by imposing carbon prices on imported goods, "leveling the playing field" between EU and foreign producers.	a) Transitional Phase – importers are required to report the embedded emissions in the products they import b) Full implementation – importers will have to purchase CBAM certificates to cover for the CO_2 of their products; the cost will be the one established by the EU ETS[65]	Hard law active in 2026

[61] *Regolamento - UE - 2024/1624 - EN - EUR-LEX*. (n.d.). https://eur-lex.europa.eu/legal-content/IT/TXT/?uri=CELEX%3A32024R1624

[62] Prudential plans refer to the internal processes through which banks ensure they hold enough capital to cover their risks, including future and systemic ones like those related to climate change. Pillar 3 of the Basel framework specifically addresses transparency, requiring banks to publicly disclose their risk profiles and capital adequacy. CRR3 strengthens Pillar 3 by mandating the disclosure of ESG and climate-related risks, making them visible and quantifiable. X, C. (2025, January 17). EBA proposes adding climate risk to bank prudential rules. *Climate X's Substack*. https://climatex.substack.com/p/eba-proposes-adding-climate-risk.

[63] The Capital Requirements Directive VI (CRD VI) complements CRR3 by reinforcing the supervisory framework around ESG risks. It requires banks to integrate environmental and social risks into their governance, risk management, and internal control systems. Most importantly, it grants supervisors the authority to evaluate how well institutions manage climate-related and transition risks through the Supervisory Review and Evaluation Process (SREP). Where risk management is deemed insufficient, supervisors may impose additional capital requirements or corrective measures. Frattini, M., Fischer, M. R., GréGoire, M., Goutay, P., & Martín-BarbóN, I. (2024, October 23). CRD VI requires banks to focus even more on ESG risk management. *Insights | Jones Day*. https://www.jonesday.com/en/insights/2024/10/crd-vi-requires-banks-to-focus-even-more-on-esg-risk-management.

[64] « Carbon leakage refers to the situation that may occur if, for reasons of costs related to climate policies, businesses were to transfer production to other countries with laxer emission constraints. This could lead to an increase in their total emissions ». *Carbon leakage*. (2021). Climate Action. https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/free-allocation/carbon-leakage_en.

[65] As of the last quarter of 2024, the price of carbon dioxide is of 80€ x ton of CO_2 emitted. TRADING ECONOMICS. (n.d.). *EU carbon permits - price - chart - Historical data - news*. https://tradingeconomics.com/commodity/carbon.

2.3 The Omnibus Package of February 2025

In February 2025, a set of legislative proposals – later on renamed the Omnibus Package[66] – was presented by the European Commission, aiming at simplifying and streamlining some existing sustainability regulations, which may have been hindering the overall competitiveness of EU businesses – especially small and medium businesses (SMEs). While the agenda set by the European Green Deal remains in place, some adjustments are made, directly to reporting obligations (CSRD and CSDDD) and indirectly to the EU ETS.
The main areas addressed by the Omnibus Package are the following:

a. Corporate Sustainability Reporting Directive (CSRD) – Shifting up of reporting requirements, making ESG (according to ESRS criteria) mandatory only for large companies, hence those that exceed at least two of the following three criteria: more than 250 employees, annual net sales of more than €50 million, or a balance sheet total of more than €25 million. In terms of smaller entities, obligations remain only for listed SMEs, but in a simplified version and with other more clement options[67] (proportionate ESRS standards). This move essentially frees about 80% of companies from sustainability reporting obligations, which, however, they can commit to on a voluntary basis or simplified basis.
b. Corporate Sustainability Due Diligence Directive (CSDDD) – Shifting up of sustainability and human rights reporting requirements to enterprises with more than 1,000 employees and an annual global turnover of more than €450 million. Again, this lifts a significant portion of enterprises from obligations, but they might still be involved (in terms of disclosure of internal information) as part of a larger company's value chain. Additionally, proposals on the CSDDD seek to simplify due diligence sustainability requirements for companies, specifically focusing on direct business partners (Tier 1), by increasing the frequency of periodic assessments and removing the requirement to terminate business relationships in case of negative impacts, and favouring, instead, suspension and collaboration to find potential solutions.

[66] *Directive - 2019/2161 - EN - omnibus directive - EUR-Lex.* (n.d.). https://eur-lex.europa.eu/eli/dir/2019/2161/oj/eng.
[67] Still, if reporting obligations impose too much of a burden on listed SMEs, they can access a temporary "opt out" option, allowing them an exemption of two more years to become CSRD-compliant; listed SMEs can do so without incurring in any penalty, so long as they publicly share their opting out briefly explaining the rationale behind such a move.

Furthermore, postponements for implementation of CSDDD requirements are proposed for larger companies[68].

c. EU Taxonomy – Also in this case, reporting requirement only for enterprises with more than 1,000 employees and turnover exceeding €450 million. This applies specifically to reporting obligations under Article 8 of the taxonomy regulation, which require disclosure of the share of turnover, Capex, and Opex aligned with taxonomy criteria. Companies below the €450 million threshold may still be indirectly affected through supply chain pressures from larger clients or investors.
d. Carbon Border Adjustment Mechanism (CBAM) – Introduction of a minimum threshold ("de minimis") to exempt companies that import less than 50 metric tons per year, excluding about 182,000 importers: the threshold applies per importer per year, and the exemption does not apply to high-volume operators splitting shipments to circumvent regulation.

Table 3: New Enterprises Size Threshold according to the Omnibus package[69]

New Enterprises Size Thresholds			
Type of Enterprise	Total Assets	Annual Turnover	Number of Employees
Microenterprise	≤ EUR 450,000	≤ EUR 900,000	≤ 10
Small Enterprise	≤ EUR 5,000,000	≤ EUR 10,000,000	≤ 50
Medium Enterprise	≤ EUR 25,000,000	≤ EUR 50,000,000	< 250
Large Enterprise	≤ EUR 25,000,000	≤ EUR 50,000,000	> 250

The main change concerns the change of the monetary values of the thresholds used to classify enterprises. The basic criteria used for classification (balance sheet, net revenue, average number of employees) and the very definitions of size categories (micro, small,

[68] Under the revised CSDDD, large companies can benefit of a phased-out implementation schedule (which is much different from the listed SMEs 2 year opt-out option): obligations will be applied progressively based on company size and turnover. Specifically, companies with over 5,000 employees and €1.5 billion in global turnover will be required to comply by 2027; those with more than 3,000 employees and €900 million turnover by 2028; and companies with more than 1,000 employees and €450 million turnover by 2029. This delayed timeline aims to ease the transition for larger enterprises by allowing more time to adapt their internal processes, risk management systems, and contractual arrangements with business partners. *Directive - EU - 2024/1760 - EN - EUR-LEX*. (n.d.). https://eur-lex.europa.eu/eli/dir/2024/1760/oj.

[69] European Commission. (2025, February 26). Questions and answers on simplification omnibus I and II. https://ec.europa.eu/commission/presscorner/detail/bg/qanda_25_615.

medium, and large enterprises) remained unchanged, but the numerical limits (in EUR) that an enterprise must exceed (or not) to fall into that category did instead[70].

The main reason for this change, which increased the monetary thresholds by about 25%, was the significant inflation experienced in the EU since the previous update in 2013. Without this intervention, the purely nominal increase in balance sheet values and turnover because of inflation would have pushed many firms, especially those close to the previous limits, into higher size categories ("bracket creep"), potentially subjecting them to more onerous regulatory obligations, such as those under CSRD, designed for economically larger entities, without a real increase in their relative economic size. Thus, the goal was to restore the original intent of the thresholds, preventing inflation alone from unintentionally expanding the scope of regulation.

However, while it was presented as a technical adjustment to inflation, the increase in thresholds provided regulatory relief, especially for firms that were near the previous limits for medium and large firm categories; for these firms, this adjustment could result in a delay in entering the scope of CSRD. However, this situation could also induce a sense of overconfidence or a delay in preparing for those firms that, due to organic growth or continued inflation, could still exceed the new thresholds in the near future. A delay in preparation today could cause a compressed and more difficult timeline for adopting sustainability reporting practices when the requirement becomes effective.

3 Regulatory Limits: too broad of a compliance

As shown in this chapter, the legal environment in which companies operate (whether they are international or European) is varied, fragmented, and yet to some extent still too vague.

At the international level, while the Paris Agreement and the Agenda 2030's SDGs are binding and have a legal standing, their role is openly defined as that of "agenda setting", rather than "agenda achieving": aside from stressing the need to act, international legal instruments provide no actual information that companies could translate into practical behavior. More simply, they point out the "what" to do but leave open the interpretation of the

[70] To be classified in a category (Micro, Small, Medium), an enterprise must not exceed the limits of at least two of the three criteria stated on the balance sheet date. A Large Enterprise is an enterprise that exceeds the limits of at least two of the three criteria established for Medium Enterprises. It is also important to note that the threshold for the average number of employees employed during the fiscal year has not been changed by this specific Delegated Directive. The classification of a firm in a particular size category continues to depend on whether at least two of the criteria mentioned just above.

"how". Supposedly, given the lack of jurisprudence of international bodies on countries and private entities – aside from some "sacred" areas such as human rights[71] – it seems hard to argue that there were genuine possibilities for a larger or different intervention on their part. However, the expected result of agenda setting should have been a declination towards more practical, country-specific, tailor-made measures based on NDCs and CBDRs. This is the case, at least theoretically. In practice, few states have mobilised to internalise these targets, and those entities that have done so, such as the European Union, have set even broader objectives. However, although the ratio of objectives ("what") to rules ("how") is shifted toward the former, certain policies adopted by the EU have drawn a clear line between what is compliant and what is not, and they are the following:

a) EU Emission Trading System (ETS)[72], a cap-and-trade mechanism where companies can trade emission allowances according to emission limits mandated by the EU.
b) Industrial Emission Directive (IED) 2.0[73], a revised version of the 2010 directive aimed at controlling harmful emissions.
c) EU CBAM[74], a policy imposing carbon pricing on goods imported into the EU to prevent carbon leakage and level the playing field between European and foreign producers.
d) EU Taxonomy[75], a classification system defining what is an environmentally sustainable economic activity.

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[71] At the moment, the only grounds for international courts to deliberate on climate change related matters is violation of human rights. The first case establishing this doctrine was the Advisory Opinion No. 23 (2017) of the International American Court of Human Rights, where the court explicitly recognized for the first time that environmental degradation, including climate change, can violate the right to life and other human rights, imposing on states the obligation to prevent significant environmental harm even when it occurs outside of their borders. In 2020 Ioane Teitiota, a citizen of Kiribati, sought asylum in New Zealand claiming that the rising sea levels posed a threat to his life and livelihood, appealing to the United Nations Court for Human Rights (UNHCR); while the Court did not accept his request for non-refoulement due to the lack of imminent risk to his life, it did acknowledge that, in principle, climate change can potentially prohibit individuals from returning to their homelands. More recently, in 2024, Vanuatu and other Pacific islandic nations have submitted a case to the International Court of Justice (ICJ) soughing and advisory opinion on the clarification of legal responsibilities of states concerning climate change, especially with regards to the threat to the life of populations threatened by rising sea levels. Bergova, I. (2021). Environmental Migration and Asylum: Ioane Teitiota v. New Zealand. *Justice System Journal*, *42*(2), 222-224. https://doi.org/10.1080/0098261x.2021.1994796.

[72] *EU Emissions Trading System (EU ETS)*. (n.d.). Climate Action. https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en.

[73] *Directive 2010/75/EC on industrial emissions*. (n.d.). European Environment Agency. https://www.eea.europa.eu/policy-documents/directive-2010-75-ec-on.

[74] *Carbon Border Adjustment Mechanism*. (n.d.). Taxation and Customs Union. https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en?.

[75] *EU taxonomy for sustainable activities*. (n.d.). Finance. https://finance.ec.europa.eu/sustainable-finance/tools-and-standards/eu-taxonomy-sustainable-activities_en.

e) CRR3[76], a reform of the Capital Requirements Regulation that integrates ESG risks into banks' prudential frameworks, requiring them to assess climate-related exposures in their internal capital planning and public disclosures (Pillar 3).

f) CRD VI[77], an update of the Capital Requirements Directive that enhances supervisory oversight of environmental and social risks, empowering regulators to evaluate banks' climate risk management and impose additional capital requirements where needed.

g) CSRD and CSDDD[78], where the first requires companies to disclose detailed information on their sustainability risk and impact, and the second mandates them to identify and address adverse effects on human rights and the environment across their supply chain.

Last, the Omnibus Package presented in February 2025 introduced a series of downward amendments in the scope and complexity of existing sustainability obligations (primarily CSRD, CSDDD, CBAM and the EU Taxonomy) – ideally, without compromising Green Deal objectives.

While this may increase clarity and feasibility for many companies, it also delays preparation for those that are near thresholds, causing their exposure to risk increasing even more.

To conclude, every company faces a web of policies that, despite being complex and comprehensive, lacks details on the immediate, enforceable measures necessary to drive a rapid change towards compliance – which, however, is precisely what one can expect from such high jurisprudences.

As a result, it is natural for companies to feel overwhelmed by the daunting number of regulations, especially since they mandate plenty of goals to be achieved while completely omitting the manner in which this is supposed to be achieved.

For this reason, other regulatory instruments, even if not mandatory, will be analyzed in the following chapter, searching for specific requirements for transition alignment.

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[76] *Latest updates on the banking package*. (2023, December 14). Finance. https://finance.ec.europa.eu/news/latest-updates-banking-package-2023-12-14_en.

[77] *Latest updates on the banking package*. (2023b, December 14). Finance. https://finance.ec.europa.eu/news/latest-updates-banking-package-2023-12-14_en.

[78] *Corporate sustainability reporting*. (n.d.). Finance. https://finance.ec.europa.eu/capital-markets-union-and-financial-markets/company-reporting-and-auditing/company-reporting/corporate-sustainability-reporting_en.

Findings

Given the complex regulatory framework that emerged in this chapter, some implications derive from the sector under analysis, namely the aluminium manufacturing industry.

First, aluminium is widely recognised as a key enabler of the green transition due to its recyclability and strategic applications, but – at the same time – it is among the most energy-intensive and emissions-heavy materials to make, especially when produced from scratch. This puts aluminium producers in a unique situation: on the one hand, the EU ETS and CBAM heighten the level of feasibility for both domestic and importers operating in the European market, encouraging them to internalise previously unaccounted-for externalities; on the other hand, companies are increasingly required to disclose their performance in an ESG-aligned manner to demonstrate compliance with these same instruments. Plus, these reporting frameworks are now among the informational basis through which financial institutions assess their clients' exposure to climate-related physical and transition risks – whether it be carbon leakage, supply chain vulnerabilities, stranded asset or other risks linked to delayed decarbonisation.

To some extent, financial institutions not only encourage "coming clean" but also consider it essential. Transparent reporting may reveal areas of environmental underperformance that negatively affect a firm's climate resilience profile, but failure to report, or incomplete and inconsistent reporting or non-compliance, now has – beyond legal – direct financial consequences. After the Basel Committee on Banking Supervision (BCBS)[79] acknowledged that climate-related and environmental risks can significantly impact financial stability, the European Banking Authority (EBA)[80] has put related risk assessments into practice within the EU's financial rules: banks must now officially identify, evaluate, and include both physical and transition climate risks in their credit risk management, internal capital assessments (ICAAP), and public reports. This shift has made climate risk a core dimension of financial analysis – where banks are now formally required to integrate both physical and transition climate risks into their credit assessments, risk appetite frameworks, and capital adequacy planning. More simply, companies failing to provide credible disclosure may face restricted access to credit, heightened risk premiums, or exclusion from financing altogether.

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[79] *The Basel Committee - overview*. (2011, June 28). https://www.bis.org/bcbs/index.htm.

[80] *The EBA publishes its final Guidelines on the management of ESG risks | European Banking Authority*. (n.d.). https://www.eba.europa.eu/publications-and-media/press-releases/eba-publishes-its-final-guidelines-management-esg-risks?.

Chapter 3 – *Voluntary Initiatives and Best Practices Review*

Introduction

As discussed in the previous chapter, the need for an ecological transition has led to a series of policies at the international and European levels, which, despite their stringency, fail to provide detailed plans on how to achieve the goals set.

This chapter aims to discuss how to shape pragmatic responses to regulatory gaps in the climate transition; it will analyze how different voluntary regulatory frameworks, though with distinct approaches, converge (or sometimes diverge) trying to translate overarching policy objectives into concrete business actions, exploring the interconnections, critical issues, and synergies of these instruments in the context of the aluminium industry.

In fact, searching for a granular translation of targets into practical actions, several voluntary initiatives emerged, ranging from corporate ESG metrics to internationally recognized standards like ISO certifications and industry-specific alliances, all of which try to bridge the gap left by regulatory frameworks.

The chapter will proceed according to the following structure: Section 1 will examine Sustainability at the Corporate Level, specifically, Science-Based targets initiative (SBTIs)[81]; Section 2 will instead focus on Aluminium Industry-Specific Standards and Best Practices, the most established ones being European Aluminium[82] (Section 2.1), the Aluminium Stewardship Initiative (ASI[83], Section 2.2), and The Net Zero Industry Tracker[84] (Section 2.3); at last, Section 3 will deal with Benchmarking, which in the context of "greening" businesses « […] is fundamentally about understanding where you stand relative to others and using that knowledge to drive improvements in your environmental and social performance[85]; specifically, this section will present some climate-aligned benchmarking methodologies and their application to the aluminium industry. The benchmark looked at are the following: the First Movers Coalition (FMC[86], Section 3.1), the Materials and Embodied Carbon Leaders' Alliance (MECLA[87], Section 3.2), the International Aluminium Institute (IAI[88], Section 3.3), and the Transition Pathway Initiative (TPI[89], Section 3.4). At last, Section 4 will gather insights from the Network for Greening the Financial System (NGFS[90]), which translates different benchmarks – and their targeted temperature goals – into possible future scenarios.

1 Sustainability at the Corporate Level: SBTis

The first section of this chapter focuses on the Science-Based Targets initiative (as mentioned, SBTi). This framework, while relevant to the aluminium industry, is not exclusive to it, offering a foundation for a broader application of sustainability at the corporate level.

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[81] *Ambitious corporate climate action*. (n.d.). Science Based Targets Initiative. https://sciencebasedtargets.org/.
[82] *European Aluminium: ALUMINIUM, THE BASE METAL FOR THE GREEN TRANSITION*. (2025). European Aluminium. https://european-aluminium.eu.
[83] International Aluminium Institute. (2024e, December 4). *International Aluminium Institute | global voice of the primary aluminium industry*. https://international-aluminium.org/.
[84] World Economic Forum & Net-Zero Industry Tracker. (2024, December 12). *Net-Zero Industry Tracker 2024*. World Economic Forum. https://www.weforum.org/publications/net-zero-industry-tracker-2024/.
[85] Directory, S. (2025, March 17). *Benchmarking for Sustainability → Term*. Energy → Sustainability Directory. https://energy.sustainability-directory.com/term/benchmarking-for-sustainability/
[86] First Movers Coalition & World Economic Forum. (2022). First Movers Coalition – Aluminium Commitment. In *World Economic Forum*. World Economic Forum. https://www3.weforum.org/docs/WEF_Aluminum_one_pager_2022.pdf.
[87] MECLA. (2024, July 24). *Home - mecla.org.au*. mecla.org.au. https://mecla.org.au/.
[88] International Aluminium Institute. (2024e, December 4). *International Aluminium Institute | global voice of the primary aluminium industry*. https://international-aluminium.org/.
[89] *Transition Pathway Initiative*. (2025a). Transition Pathway Initiative (TPI). https://www.transitionpathwayinitiative.org.
[90] *NGFS Scenarios Portal*. (n.d.-a). NGFS Scenarios Portal. https://www.ngfs.net/ngfs-scenarios-portal/.

Born in 2015 to help companies set GHG reduction targets in alignment with climate science[91], SBTi requires companies to establish measurable, time-bound emission reduction plans across their whole supply chains and covering both their Scope 1, Scope 2 and Scope 3 emissions[92]. Once developed, targets undergo validation by a SBTi team of experts, ensuring they are scientifically sound and aligned with well-below 2°C or – ideally – 1.5°C climate scenarios.

Given its relevance, SBTi is dedicated an entire section, namely Chapter 6 on Target Setting, where its methodology is presented as the primary source of validation for evaluation decarbonization trajectories.

However, while SBTi most certainly offers valuable guidance for the harmonization of business processes with climate targets, its emissions-only generic scope may not fully capture the challenges and opportunities laying at the sector-specific level. Therefore, the next section will delve into initiatives developed specifically for the aluminium industry, examining how they complement general frameworks by understanding their value chain.

2 Industry-Specific Standards and Best Practices: European Aluminium, Aluminium Stewardship Initiative, The Net Zero Industry Tracker

The second section of this chapter focuses, instead, on initiatives and standards specific to the aluminium industry. Voluntary certification schemes offer an approach that complements more rigid reporting methods, as they usually target a wider range of sustainability issues.

A primary example of such industry-specific collaboration and standard-setting at EU level can be found in The European Aluminium Alliance.

2.1 The European Aluminium Alliance

While it is true that the EU has always addressed its industries as one entity, it is also true that industries themselves have always benefited from their joint teamwork – especially when it comes to rare materials such as aluminium. There are both bottom-up and top-down reasons for the EU aluminium sector to play as a team rather than as single players. Over time, several

[91] *How it works - Science Based Targets*. (n.d.). Science Based Targets Initiative. https://sciencebasedtargets.org/how-it-works.

[92] *Draft Corporate Net-Zero Standard V2 explained: Scopes 1, 2 and 3 - Science Based Targets Initiative*. (n.d.). Science Based Targets Initiative. https://sciencebasedtargets.org/blog/draft-corporate-net-zero-standard-v2-explained-scopes-1-2-and-3.

voluntary pledges have crystallized within European Aluminium (EA)[93], founded in 1981 in Brussels. This trade association fulfils the role of advocacy for the industry, representing over 100 m members, from primary aluminium producers to downstream manufacturers and recyclers.

More specifically, European Aluminium acts in the following ways:

a) Policy Advocacy
b) Research and Innovation
c) European and International Standards[94] and Life Cycle Assessment (LCA).

European Aluminium efforts have culminated in their Sustainability Roadmap 2025, which aims to reduce the industry's environmental impact while improving its competitiveness[95] according to six cornerstones (see Chart 4). Among them, Step 4 stands out, arguing that « a robust EU Strategic Raw Materials Strategy, alongside a Circular Economy framework, is essential […] to support […] the availability and quality of secondary raw materials (SRMs) […] to address the growing issue of aluminium scrap exports outside of the EU. Recycling aluminium uses just 5% of the energy required to produce primary aluminium, effectively turning scrap into an energy "bank" that should be kept within Europe ».

European Aluminium is part of a wider network for sustainable management of rare materials, whose members include both European[96] and international[97] actors; among them, the Aluminium Stewardship Initiative, stands out.

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[93] *European Aluminium: ALUMINIUM, THE BASE METAL FOR THE GREEN TRANSITION*. (2025). European Aluminium. https://european-aluminium.eu.

[94] With the collaboration of the EU more than 120 standards have been developed; furthermore, EA incorporates and encourages the ASI certification. European Aluminium. (2009). *OUR TECHNICAL ADVOCACY:: STANDARDS & LIFE CYCLE ASSESSMENT*. https://european-aluminium.eu/our-work/standards-life-cycle-assessment/.

[95] Since the publication of the Draghi Report on European Competitiveness (2024), many industries have pledged to the decoupling of environmental impact from economic growth, accordingly with the "doing more with less" approach of sustainable development. Specifically the EU has recognized the weaknesses to which it is exposed, especially in terms of strategic interdependencies of resources such as gas and rare earths. Accordingly, circularity (declined as secondary use of rare materials) has become a need, rather than a fashion.

[96] European Raw Materials Alliance (ERMA), Eurometaux, Aegis Europe, CSR Europe, Solar Power Europe, the RE-Source Platform, EU Construction 2050 Alliance. *OUR NETWORK: IN AND BEYOND BRUSSELS*. https://european-aluminium.eu/network/.

[97] The Aluminium Stewardship Initiative (ASI), International Aluminium, the Aluminium Association, the Aluminium Association of Canada, the Japan Aluminium Association, Business Advocacy at the OECD, Metals for Buildings. European Aluminium. (2025). *OUR NETWORK: IN AND BEYOND BRUSSELS*. https://european-aluminium.eu/network/.

2.2 The Aluminium Stewardship Initiative

The Aluminium Stewardship Initiative (hereinafter referred to as ASI) is the only responsible sourcing program that addresses practices along the entirety of the aluminium value chain, addressing both performance (responsible production) and chain of custody (responsible sourcing)[98]. It does so by promoting two standards:

a) ASI Performance standard (now at its v3.3)[99] for the aluminium value chain on environmental, social and governance performance; notably, this standard provides for mine-to-metal direct and indirect emission reductions with gradually lower emission intensity limits according to climate scenarios.

b) ASI Chain of Custody (CoC) standard[100], setting out requirements for the flow of Chain of Custody (CoC) through the value chain (from mining or recycling to final products), with assurance of responsible production at each link in the chain.

Chart 3: The six essential steps to safeguard Europe's aluminium value chain while contributing to EU's strategic goals[101]

To obtain ASI certifications, companies should follow the steps displayed in Chart 5.

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[98] Aluminium Stewardship Initiative. (2022, December 6). *ASI Home | Aluminium Stewardship Initiative*. https://aluminium-stewardship.org/.

[99] Aluminium Stewardship Initiative. (2025, February 5). *ASI Performance Standard | Aluminium Stewardship Initiative*. https://aluminium-stewardship.org/asi-standards/performance-standard. Version 3.3 available at https://aluminium-stewardship.org/wp-content/uploads/2022/05/ASI-Performance-Standard-V3-May2022-2.pdf. In Aluminium Stewardship Initiative. (2022a). ASI Performance Standard: Version 3. In *Aluminium Stewardship Initiative*.

[100] Aluminium Stewardship Initiative. (2024, December 6). *ASI Chain of Custody Standard | Aluminium Stewardship Initiative*. https://aluminium-stewardship.org/asi-standards/chain-of-custody-standard#:~:text=The%20ASI%20Chain%20of%20Custody,and%20accounting%20for%20material%20flow.

[101] European Aluminium. (2025b). STRATEGIC METAL, STRATEGIC ACTION:: AN ACTION PLAN FOR EUROPEAN ALUMINIUM. In *European Aluminium*. https://european-aluminium.eu/wp-content/uploads/2025/01/25-01-13-An-Action-Plan-for-European-Aluminium.pdf.

In terms of credibility among voluntary schemes, ASI performs well, since its Performance Standard includes criteria that specifically seek to set the aluminium sector on a 1.5 degree aligned pathway: to reduce total sector wide emissions by over 95% by 2050, as defined by the latest science[102], where "latest science" refers to the International Aluminium Institute's decarbonization path for the aluminium sector – as discussed in more detail in the following section.

Furthermore, ASI "stole" the identification of the dimensions it impacts from the ESGs while enriching it with a specific declination of numerous subcategories[103] for each, allowing its standards to be among the most robust in the field.

Beyond certification schemes like ASI that focus on responsible sourcing and production practices, other initiatives aim to provide a broader view of sectoral progress towards climate targets. The Net Zero Industry Tracker serves as such a tool, offering assessment frameworks for heavy industries, including aluminium.

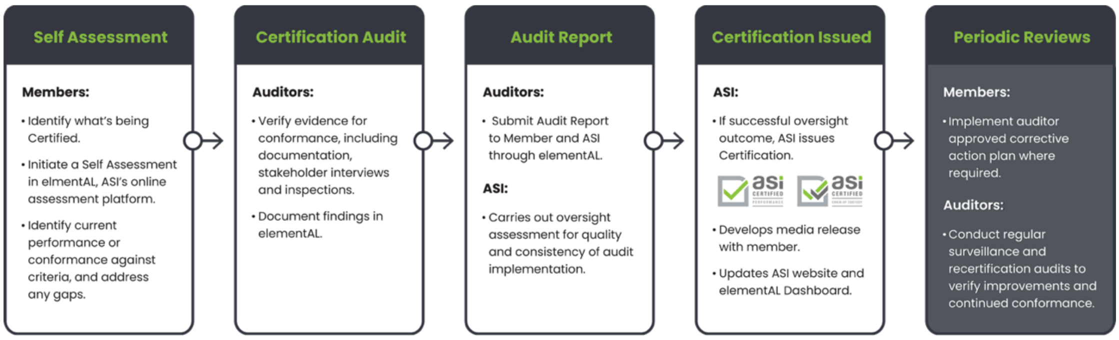

Chart 4: The ASI certification timeline[104]

[102] Aluminium Stewardship Initiative. (2024a, November 28). *Climate change | Aluminium Stewardship Initiative*. https://aluminium-stewardship.org/drive-change/sustainability-priorities/climate-change.

[103] Based in Melbourne, Australia, ASI has inherited its nations wildest side, declining it into a sincere commitment to preserve the environment and the Indigenous communities that thrive in it. The longest section in its Performance Standard Guidance belongs to the "S" of social, where, aside from an outstanding HR decision tree, a whole section (pp. 219 – 226) devoted to the Recognition of Indigenous People catches the eye: in short, ASI recognizes the growing threat of mining to nature reserves and/or lands belonging to Indigenous peoples, mapping their presence not only in Australia, but in all aluminium mining areas worldwide, stressing the need for a mining strategy that acknowledges, informs, and respects the will of Indigenous populations based on Free, Prior, and Informed Consent (FPIC) in order to avoid damage to land and its people. Aluminium Stewardship Initiative. (2025, February 5). *ASI Performance Standard | Aluminium Stewardship Initiative*. https://aluminium-stewardship.org/asi-standards/performance-standard; Jazeera, A. (2025, February 19). Aboriginal group seeks $1.1bn in damages over Australia mining project. *Al Jazeera*. https://www.aljazeera.com/news/2025/2/19/aboriginal-group-seeks-1-1bn-in-damages-over-australia-mining-project; Evans, S. (2020, August 26). Sacred spaces and the social contract: how Australian mining affects Aboriginal communities. *Mining Technology*. https://www.mining-technology.com/features/sacred-spaces-and-the-social-contract-how-australian-mining-affects-aboriginal-communities/.

[104] Aluminium Stewardship Initiative. (2024a, November 14). *Steps to ASI Certification | Aluminium Stewardship Initiative*. https://aluminium-stewardship.org/get-certified/overview.

2.3 The Net Zero Industry Tracker

The Net Zero Industry Tracker is a tool designed in collaboration with the World Economic Forum (WEF) to assess and track the progress of heavy industrial sectors (especially those defined as Hard to Abate) towards achieving net-zero emissions. The Aluminium Industry Net Zero Industry Tracker has identified three technology routes that have the potential to contribute to the decarbonization of the aluminium industry with the aim of, namely:

i. Decarbonization of electricity for secondary aluminium smelting (TRL 8: demonstration stage)
ii. Use of inert anodes in aluminium smelting instead of carbon anodes (TRL 7: demonstration stage)
iii. Carbon Capture Utilization and Storage (CCUS) (TRL 3: concept stage).
Furthermore, the same report advances two sets of solutions, one classified as company-led, the other as ecosystem-enabled, both of which are divided between mid-term (2030) and long-term (2050) – as shown in Chart 6 below.

As shown in Section 2, there are several practical actions an aluminium producer can commit to align with climate targets.

However, for a company's transition plan to be understandable, comparisons are necessary. There must be something to measure it against, a sort of "ideal pathway". This is precisely the role of benchmarks, which provide a transition plan for each of the most popular climate targets (1.5°, below 2°, NDCs, or Paris pledges – as shown in the following section), allowing companies' actions to be evaluated based on how closely they are aligned with them.

3 Benchmarking: strategic directions and future outlooks

As anticipated just above, the third section of this chapter focuses on industry-specific benchmarks, which constitute fundamental elements of any company's transition plan evaluation.

Several key initiatives provide benchmarks; however, each has a slightly different focus. The initiatives analyzed are, respectively, the First Movers Coalition (FMC, Section 3.1), the Materials and Embodied Carbon Leaders' Alliance (MECLA, Section 3.2), International Aluminium Institute (IAI, Section 3.3) and the Transition Pathway Initiative (TPI, Section 3.4 at last).

Chart 5: Company-led and ecosystem-enabled solutions identified by Net Zero Industry Tracker for the aluminium sector[105]

3.1 The First Movers Coalition (FMC)

The First Movers Coalition (FMC)[106] has set out ambitious goals for the aluminium sector, including:

- Securing at least 10% (by volume) of all primary aluminium per year from low-carbon sources by 2030
- Encourage the use of secondary near-zero emissions aluminium and ensure that at least 50% of all aluminium procured per year is sourced from secondary aluminium by 2030.

Furthermore, the FMC pushes its members to produce aluminium via breakthrough technologies and encourages an emission intensity no greater than 3 tons of CO2 per ton

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[105] Net-Zero Industry Tracker. (2024). Aluminium industry net-zero Tracker. In *The World Economic Forum*. The World Economic Forum. https://reports.weforum.org/docs/WEF_Net_Zero_Industry_Tracker_2024_Aluminium.pdf.

[106] *Commitments | First Movers Coalition*. (n.d.). https://initiatives.weforum.org/first-movers-coalition/commitments.

of aluminium produced, including all emissions from cradle to gate – a very ambitious figure[107].

Complementing the demand-side signals sent by the FMC, organisations like the Materials and Embodied Carbon Leaders' Alliance focus on defining what "low carbon" aluminium is.

3.2 Materials and Embodied Carbon Leaders' Alliance

Materials and Embodied Carbon Leaders' Alliance (MECLA)[108] has released a Specification Guide for Low Carbon Aluminium[109] defining it, generally, as aluminium with a carbon intensity lower to the global average. The carbon intensity of aluminium can be lowered to:

- ~ 4 kg of CO2 per kg of aluminium produced (less than one third of the global average) by using renewable energy sources like hydropower
- ~ 2.3 kg of CO2 per kg of aluminium produced, by creating a product with 75% of post-consumer recycled scarp.

According to the same document by MECLA[110], the 2023 global average of CO2 intensity is 11.9 – 12.4 kg of CO2 per kg of aluminium produced, while the worst- performing aluminium is the one produced in China, with an intensity of 17 – 20 kg of CO2 per kg of aluminium produced.

While MECLA focuses on practical guidelines, organisations like the International Aluminium Institute take a step back and look at the bigger picture, offering decarbonization pathways built around medium- and long-term global climate goals.

3.3 The International Aluminium Institute

The International Aluminium Institute (hereinafter referred to as IAI) has developed a 1.5° Pathway for the Aluminium Sector, indicating that by 2050 the aluminium sector would need to reduce its emissions from 1,100 million tons of CO2e[111] to ~50 million tons of CO2e

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[107] First Movers Coalition & World Economic Forum. (2022). First Movers Coalition – Aluminium Commitment. In *World Economic Forum*. World Economic Forum. https://www3.weforum.org/docs/WEF_Aluminium_one_pager_2022.pdf.
[108] MECLA. (2024, July 24). *Home - mecla.org.au*. mecla.org.au. https://mecla.org.au/.
[109] MECLA. (2023). Low Carbon Aluminium Specification Guide: Market Feedback requested guidance on how to specify low carbon aluminium in projects. In *Materials Embodied Carbon Leaders Alliance (MECLA)*. https://mecla.org.au/wp-content/uploads/2023/07/SpecificationGuide-WG5c-Aluminium.pdf.
[110] See Note 48.
[111] Meaning tons of carbon dioxide equivalent per ton of primary aluminium produced. *Carbon dioxide equivalent | ClimatePartner*. (n.d.). ClimatePartner. https://www.climatepartner.com/en/knowledge/glossary/carbon-dioxide-equivalent.

(according to the 2018 baseline), resulting in a 95.5% reduction. Consequently, significant reductions in carbon intensity of primary aluminium will be required to meet the climate scenarios (see Chart 7).

3.4 The Transition Pathway Initiative

The Transition Pathway Initiative[112] (hereinafter referred to as TPI) is a global initiative led by investors whose aim is to evaluate a company's readiness and resilience for the transition to a low-carbon economy. More practically, TPI quantitatively benchmarks companies' carbon emissions considering international climate goals defined by the Paris Agreement, using the Sectoral Decarbonization Approach (SDA). This approach translates global climate targets into sector-specific benchmarks with which to compare the intensity of emissions of individual companies.

In its methodology for devising benchmarks for the aluminium sector, TPI relies on data and modelling from the International Energy Agency (IEA), specifically from its 2024 Annual Report on Energy Technology Perspectives[113]. IEA provides projections of total GHGs specific to the aluminium sector, adjusting them based on the total amount of aluminium (primary and secondary) expected to be produced globally.

TPI translated this data into a sectoral emissions intensity benchmark, which represents an average performance target in terms of emissions per unit of product (in this case, per ton of aluminium produced) that the analyzed sector would have to achieve each year to be aligned to a specific climate scenario. This figure is calculated by dividing the total projected emissions for the aluminium sector by the total amount of aluminium expected to be produced in the same year and under the same scenario. The result is the average carbon intensity (expressed in tons of CO2 equivalent per ton of aluminium produced) that an "average" producer would have to have to contribute to meeting the climate goals of that specific scenario[114].

These projections are consistent with three different climate scenarios:

i. "Below 2 Degrees" scenario, represents the most ambitious decarbonization pathway out of the three, consistent with the goal of limiting global

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[112] *Transition Pathway Initiative*. (2025). Transition Pathway Initiative (TPI). https://www.transitionpathwayinitiative.org.
[113] International Energy Agency. (2024, October 30). *Energy Technology Perspectives 2024*. https://www.iea.org/reports/energy-technology-perspectives-2024.
[114] Transition Pathway Initiative. (2025b). *Transition Pathway Initiative: Methodology*. Transition Pathway Initiative (TPI). https://www.transitionpathwayinitiative.org/methodology.

temperature increase well below 2°C and pursuing efforts to limit it to 1.5°C above pre-industrial levels.

ii. “2 Degrees” scenario, which is consistent with the goal of limiting global warming but represents a lower level of ambition than the “Below 2 Degrees” scenario.

iii. “Paris Pledges” scenario, relying on the aggregate of emission reduction commitments submitted by countries under the Paris Agreement (so-called National Determined Contributions or NDCs). However, this scenario is considered insufficient to achieve the goal of limiting warming to 2°C.

Chart 8 shows the benchmark emissions intensity paths for the aluminium sector, while Chart 9 provides the underlying data on emissions and aluminium production.

According to TPI « under the Paris Pledges scenario in 2025, global Scope 1 + 2 emissions of the aluminium sector are projected to be 850 million metric tons or megatons of CO2. Under the same scenario, total aluminium production is projected to be 177 Mt in 2025. Therefore, the average carbon intensity of an aluminium producer aligned with the Paris Pledges path is 850 / 177 = 4.80 tons of CO2 per ton of aluminium produced ».

However, IEA data only accounts for CO2, while aluminium production also releases other highly polluting gases like perfluorochemicals (see Chapter 5), released during the aluminium production chain. According to the International Aluminium Institute (IAI), global PFC emissions in 2014 were equivalent to 34 million metric tons of CO2. Including PFC emissions, the average carbon intensity of an aluminium producer aligned with the Paris Pledges scenario in 2014 is calculated as (766 + 34) / 126 = 6.34 tons of CO2e per ton of aluminium produced – 4.27% higher than the CO2-only benchmark. The latter 4.27% adjustment is applied by TPI to all future years, assuming PFC emissions decline in proportion to CO2 emissions.

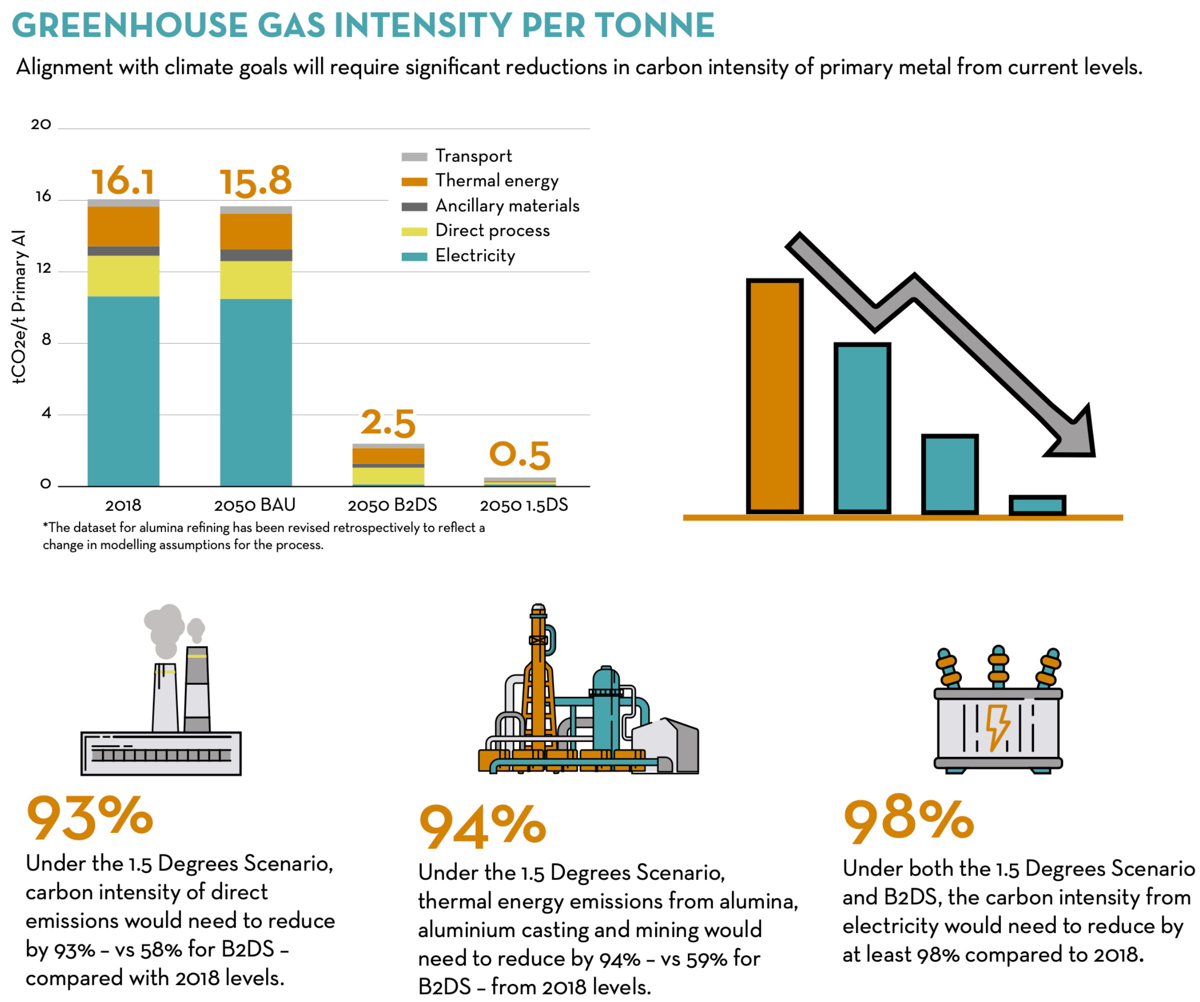

Chart 6: IAI – Greenhouse Gas Intensity Reductions required to meet climate goals[115]

This image illustrates the necessary reductions in greenhouse gas intensity per ton of primary aluminium to align with the 1.5° Scenario (*1.5DS*) and the Beyond 2 Degrees Scenario (*B2DS*), compared to a Business as Usual (*BAU*) projection for 2050. The bar chart on the left shows the carbon intensity (in tons of CO2e per ton of primary aluminium) in 2018, the projected 2050 BAU, and the targeted intensity for 2050 under the B2DS and 1.5DS. The graph highlights a dramatic reduction in carbon intensity, moving from 16.1 tons of CO2e / ton of aluminium in 2018 to just 0.5 tons of CO2e / ton of aluminium in 2050 under the 1.5DS.

[115] International Aluminium Institute. (2024, September 19). *1.5 degrees scenario: A model to drive emissions reduction - International Aluminium Institute*. https://international-aluminium.org/resources/1-5-degrees-scenario-a-model-to-drive-emissions-reduction/.

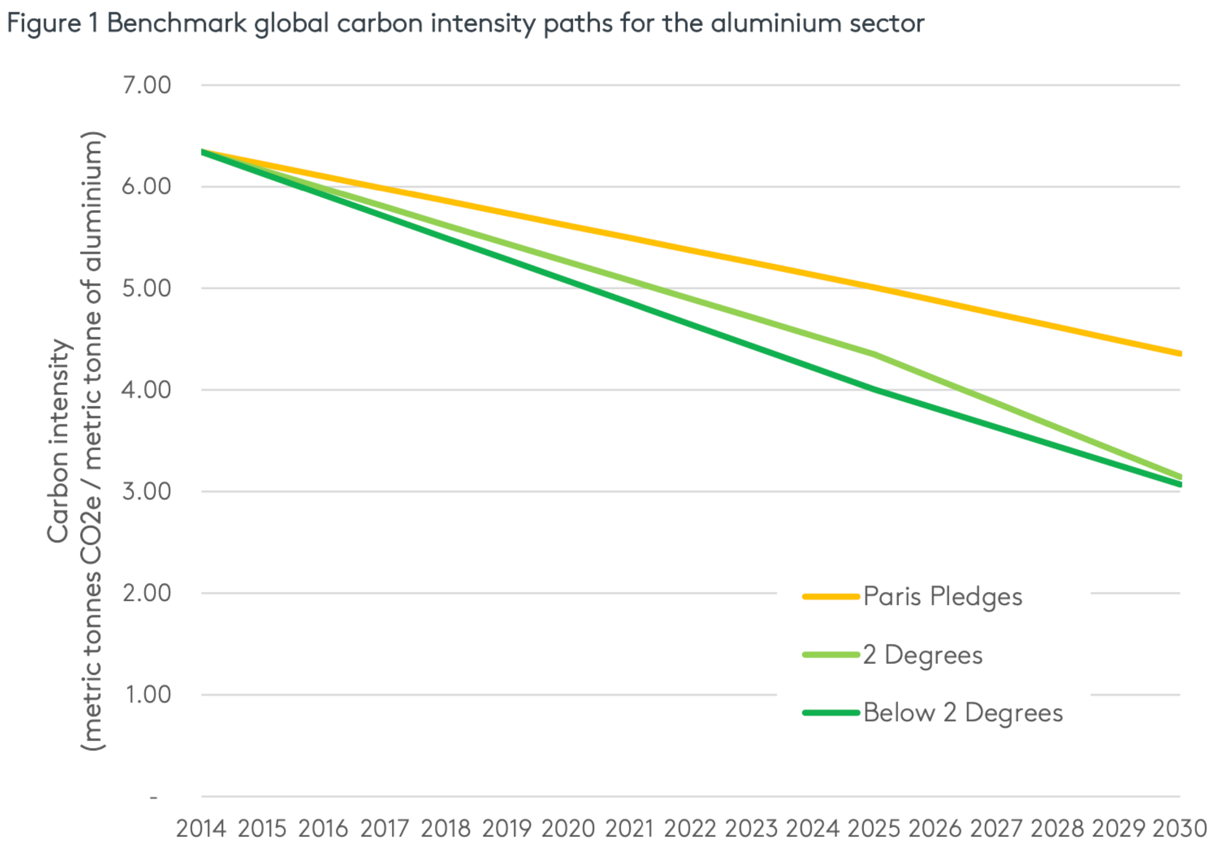

Chart 7: Benchmark for global carbon intensity paths for the aluminium sector[116]

To better understand the climate scenarios to which sectoral benchmarks are supposed to align, the broader set of climate transition narratives developed by the Network for Greening the Financial System (NGFS) is worth mentioning: these scenarios translate global warming trajectories into concrete economic and financial impacts, providing the analytical foundation—and the financial relevance, hence urgency— for many of the targets described above.

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[116] Dietz, S., Noels, J., & Jahn, V. (2019). CARBON PERFORMANCE ALUMINIUM PRODUCERS METHODOLOGY NOTE. In *Transition Pathway Initiative*. Transition Pathway Initiative. https://www.transitionpathwayinitiative.org/publications/uploads/2019-carbon-performance-assessment-of-aluminium-producers-note-on-methodology#:~:text=Therefore%2C%20the%20average%20carbon%20intensity,aluminium%20sector%20only%20include%20CO2.

4 NGFS Scenarios

The Network of Central Banks and Supervisors for Greening the Financial System[117] offers a « window into different plausible futures » through the identification of seven possible scenarios[118] – as shown in Chart 9 below – describing how the economy could respond to the climate crisis. Each scenario is derived from climate targets (similar to TPI's methodology) at a systemic level, reflecting different futures based on the timing and nature of climate action.

	2014	2020*	2025	2030
Paris Pledges scenario				
Scope 1+2 CO_2 emissions (Mt CO_2)	766	811	850	848
Scope 1 PFC emissions (Mt CO_2e)	34	35	36	36
Aluminium production (Mt)	126	154	177	203
Carbon intensity (tCO_2 / t aluminium)	6.08	5.38	4.80	4.18
Carbon intensity (tCO_2e / t aluminium)	6.34	5.61	5.01	4.35
2 Degrees scenario				
Scope 1+2 CO_2 emissions (Mt CO_2e)	766	751	738	612
Scope 1 PFC emissions (Mt CO_2e)	34	32	31	26
Aluminium production (Mt)	126	154	177	203
Carbon intensity (tCO_2 / t aluminium)	6.08	5.04	4.17	3.02
Carbon intensity (tCO_2e / t aluminium)	6.34	5.26	4.35	3.14
Below 2 Degrees scenario				
Scope 1+2 CO_2 emissions (Mt CO_2e)	766	671	607	500
Scope 1 PFC emissions (Mt CO_2e)	34	29	26	21
Aluminium production (Mt)	126	144	158	170
Carbon intensity (tCO_2 / t aluminium)	6.08	4.86	3.84	2.94
Carbon intensity (tCO_2e / t aluminium)	6.34	5.07	4.00	3.07

Chart 8: Projections of emissions and aluminium production used to calculate intensity paths[119]

Emissions, production and carbon intensity for the year 2020 are estimated by TPI by linearly interpolating between 2014 and 2025 data points

[117] *NGFS Scenarios Portal*. (n.d.). NGFS Scenarios Portal. https://www.ngfs.net/ngfs-scenarios-portal/.
[118] *NGFS Scenarios Portal*. (n.d.-b). NGFS Scenarios Portal. https://www.ngfs.net/ngfs-scenarios-portal/explore.
[119] Dietz *et al.* (2019)

Each future scenario is identified starting from science-based climate models and is later projected in time based on different societal responses to the climate crisis: "responses" are classified according to the exposure to physical or transition risks. Depending on the measures taken, scenarios can be grouped in four macro areas:

1. Orderly Transition – Net Zero 2050, Low Demand, Below 2°C
2. Disorderly Transition – Delayed transition,
3. Hot House World – Nationally determined contributions (NDCs), Current policies
4. Fragmented World

Each macro area and its related scenarios will be analysed appropriately.

5.1 Orderly Transition

i. Net Zero 2050, where global warming is limited to 1.5°C through stringent climate policies implemented immediately, along with technologies like carbon dioxide removal (CDR), whose use should, however, be kept to the minimum possible to align with sustainable bio-energy levels. This strategy has at least a 50% chance of limiting global warming to below 1.5°C by the end of the century; physical risks are relatively low, but transition risks are high due to the necessarily fast-paced process.

ii. Low Demand, where significant behavioural changes mitigate pressure on the economy to reach Net Zero in 2050, resulting in a scenario identical to i. aside from a lower need to intervene in carbon removals.

iii. Below 2°C, where climate policies are even more stringent and ambitious, reducing even more the need of CDR. This scenario has a 67% chance of limiting global warming to below 2°C; Physical and transition risks are both relatively low.

5.2 Disorderly Transition

iv. Delayed transition, where global annual emissions do not decrease until 2030, and the level of action differs across counties. CDR technologies are assumed to have limited availability due to low demand, leading to exceeding carbon budgets. This scenario has a 67% chance of success after the year 2030, leading, however, to higher physical and transition risks (especially the latter because of delayed action).

5.3 Hot House World

v. Nationally determined contributions (NDCs) scenario, reflecting the pledges made in the Paris Agreement. Emissions decline, but not enough, resulting in a temperature of 2.3°C, corresponding to severe physical risks and relatively low transition levels.

vi. Current policies, assuming the existence of measures already in place only. Emissions grow, resulting in a climate change of 3°C, corresponding to massive physical risks: this scenario is the projection in time of our business-as-usual behavior, leading to a so-called hot house world.

5.4 Fragmented World

vii. Fragmented world, assuming delayed and divergent climate policies leading to inefficiencies resulting in high physical and transition risks; countries with Net Zero ambitions achieve 80% of their targets, while others lag behind.

To conclude, NGFS scenarios explore the different combinations of adaptation and mitigation strategies, showing that relying on just one leads to suboptimal outcomes. The key lies in the extremes:

- Adaptation only approaches, as recent trends show, leave large physical risks unaddressed, creating a cycle of escalating damage and further adaptation needs.
- Mitigation only approaches, while reducing emissions, fail to prepare for inevitable climate impacts, leaving systems vulnerable to disruption.

A balanced strategy is essential to minimise both risks effectively.

Sectoral benchmarks and macroeconomic climate scenarios work together to create a clear way to evaluate progress, where the benchmarks turn the scenarios into specific expectations for different industries, making them easier to apply and, most importantly, to measure.

Findings

To conclude, while voluntary initiatives provide industry-specific frameworks that help companies move toward environmental compliance – and in some cases even go beyond regulatory expectations – their emergence as a response to mandatory reporting has led many companies to shift the focus from “what they do” to “what they say they do”: more simply, companies treat these frameworks as a compliance exercise. This is because, under the current regulatory landscape, only reporting obligations and certain emission caps are legally binding, leaving businesses with ample room to continue "business as usual" without failing to meet compliance requirements.

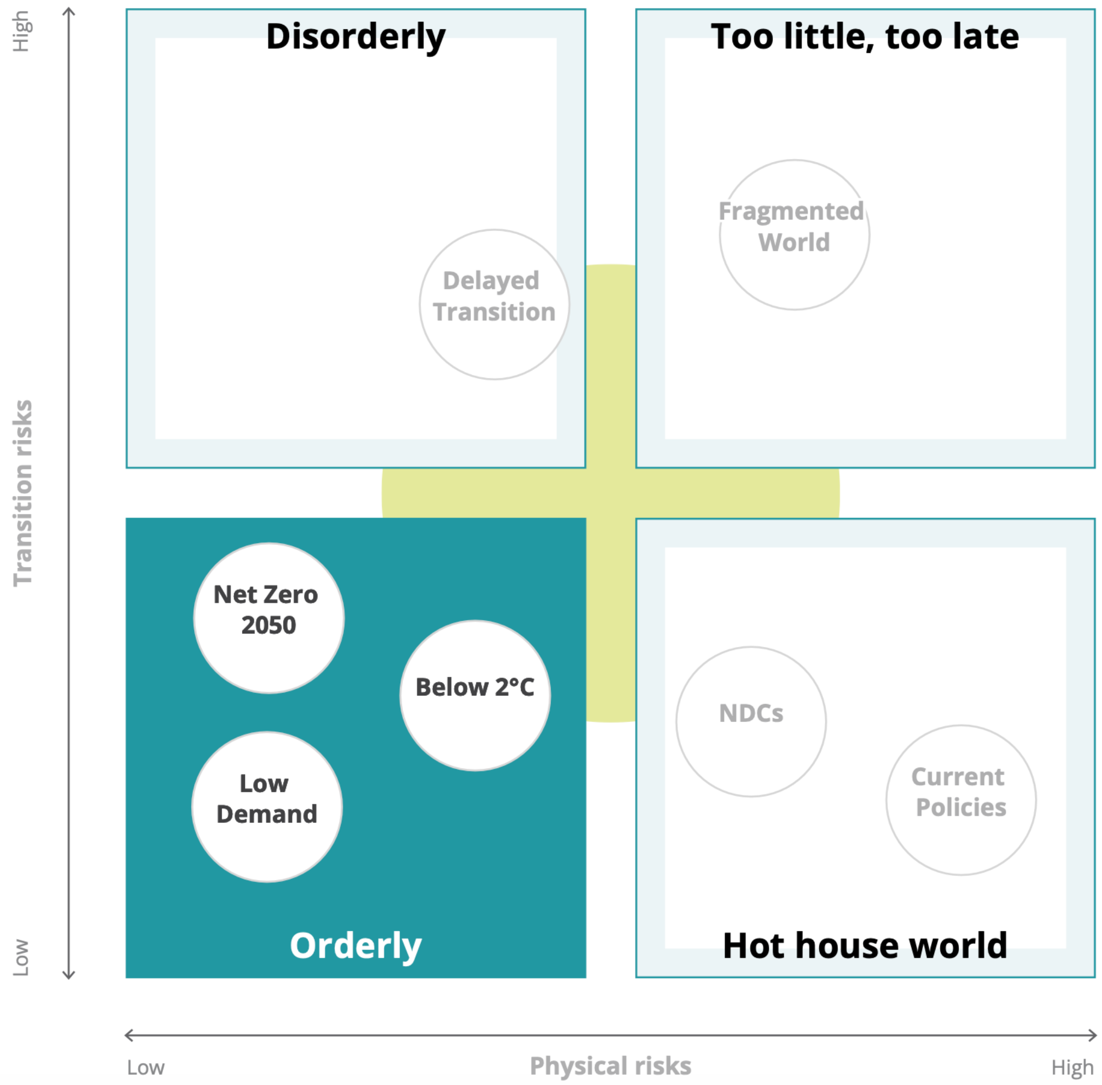

Chart 9: Classification of NGFS Climate Scenarios based on Physical and Transition Risks[120]

Yet, some more serious initiatives exist, and the benchmarks presented in this chapter, such as those from the FMC, MECLA, IAI, and TPI, are among the ones that offer concrete, measurable targets for decarbonization: grounded in scientific projections and industry consensus, they clearly define what "climate-scenario-aligned" performance looks like, setting a higher bar than “mere compliance”.

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[120] *NGFS Scenarios Portal*. (n.d.-b). NGFS Scenarios Portal. https://www.ngfs.net/ngfs-scenarios-portal/explore.

However, these initiatives are not mandatory, which makes them a niche practice few organizations are willing to adopt. Yet, it would be appropriate to interpret how “mere compliance” becomes tighter and more uncomfortable every day: with the price of carbon increasing and the emission caps decreasing, all while considering a Green Deal that aims for climate neutrality by 2050, it doesn't take a genius to realize that action will be needed[121] – sooner or later.

Many firms, often guided by consultants, engage in so-called creative compliance instead of proactively transitioning towards sustainable practices, which are different from merely being compliant. However, this short-term mindset, which seeks to maximize revenue today rather than invest in long-term resilience, mirrors the same economic behaviors that led to climate change in the first place. A forward-looking, rational approach would involve gradually integrating sustainable practices, spreading the cost of transition over time. Instead, many businesses delay action until new laws force them to change, at which point they may face sudden and severe disruptions that, one day or another, will have them shutting down overnight. This reactive rather than proactive approach will eventually become uninvestible, uninsurable, or unprofitable.

Chapter 4 – *Overview of the Aluminium Industry*

[121] BloombergNEF. (2025, March 6). *Europe's New Emissions Trading System Expected to Have World's Highest Carbon Price in 2030 at €149, BloombergNEF Forecast Reveals | BloombergNEF*. BloombergNEF. https://about.bnef.com/blog/europes-new-emissions-trading-system-expected-to-have-worlds-highest-carbon-price-in-2030-at-e149-bloombergnef-forecast-reveals/?

Introduction

Aluminium production is currently carried out through two primary methods, each characterised by distinct raw materials and energy requirements.
The first method (the primary route) involves the Bayer process and the Hall-Héroult process, where the bauxite ore is refined into alumina and then subjected to energy-intensive electrolytic reduction in a molten cryolite bath, eventually producing virgin aluminium.
The second method (the secondary recycling route) entails the utilisation of recycled aluminium scrap (either pre- or post-consumer), which is directly melted into new aluminium using a remelting furnace[122].

1 The Production of Primary Aluminium

The primary aluminium route consists of three main phases, namely: Extraction and Refining from Bauxite (the Bayer Process, Section 1.1.1), Electrolytic Reduction (the Hall-Héroult Process, Section 1.1.2) and Casting, Solidification and Alloying (Section 1.1.3).
This is because, while aluminium is the most abundant metal on the Planet (adding up to 8% of the Earth's crust), it is rarely found in its pure form (*Al*)[123].

1.1 Primary Aluminium Production Route

1.1.1 Extraction and Refining from Bauxite – the Bayer Process

Aluminium is primarily extracted from the bauxite ore, a mixture of aluminium and iron hydroxides[124].
Based on varying water content, bauxite can be either:

- Monohydrate ($Al_2O_3 + H_2O$), known as Boehmite and Diaspora.

or

- Trihydrate ($Al_2O_3 + 3H_2O$), known as Gibbsite.

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[122] Science Direct. (n.d.). *Aluminium production*. https://www.sciencedirect.com/topics/engineering/aluminium-production.
[123] *Aluminium - Element information, properties and uses | Periodic Table*. (n.d.). https://periodic-table.rsc.org/element/13/aluminium.
[124] Other impurities such as silica and titanium dioxide. Alex, T. C., Kailath, A. J., & Kumar, R. (2020). Al-Monohydrate (Boehmite) to Al-Trihydrate (Bayerite/Gibbsite) transformation during High-Energy milling. *Metallurgical and Materials Transactions B*, *51*(2), 443–451. https://doi.org/10.1007/s11663-020-01771-6.

When it comes to extraction of aluminium, Gibbsite is preferable, for it dissolves mor easily in sodium hydroxide, commonly known as caustic soda (NaOH), while Boehmite and Diaspore are more energy intensive to work on[125].

Bauxite is very abundant and is often mined and processed into alumina in the same geographic location before being transported to an aluminium smelter (which is often located outside from the bauxite-producing country). Deposits can be found in many parts of the world, including Europe[126], but the preferable mixture for aluminium production is typically found in tropical areas.

Bauxite and alumina producers capitalize either on their deposits (Jamaica and Guinea or on their technological advancement and vast land availability (like Australia) to artificially produce bauxite and alumina. Currently, the top bauxite producers are Australia and China, with China being also the world's top aluminium producer[127].

The estimated primary energy demand for producing 1 ton (t) of bauxite is about 1 Gigajoule (GJ)[128].

After being crushed and ground, and after clay is removed, the ore undergoes refining, also known as the Bayer process, where it is mixed with caustic soda at 100°C – 250°C and a high pressure depending on the type of bauxite[129]; the process dissolves the aluminium oxide into sodium aluminate ($NaAlO_2$), allowing to wash off impurities also known as "red or white muds".

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[125] The first type is typically found under high temperature and pressure conditions (such as metamorphic environments), while the second forms under low temperature, tropical and humid conditions (such as lateritic soils). Monohydrate bauxite (Boehmite and Diaspore), is "denser" due to the conditions it was naturally subjected to, and thus, is more energy intensive: in the Bayer process, the only way to refine this ore is by separating it under high pressures and temperatures (melts around ~200–250°C), which can be quite energy demanding. Differently, Trihydrate bauxite (Gibbsite), given its more hydrated composition and different development, can be more easily refined by being immerged into caustic soda; for this reason, the second ore is preferable when it comes to the extraction of aluminium, for it requires significantly less energy. Patterson, S. H., Kurtz, H. F., Olson, J. C., & Neeley, C. L. (1986). World bauxite resources. In *U.S. Geological Survey*. U.S. Geological Survey. https://pubs.usgs.gov/pp/1076b/report.pdf.

[126] In Europe, the most relevant mines are in the Parnassos-Ghiona region in Greece (managed by Mytilineos, the main Greek player in the field), in Hungary (declining mining activity), in Spain (in Galicia and Andalusia), Italy (Sardinia and Calabria), Romania (in Dâmbovița) and in France (in Les Baux-de-Provence), however all of them are either mostly depleted, or inactive because of inconvenient bauxite compositions (see Paragraph 1.1) and high production costs compared to imported bauxite.

[127] *The largest bauxite mines in the world - Global insights on bauxite production and key players*. (n.d.). https://aritral.com/minerals/bauxite/the-largest-bauxite-mines-in-the-world.

[128] Springer, C., & Hasanbeigi, A. (2016). Emerging Energy Efficiency and Carbon Dioxide Emissions-Reduction Technologies for Industrial Production of Aluminium: *Berkley Lab*. https://escholarship.org/content/qt2327g97d/qt2327g97d.pdf?t=p0lnsa.

[129] Low temperature digestion (100°C) of Gibbsite bauxite requires 7.5 – 12 GJ x t, while high temperature digestion (250°C) of Boehmite or Diaspora bauxite requires 11 – 18 GJ x t. Tabereaux, A., & Peterson, R. D. (2013). Aluminium production. *Treatise on Process Metallurgy*, *3: Industrial Processes*.

As the obtained sodium aluminate cools down, some seed crystals are added, causing it to precipitate into *aluminium hydroxide* ($Al(OH)_3$). This last product is then heated at 900° – 1300°C in a calcination furnace[130], causing calcination to take place, which eventually drives off water and leaves pure solid *alumina* behind (Al_2O_3).

The aluminium industry is gradually discontinuing rotary kilns in favor of stationary calciners (GSC and FBC, see note 30), as they consume about 33% less energy[131].

In general, about two tons of bauxite are required to produce one ton of alumina, and two tons of alumina are required to produce one ton of aluminium.

Overall, the Bayer process requires about 14.5 GJ x t of primary alumina produced, which is equal to 29 GJ x ton of aluminium produced[132].

1.1.2 Electrolytic Reduction – the Hall-Héroult Process

The obtained alumina is dissolved into molten cryolite (*sodium hexafluoroaluminate*, Na_3AlF_6) at about 950°C. The following steps take place in an *Electrolytic Cell*, also known as *Aluminium Smelting Cell* (see Chart 12). Within the machinery, an electric current is passed through to the product, causing aluminium ions to migrate to the carbon cathode, where they gain electrons and form liquid aluminium. The molten aluminium sinks to the bottom of the machinery, where it is periodically syphoned off.

The Aluminium Smelting Cell operates at a temperature of 950 – 960°C, consuming approximately 47 – 54 GJ of energy per ton of aluminium produced[133]. This stage accounts for the highest energy consumption in primary aluminium production, adding up to 80% of total energy consumption (see Chart 12) and contributing to roughly 60% of total emissions in the process, also due to its reliance on carbon anodes, which produce CO2 as a byproduct. The overall Hall-Héroult process implies the oxidation – that releases CO2 – of the carbon anodes. Therefore, over time, the consumption of carbon anodes necessitates their replacement approximately once a month. Anode production itself is an energy-intensive process, requiring up to 1.6 GJ x t of carbon anodes under best-practice conditions[134].

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130 Calcination furnaces can be either gas suspension calciners (GSC), fluidized bed calciners (FBC), or rotary kilns.

131 Raahauge, B. E., & Devarajan, N. (2015). *Experience with particle breakdown in gas suspension calciners*. 33rd International ICSOBA Conference. https://icsoba.org/assets/files/publications/2015/Shorts/AA12S%20-%20Experience%20with%20Particle%20Breakdown%20in%20Gas%20Suspension%20Calciners.pdf.

132 Springer & Hasanbeigi (2016)

133 Springer & Hasanbeigi (2016)

134 Worrell, E., Price, L., Neelis, M., Galitsky, C., & Zhou, N. (2007, June 5). *World Best Practice Energy Intensity Values for selected industrial sectors*. https://escholarship.org/uc/item/77n9d4sp.

1.1.3 Casting, Solidification and Alloying

Liquefied aluminium can be cast into ingots, rolled into sheets, or alloyed with other metals, such as copper, magnesium, or silicon, to enrich the final product with specific industrial properties. Best practices for this last step are estimated at 1 GW x t of final aluminium produce[135].

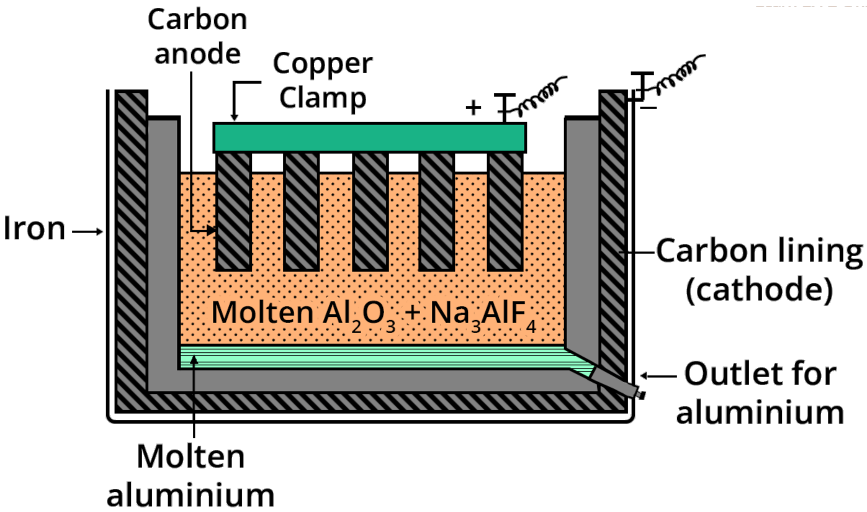

Chart 10: An Electrolytic Cell used in the Hall-Héroult process[136]

The image illustrates the Hall-Héroult process, an industrial method used to extract aluminium from alumina. The Electrolytic Cell (or Aluminium Smelting Cell) consists of a container lined with carbon that acts as a cathode (a negative electrode) on the outside, while several carbon anodes (positive electrodes) are suspended from the top of the cell through a copper clamp. The electrolyte used is sodium hexafluoroaluminate, in which alumina is dissolved; the cryolite lowers the melting point of alumina, enabling electrolysis to occur at approximately 950 – 980°C instead of the much higher melting point of pure alumina (which is over 2000°C). As the electric current flows through the electrolyte, *aluminium ions* (Al^{3+}) at the cathode (the carbon lining) gain electrons and form molten aluminium, which accumulates at the bottom of the cell, where it is periodically collected. Meanwhile, *oxygen ions* (O^{2-}) at the anode (the carbon anode suspended in the cell) lose electrons and react with the carbon, releasing carbon dioxide (CO_2), into the air.

1.2 Pollution Flows

In this section, the various pollution flows of the aluminium are going to be analyzed. The section will address the pollution flows from each stage of production, categorising them

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[135] Worrell *et al.* (2016).
[136] Vedantu. (2025). *Hall Heroult Process with Reaction for JEE*. VEDANTU. https://www.vedantu.com/jee-main/chemistry-hall-heroult-process-with-reaction.

accordingly. Section 1.2.1 focuses on the waste flows of Bauxite Mining and Refining (the Bayer Process, Section 1.1.1), namely red and white mud and caustic soda; Section 1.2.2 targets the waste flows of pure aluminium production (the Hall-Héroult Process, Section 1.1.2), namely, perfluorocarbons, sulfur dioxide, hydrogen fluoride and spent pot linings; Section 1.2.3 focuses instead of white and black aluminium dross, and salt slag, all of which are generated from Casting, Solidification and Alloying of aluminium (Section 1.1.3). Section 1.5 will address carbon dioxide separately.

1.2.1 Red and White Mud and Caustic Soda

During the Bayer process, several wastes are generated, including red and white mud, and caustic soda; however, given the aggregated nature of these wastes, they often add up to reach the status of radioactivity, going from Naturally Occurring Radioactive Materials (NORM)[137] to Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM)[138].

To begin with, leftover muds are by-products of bauxite refining via the Bayer process, specifically due to the treatment of caustic soda. However, depending on the composition of the initial bauxite, the resulting mud can be classified as either "red" or "white": red mud contains a mix of iron oxides (hence the red color) along with other minerals like silica and titanium dioxide; white mud is very similar to its red counterpart but contains high levels of *calcium oxide* (CaO) and residues of aluminium oxide (Al_2O_3).

As mentioned above, bauxite naturally contains primary radionuclides like uranium, thorium, radium and their respective decay products, constituting a Naturally Occurring Radioactive Materials (NORM). However, as the bauxite is processed and refined, its radioactive components are aggregated into the leftover mud, resulting in Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM). The United States Environmental Protection Agency[139] estimates that there are approximately three billion tons of bauxite residue stored at both active and legacy processing sites worldwide.

137 *Naturally-Occurring Radioactive Materials (NORM) - World Nuclear Association*. (n.d.). https://world-nuclear.org/information-library/safety-and-security/radiation-and-health/naturally-occurring-radioactive-materials-norm.

138 *Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) | US EPA*. (2025, January 14). US EPA. https://www.epa.gov/radiation/technologically-enhanced-naturally-occurring-radioactive-materials-tenorm.

139 *TENORM: Bauxite and alumina production wastes | US EPA*. (2025, January 14). US EPA. https://www.epa.gov/radiation/tenorm-bauxite-and-alumina-production-wastes#:~:text=The%20refinery%20processes%20used%20to,These%20wastes%20can%20contain%20TENORM.

Aside from being radioactive, red and white muds are also alkaline and could thus damage environmental balances due to their caustic nature[140].

In addition to leftover muds, the refining process of aluminium generates a significant amount of leftover caustic soda. Due to its high solubility, caustic soda easily contaminates water, and given its alkalinity, it can seriously alter the natural pH level of aquatic bodies[141].

1.2.2 Perfluorocarbons, Sulfur Dioxide, Hydrogen Fluoride and SPL

The Hall-Héroult Process generates several pollutants, namely carbon dioxide, perfluorocarbons, sulfur dioxide, hydrogen fluoride and spent pot linings (SPL).

The first and more obvious gaseous waste is *carbon dioxide* (CO_2), released during the electrolysis as carbon anodes are consumed in the process, reacting with the oxygen and forming the CO_2 which is then released into the atmosphere. It will be looked at more closely in section 1.3.5.

Second, if there is not enough alumina in the electrolyte, the anodes start reacting with the fluorine contained in the cryolite instead, creating *perfluorocarbons* (PFCs) like *tetrafluoromethane* (CF_4) and *hexafluoro ethane* (C_2F_6)[142]. Perfluorocarbons and other alike gases could be defined as "the older and meaner brother of CO2"; they can for thousands of years in the atmosphere[143], and have a much greater warming potential: according to the

[140] Indian Ministry of Environment, Forest and Climate Change. (2023). Guidelines for Handling and Management of Red Mud Generated from Alumina Plants. In *Central Pollution Control Board*. Central Pollution Control Board. https://cpcb.nic.in/uploads/hwmd/Guidelines_HW_6.pdf.

[141] MicroGO. (2024, March 18). An ESG perspective on the use of Caustic Soda in food industry. *MicroGO*. https://www.microgo.in/post/an-esg-perspective-on-the-use-of-caustic-soda-in-food-industry.

[142] This phenomenon is called "anode effect". Science Direct. (n.d.-a). *Aluminium Electrolysis*. https://www.sciencedirect.com/topics/engineering/aluminium-electrolysis. Tabereaux, A. (1994). Anode Effects, PFCs, Global Warming, and the Aluminium Industry. *JOM: The Journal of the Minerals, Metals & Materials Society*. https://doi.org/10.1007/BF03222629.

[143] Tetrafluoromethane (CF_4) can last up to 50'000 years in the atmosphere. Mühle, J., Ganesan, A. L., Miller, B. R., Salameh, P. K., Harth, C. M., Greally, B. R., Rigby, M., Porter, L. W., Steele, L. P., Trudinger, C. M., Krummel, P. B., O'Doherty, S., Fraser, P. J., Simmonds, P. G., Prinn, R. G., & Weiss, R. F. (2010). Perfluorocarbons in the global atmosphere: tetrafluoromethane, hexafluoroethane, and octafluoropropane. *Atmospheric Chemistry and Physics*, *10*(11), 5145–5164. https://doi.org/10.5194/acp-10-5145-2010.

Global Warming Potential (GWP)[144], where CO_2 – by reference – has a GWP of 1, CF_4 scores about 7,390 of GWP, while C_2F_6 is even worse, accounting to about 12,200 of GWP[145].

A further source of concern can be the sulfur impurities in the anodes that can generate *sulfur dioxide* (SO_2) and *hydrogen fluoride* (HF). The latter is caused by the high temperatures in the electrolysis that vaporize fluorides which react with the moisture in the air, leading to HF formation; the same waste is also generated when the cryolite decomposes over time. Both substances are highly toxic to humans and the environment.

In addition to gaseous waste, the Hall-Héroult Process also generates a solid waste, namely the spent pot lining of the electrolytic cell, which degrades over time; also in this case, the waste is highly toxic, as it contains fluorides, cyanides, and heavy metals[146].

1.2.3 White and Black Aluminium Dross, Salt Slag

When molten aluminium is poured into molds or transported, it reacts with oxygen in the air, forming aluminium oxide on the surface; more practically speaking, a solid, crusty layer of oxide forms on top of the metal, known as primary dross. This process unavoidably occurs anytime the aluminium is melted, including remelting cycles for recovery and recycling; however, more precise management of melting temperatures and avoidance of prolonged exposure to oxygen can lessen the effects[147]. The Hall Héroult process also generates the same product, albeit with a minor contribution.

Dross can be white, and black, based on the properties of the initial product. White dross is generated during primary aluminium production and secondary refining. Black dross is instead a byproduct of secondary aluminium recycling and refining scrap. In terms of composition, white dross contains approximately 30 – 50% of metallic aluminium, and 50% of *aluminium oxide* (Al_2O_3), while black dross only contains between 5 and 10% of metal, as

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[144] From 1990s onwards, the Intergovernmental Panel on Climate Change (IPCC) has adopted the Global Warming Potential (GWP) as a method of comparison between different greenhouse gases: more in detail, « the GWP is a measure of how much energy the emission of 1 ton of a gas will absorb over a given period of time, relative to the emission of 1 ton of carbon dioxide (CO_2). The larger the GWP, the more that a given gas warms the Earth compared to CO_2 over that time period. The time period usually used for GWPs is 100 years » (*Understanding Global Warming Potentials | US EPA*, 2025).

[145] *Understanding global warming potentials | US EPA*. (2025, January 16). US EPA. https://www.epa.gov/ghgemissions/understanding-global-warming-potentials?.

[146] Li, X., Liu, Y., & Zhang, T.-A. (2023). A comprehensive review of aluminium electrolysis and the waste generated by it. *Sage Journals*. https://doi.org/10.1177/0734242X231164321.

[147] K. Das, Dr. S. (2006). *Reduction of Oxidative Melt Loss Of Aluminium and Its Alloys*. https://digital.library.unt.edu/ark:/67531/metadc880911/m2/1/high_res_d/877410.pdf.

secondary aluminium scrap is much more likely to contain a wider range of contaminants, primarily salt[148].

Last, salt slag is also a hazardous by-product generated during this step. During melting, salt fluxes like sodium chloride (NaCl) and potassium chloride (KCl) are added to the molten metal to protect the metal from oxidation and help separate alumina from impurities[149]. Salt slag is left after the melting, consisting of a mix of the used salt fluxes, aluminium oxide, smaller aluminium particles and other impurities. Due to its reactivity with moisture and the presence of salts[150] has a high environmental harm potential; however, the valuable materials it contains can be – sometimes – recovered based on its specific composition.

It is now essential to assess how these waste flows can be reduced or reintegrated into the production cycle after the main pollution streams have been identified. Current procedures and technological advancements for recycling waste materials within the aluminium value chain will be covered in detail in the next section.

1.3 Recycling Flows

As shown above, the production of aluminium generates significant amounts of waste, some of which, however, can be reintegrated into other production processes. The following section will identify, quantify and analyze the possible reusage flows (when present) of the wastes presented above.

1.3.1 Red and White Mud and Caustic Soda

First and foremost, to be safely reused, the leftover mud from the Bayer process must be triturated[151] with other substances to reduce the concentration of their radioactive components.

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[148] A prominent feature of black dross is the presence of chloride salts, particularly sodium chloride (NaCl) and potassium chloride (KCl); these salts are used during secondary smelting to aid in separating aluminium from impurities.

[149] Xiao, Y., Reuter, M. A., & Boin, U. (2005). Aluminium recycling and environmental issues of salt slag treatment. *Journal of Environmental Science and Health Part A*, *40*(10), 1861–1875. https://doi.org/10.1080/10934520500183824.

[150] Jaishankar, M., Tseten, T., Anbalagan, N., Mathew, B. B., & Beeregowda, K. N. (2014). Toxicity, mechanism and health effects of some heavy metals. *Interdisciplinary Toxicology*, *7*(2), 60–72. https://doi.org/10.2478/intox-2014-0009.

[151] *Trituration*, or *comminution*, refers to « the shredding or pulverizing of waste in order to reduce its size, as used in solid waste management and wastewater treatment ». This term also refers to the equivalent of *dilution*,

Given their different compositions, red and white mud have differing potential reusage flows.

Red mud can be reused in the following ways:

a) As an additive in cement and concrete production[152]
b) As a raw material for iron extraction[153]
c) As a substitute of clay in the production of bricks and ceramics[154]
d) As a soil amendment, for it can neutralize acidic soils[155]
e) As a recovery flow for Rare Earth Elements (REE), especially scandium
f) As an environmental remediation to absorb heavy metals and neutralize acidic wastewaters[156]

There are several ways to reuse white mud, most of which align with red mud's uses. However, given its composition rich in calcium, white mud can be used to produce calcium aluminate, which can be used as a refining flux for the steel industry[157].

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but for the solid state of matter. In the context of bauxite residue management, comminution also facilitates the incorporation of other materials to dilute hazardous components, particularly TENORMs (see Notes 102 and 103), since – after aluminium extraction via the Bayer process – the remaining bauxite red mud's proportions are altered, making the density of radionuclides to increase, along with its potentially radioactivity. As such, to mitigate radioactive elements and enable safe reuse, red mud is often blended with inert materials like kaolinite or other silicates; this blending process, sometimes involving co-calcination, reduces the concentration of radioactive elements, thereby lowering the overall radiological risk and making the material suitable for further applications. Taylor & Francis. (n.d.). *Trituration - Knowledge and References | Taylor & Francis*. https://taylorandfrancis.com/knowledge/Medicine_and_healthcare/Pharmaceutical_medicine/Trituration/.

[152] Where it can be added up to 20% of the total weight of cement. Viyasun, K., Anuradha, R., Thangapandi, K., Kumar, D. S., Sivakrishna, A., & Gobinath, R. (2021). Investigation on performance of red mud based concrete. *Materials Today Proceedings*, *39*, 796–799. https://doi.org/10.1016/j.matpr.2020.09.637.

[153] Red mud contains a significant amount of iron, ranging from 30% to 60% by weight. Various extraction methods have been developed to recover this iron content. For instance, sulfuric acid leaching has achieved iron recovery rates of up to 67.93%, while oxalic acid leaching coupled with photocatalytic reduction has demonstrated iron extraction efficiencies as high as 96%. Kong, H., Zhou, T., Yang, X., Gong, Y., Zhang, M., & Yang, H. (2022). Iron Recovery Technology of Red Mud—A review. *Energies*, *15*(10), 3830. https://doi.org/10.3390/en15103830; Yang, Y., Wang, X., Wang, M., Wang, H., & Xian, P. (2015). Recovery of iron from red mud by selective leach with oxalic acid. *Hydrometallurgy*, *157*, 239–245. https://doi.org/10.1016/j.hydromet.2015.08.021.

[154] Studies show that replacing up to 20% of total clay with red mud can improve ceramic density, flexural strength and glassiness. Sglavo, V. M., Maurina, S., Conci, A., Salviati, A., Carturan, G., & Cocco, G. (2000). Bauxite "red Mud" in the ceramic industry. Part 2. Production of clay-based ceramics. *Journal of the European Ceramic Society*, *20*(3), 245–252. https://doi.org/10.1016/S0955-2219(99)00156-9.

[155] Given its highly alkaline nature (with a pH often exceeding 10), red mud can be used to balance acid soils. When applies with a proportion of 40 tons per hectare, red mud managed to raise the pH of soil by 1 point, resulting in an increase of 24% of crops productivity. Summers, R., Guise, N., Smirk, D., & Summers, K. J. (n.d.). *Bauxite residue (red mud) improves pasture growth on sandy soils in Western Australia*. Digital Library. https://library.dpird.wa.gov.au/j_article/15/.

[156] According to Rajković et al. (2025), « using red mud as a cost-effective adsorbent for the remediation of industrial wastewater not only provides an efficient solution for removing heavy metals and radionuclides but also leverages an otherwise problematic waste material, aligning with both environmental preservation and economic feasibility ». Rajković, M., Jelić, I., Janković, M., Antonijević, D., & Šljivić-Ivanović, M. (2025). Red mud as an adsorbent for hazardous metal ions: Trends in utilization. *Toxics*, *13*(2), 107. https://doi.org/10.3390/toxics13020107.

[157] McLean, A., Yang, Y., & Barati, M. (2017). Refining fluxes for metallurgical melts based on waste materials of the aluminium industry. *Research Gate*. https://doi.org/10.1080/03719553.2016.1268854.

Second, caustic soda also contributed to significant amounts of liquid waste; per each ton of aluminium produced, approximately 85kg of caustic soda are requires[158].

However, due to its widespread use in all manufacturing industries, there are several ways to reuse it. In the context of aluminium production, a method to recover caustic soda along with significant amounts of aluminium hydroxide (for further aluminium recovery) has been patented by Davis & Co in 1990[159].

1.3.2 Perfluorocarbons, Sulfur Dioxide, Hydrogen Fluoride and SPL

Unfortunately, for gaseous waste, which as of now has proven to be the most impactful one, there seems to be an implied convention of simply releasing it into the atmosphere. The same applies to perfluorocarbons (PFCs), sulphur dioxide, and hydrogen fluoride produced along the aluminium value chain.

About perfluorocarbons, there seems to be more diffused and specific knowledge of their impact on the environment, which led to the development of technologies capable of destroying them through high-temperature combustions, that, due to their operational costs and energy intensity, remain rare among manufacturers; PFCs can also be collected and reused in some niche refrigerators and air conditioning devices, but realistically speaking, their environmental impact led to a phasing off from their usage due to the concerns related to the disposal of said appliances[160].

Sulfur dioxide (SO_2) can be converted into *sulfuric acid* (H_2SO_4) through the Contact process[161], which is widely used to produce fertilizers, detergents, and other industrial chemicals[162]; otherwise, it can be captured and neutralized in designated industrial plans

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[158] ICIS Explore. (2024, August 27). *Individual news - ICIS Explore*. https://www.icis.com/explore/resources/news/2012/01/11/9522889/caustic-soda-demand-to-fall-on-more-aluminium-cuts-us-alcoa/.

[159] Davis, T. A., & Co, G. (1990, July 6). *US5049233A - Recovery of sodium hydroxide and aluminium hydroxide from etching waste - Google Patents*. https://patents.google.com/patent/US5049233A/en.

[160] *About F-Gases*. (2024, September). Climate Action. https://climate.ec.europa.eu/eu-action/fluorinated-greenhouse-gases/about-f-gases_en.

[161] Libretexts. (2023, January 30). *The contact process*. Chemistry LibreTexts. https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Supplemental_Modules_(Physical_and_Theoretical_Chemistry)/Equilibria/Le_Chateliers_Principle/The_Contact_Process; *The Contact Process for the manufacture of sulphuric acid*. (n.d.). https://www.chemguide.co.uk/physical/equilibria/contact.html.

[162] The Editors of Encyclopaedia Britannica. (2025, March 28). *Sulfuric acid | Structure, Formula, Uses, & Facts*. Encyclopedia Britannica. https://www.britannica.com/science/sulfuric-acid; *Sulfuric acid*. (n.d.). https://www.essentialchemicalindustry.org/chemicals/sulfuric-acid.html.

through a wet scrubber system[163], where it can be later converted into gypsum (*calcium sulfate*, CaSO4), used in the production of wallboard or as a soil amendment[164].

Out of the gaseous wastes, *hydrogen fluoride* (HF) seems to be the most recyclable one. Its main reusage consists in its collection for conversion into aluminium fluoride (AlF3)[165], one of the components needed for the aluminium smelting process (Hall-Héroult process, see Paragraph 1.1.2). Furthermore, HF can also be used as a feedstock to produce several fluorinated compounds, including refrigerants, solvents, and high- [166].

Last, spent pot lining is often sent to landfills, especially when it contains high levels of hazardous substances such as cyanide and fluoride; however, it can be reused in cement, steel and mineral wood production after treatment to neutralize its hazardous compounds[167].

1.3.3 White and Black Aluminium Dross, Salt Slag

Given its high aluminium content (that varies between 15 and 75%)[168], white dross is often remelted to recover the metal, or processed into calcium aluminate, which is used as a flux in steelmaking.

Black dross is instead the leftover product of secondary aluminium smelting (see Paragraph 1.2.3) and contains much less aluminium (6 – 10%), and significant portions of salt (10 – 30%), making it much harder to recycle[169].

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[163] BMB Purification. (2025, May 22). *Gas scrubber for industrial systems and for industrial plants | BMB*. Bmbpurification. https://www.bmbpurification.com/en/gas-scrubber-purification/.

[164] Stawski, T. M., Karafiludis, S., Pimentel, C., Montes-Hernández, G., Kochovski, Z., Bienert, R., Weimann, K., Emmerling, F., Scoppola, E., & Van Driessche, A. E. (2024). Solution-driven processing of calcium sulfate: The mechanism of the reversible transformation of gypsum to bassanite in brines. *Journal of Cleaner Production*, *440*, 141012. https://doi.org/10.1016/j.jclepro.2024.141012.

[165] The conversion of hydrogen fluoride into aluminium fluoride is typically achieved by reacting *aluminium hydroxide* ($Al(OH)_3$), the most common precipitation of refined bauxite, with *hydrofluoric acid* (HF dissolved in water). Alternatively, dry scrubbing systems in smelters use alumina to adsorb gaseous HF waste, which then reacts to form AlF_3. Ntuk, U., Tait, S., White, E. T., & Steel, K. M. (2015). The precipitation and solubility of aluminium hydroxyfluoride hydrate between 30 and 70°C. *Hydrometallurgy*, *155*, 79–87. https://doi.org/10.1016/j.hydromet.2015.04.010.

[166] Singh, D. K., Krishna, K. S., Harish, S., Sampath, S., & Eswaramoorthy, M. (2016). No more HF: Teflon-Assisted ultrafast removal of silica to generate High-Surface-Area mesostructured carbon for enhanced CO2 capture and supercapacitor performance. *Angewandte Chemie International Edition*, *55*(6), 2032–2036. https://doi.org/10.1002/anie.201509054.

[167] International Aluminium. (2022). Spent Pot Lining: An Introduction. In *International Aluminium*. https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://aluminium.org.au/wp-content/uploads/2022/09/IAI-Spent-pot-lining-an-introduction.pdf&ved=2ahUKEwj9287_9oSMAxU-0wIHHQXFLR8QFnoECBQQAw&usg=AOvVaw2KqzRycBOgg6lGS752jCZB.

[168] Kudyba, A., Akhtar, S., Johansen, I., & Safarian, J. (2021). Aluminium Recovery from White Aluminium Dross by a Mechanically Activated Phase Separation and Remelting Process. *JOM*, *73*(9), 2625–2634. https://doi.org/10.1007/s11837-021-04730-x.

[169] McLean *et al.* (2017)

Despite being ineradicable, aluminium dross can be reduced (a), processed (b and c), recovered or disposed of in the following ways.

a) In-Furnace Dross Reduction can be obtained through:
   - Tilting or Rotary Furnaces[170], and Electromagnetic Stirring[171], limiting contact with oxygen
   - Inert Atmospheres, consisting of Argon or Nitrogen gas blankets laid over molten aluminium to limit contact with oxygen[172]
   - Precise Temperature Optimization[173], keeping the temperature of the furnace as close as possible to the lower melting point for the shorter time possible, as excessive heat increases aluminium reactivity with oxygen

b) "Hot" Dross Processing (and Immediate Aluminium Recovery) can be obtained with:
   - Dross Presses, that squeeze molten aluminium out of fresh dross, allowing a recovery of up to 80% of the metal[174]
   - Spinning Coolers, that cool down dross as aluminium is still motel, separating the two[175]

c) "Cold" Secondary Processing (extracting aluminium from dross) can be obtained with:
   - Salt Slag Recycling, a technique providing for the adding of fluxing agents, like *sodium chloride* (NaCl) or *potassium chloride* (KCl) to separate aluminium from dross[176].

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[170] CEng, A. P., & CEng, J. H. (2011). Technology for electromagnetic stirring of aluminium reverberatory furnaces. In *Light Metals*(pp. 1193–1198). https://doi.org/10.1007/978-3-319-48160-9_202.

[171] Andersson, J. (2019). Optimized electromagnetic stirring in melting and holding furnaces. In *˜The œminerals, metals & materials series* (pp. 1179–1183). https://doi.org/10.1007/978-3-030-05864-7_145.

[172] Secat, Inc. (2006). Reduction of Oxidative Melt Loss Of Aluminium and Its Alloys: Final Technical Report. In *Unt.edu*. Secat, Inc. https://digital.library.unt.edu/ark%3A/67531/metadc880911/m2/1/high_res_d/877410.pdf?utm_source=chatgpt.com.

[173] *Optimising aluminium furnace operation with ABB AL-EMS*. (n.d.). Metals. https://new.abb.com/metals/abb-in-metals/references/optimised-ems-in-aluminium-melting-and-holding-furnaces?.

[174] Roth, D. J., Culler, L. R., Heifner, R. D., & Co, A. (1980, December 3). *US4386956A - Metal recovery process from aluminium dross - Google Patents*. https://patents.google.com/patent/US4386956A/en.

[175] *aluminium dross recycling system*. (n.d.). Foshan Nanhai Kangyuan Machinery Co., Ltd. https://www.kyaluminium.com/product-aluminium-dross-recycling--systemaluminium-dross-recycling--system-.html?.

[176] After the primary melting of aluminium, dross is collected and mixed with salt fluxes to enhance the separation of substances; the mixture is then placed in a rotatory furnace – like the one where the aluminium is initially melted – where it is heated to around 900 – 1'000°C. The salt flux creates a protective layer around the molten dross, allowing the now separated and melted aluminium to flow out for further re-casting. The same technique is used for remelting aluminium scarp, adding up to overall dross formation. FreeBee. (2002). Freebee FY-5 Salt Flux: Salt flux is used when recycling aluminium. This is an introduction to salt flux composition, usage and ratios. Rotary furnace fluxes and techniques will be explained, and you will get to know more about environmental impact, recovery efficiency and the many benefits of using Freebee FY-5 Salt Flux. In *https://www.freebee.dk*. https://usercontent.one/wp/www.livefreebee.dk/wp-content/uploads/2020/09/Freebee_FY5_SaltFlux.pdf?.

- Recovered salt slag itself can be reused as a fluxing agent in subsequent smelting cycles, or processed to recover individual salts, minimizing waste and closing the loop within the recycling process[177].

- Plasma or Pyrolysis Treatment, a service managed only by advanced recycling plants using high temperature plasma furnaces to extract and recover aluminium from dross[178].
- Mechanical Separation, which consists of the grinding and sieving of dross to separate it from aluminium particles for further use[179].

d) Recovery or Disposal

- Black dross can be used in cement production as a filler in asphalt and bricks, while white dross can be used in the production of steel[180].
- As a last resort, companies can dispose of the dross by sending it to landfills, though this is the least preferable option due to its environmental costs.

1.4 Energy

The European primary aluminium manufacturing pathway (from mine to cast house) requires about 140 GJ per ton of primary aluminium produced[181]. Chart 13 exemplifies how different stages of production impact the overall energy consumption. As mentioned above (se Section 1.2), the Hall-Héroult process is the most energy and carbon dioxide-intensive step.

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[177] Joint Research Centre of the European Commission. (2017). Best Available Techniques (BAT) Reference Document for the Non-Ferrous Metals Industries. In *Joint Research Centre of the European Commission*. https://eippcb.jrc.ec.europa.eu/sites/default/files/2020-01/JRC107041_NFM_bref2017.pdf Section 4.4.2, page 502; Section 5.2.2, page 460.

[178] Changming, D., Chao, S., Gong, X., Ting, W., & Xiange, W. (2018). Plasma methods for metals recovery from metal–containing waste. *Science Direct*, *77*, 373–387. https://www.sciencedirect.com/science/article/pii/S0956053X18302472.

[179] Politecnico di Milano & FederAmbiente. (2010). SEPARAZIONE E RECUPERO DEI METALLI E VALORIZZAZIONE DELLE SCORIE DI COMBUSTIONE DEI RIFIUTI URBANI. In *Consorzio Imballaggi Alluminio*. Consorzio Imballaggi Alluminio. https://www.cial.it/wp-content/uploads/2020/10/STUDIO-POLITECNICO-MILANO-RECUPERO-ALLUMINIO-SCORIE-DI-POST-COMBUSTIONE.pdf.

[180] Muñoz-Vélez, M. F., Salazar-Serna, K., Escobar-Torres, D., Rojas-Manzano, M. A., Gómez-Gómez, A., & Maury-Ramírez, A. (2023). Circular Economy: Adding Value to the Post-Industrial Waste through the Transformation of Aluminium Dross for Cement Matrix Applications. *Sustainability*, *15*(18), 13952. https://doi.org/10.3390/su151813952.

[181] International Aluminium Institute. (2024b, September 19). *Aluminium recycling Factsheet - International Aluminium Institute*. https://international-aluminium.org/resources/aluminium-recycling-fact-sheet/.

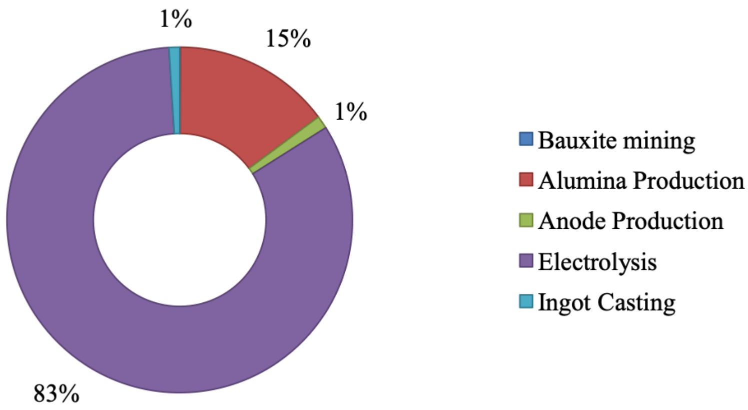

Chart 11: Summary of Primary Aluminium Production Energy Use by Process[182]

Note: Data is presented as shared of primary energy use in kilo joules n(kJ) per ton of final aluminium produced using regional production-weighted fuel energy contents.

As anticipated, the Hall-Héroult electrolysis is the most energy consuming and polluting step out of the whole primary aluminium production chain. Second is alumina production (Bayer Process), which similarly to the electrolysis, requires high temperatures for the refining to take place. In the case of aluminium, the mining phase is one of the least energy-intensive ones thanks to the soft and earthy consistency of its deposits, that do not require any drilling or blasting. The main drivers for energy consumption in this phase are loading and hauling of the ore, which are carried out by diesel-powered trucks and excavators. Lastly, anode production and aluminium casting's impact on energy bills are minimal compared to the other phases.

1.5 Carbon Dioxide

Aluminium production generates CO2 emissions both as direct emissions (where CO2 is the product of the Hall-Héroult electrolysis and carbon anode oxidation) and as indirect emissions drive by energy consumption. The second massively varies in quantity based on geographical location, as in regions where electricity is primarily generated from fossil fuels, the carbon intensity of aluminium production is remarkably higher: coal-powered plants will generate around 57.6 GJ x t/Al, while smelters co-located with hydropower plants will generate almost no emissions from energy consumption[183]. The global average carbon dioxide emissions per ton of aluminium produced is approximately 15.1 tons of CO2[184]. However, according to the Transition Pathway Initiative[185] this figure will have to decrease to 4.80 tons of CO2 for an average aluminium producer to be aligned with the Paris Pledge. Further benchmarks about

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[182] Springer & Hasanbeigi (2016)
[183] Springer & Hasanbeigi (2016)
[184] Andreotti, E. (2024a, September 17). *'Can do' attitude needed to achieve 100 per cent recycling rate for all aluminium drinks cans* International Aluminium Institute. https://international-aluminium.org/can-do-attitude-needed-to-achieve-100-per-cent-recycling-rate-for-all-aluminium-drinks-cans/.
[185] Dietz *et al.* (2019)

emission intensity – both currently and under future scenarios – can be found in Chapter 2 Section 3.

Despite the potential application of Carbon Capture and Storage and Utilization (CCS, and CCUS) technologies, the direct adoption of these technologies in the aluminium manufacturing industry remains premature and poorly documented. However, a more in-depth analysis of these – among other – potential breakthrough technologies for the aluminium sector is presented in Chapter 6.

As shown in this Section, producing aluminium from scratch not only requires significant amounts of energy and resources but also results in considerable environmental impacts. For these reasons – along with great potential for economic savings – the production of secondary aluminium represents a key strategic alternative. Much less energy- and resource- demanding, the secondary route for aluminium production will be analysed in the following section.

2 Secondary Aluminium Production: Recycling Route

2.1 The Secondary Production Route

The secondary aluminium route comprises three phases, namely Scrap Collection and Pretreatment (respectively Paragraphs 2.1.1 and 2.1.2) and Melting, Refining and Casting (Paragraph 2.1.3).

2.1.1 Scrap Collection

Secondary aluminium production starts with collection and sorting of scrap materials sourced both from post-consumer lots (beverage cans, automotive parts, etc.) and industrial manufacturing waste (sheet trimming parts, casting rejects, etc.).

Key aluminium sorting methods include:

- Magnetic separation[186], to discard ferrous metals like steel and iron

[186] Science Direct. (2025). *Magnetic Separation*. https://www.sciencedirect.com/topics/earth-and-planetary-sciences/magnetic-separation#:~:text=Magnetic%20separation%20is%20primarily%20used,iron%20metal%20prior%20to%20crushing.

- Eddy Current separation[187], working according to the same principle of magnetic fields, but in an opposite way, inducing electrical current in non-ferrous metals causing them to be repelled
- Density Separation (sink/float method)[188], separating materials based on their density using specific tailor-made liquids
- Spectroscopic techniques, including:
    - Laser-induced Breakdown Spectroscopy[189], where a laser pulse vaporizes a tiny portion of the material, creating a plasma light, on the base of whose color it is possible to determine the elemental composition of the material
    - X-ray Fluorescence (XRF)[190], where X-rays are directed at the material, causing it to emit back secondary X-rays with wavelengths attributable to their constitutive elements
    - X-ray Transmission (XRT)[191], where the absorption of X-rays as they pass through materials is analyzed; because different materials have different atomic densities, XRT can distinguish between them.
- AI and Robotics sorting, that leverage on one technique mentioned above while automating and enhancing the efficiency of sorting processes.

2.1.2 Scrap Pretreatment

After being sorted, aluminium scrap undergoes pretreatment, whose purpose is to prepare it for melting. This involves a deep cleaning to remove contaminants (dirt, oil) and other products (like paint) followed by the shredding or crushing of the metal to increase its surface area, which is more convenient for a variety of reasons, including increased heat transfer, allowing aluminium to melt more easily and evenly, and further removal of contaminants, since many selected materials still contain a percentage of ferrous metals, that, if finely ground, can be easily removed with a magnet.
Magnetic separation is then employed to eliminate ferrous metals.

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[187] Rem, P., Leest, P., & Van Den Akker, A. (1997). A model for eddy current separation. *International Journal of Mineral Processing*, *49*(3–4), 193–200. https://doi.org/10.1016/s0301-7516(96)00045-2.
[188] *Sink float: Efficient Density-Based Separation*. (n.d.). QR Metals. https://www.qr-metals.com/technology/sink-float/.
[189] Parisi, G. P. (n.d.). *Laser Induced Breakdown Spectroscopy (LIBS)*. https://www.ism.cnr.it/it/tempism/analisi/spettroscopia/spettroscopia-risolta-in-tempo/laser-induced-breakdown-spectroscopy-libs.html.
[190] Science Direct. (2006). *X-ray Fluorescence*. https://www.sciencedirect.com/topics/materials-science/x-ray-fluorescence-spectroscopy.
[191] SGM Magnetics. (2025, February 25). *XRT Model*. https://www.sgmmagnetics.com/en/products/xrt-model/.

2.1.3 Melting, Refining and Casting

Finally, furnaces melt the scrap using various methods to prevent the product from oxidizing (refer to Paragraph 1.3.3 for details). At this stage, alloying may occur, where other metals are added to create specific aluminium alloys with desired properties.

Finally, refined molten aluminium is cast into ingots or other forms, ready for further processing.

2.2 Pollution Flows

While secondary aluminium production is considerably less polluting than the primary route, it still generates several waste streams and harmful emissions. The main pollution flows include:

- Dross (especially black dross)[192]
- Salt Slag
- Particulate Matter (PM) which is generated during shredding, handling, and melting, particularly when organic coatings or oils are not completely removed during pretreatment; these fine particles may contain heavy metals and require filtration.

Apart from PM, these residues are also part of the primary aluminium production route, as previously explained.

2.3 Recycling Flows

The recycling flows of secondary aluminium production mirror those of the primary production route, as secondary processing is nothing but a subgroup of primary processing – featuring only the casting, re-melting and alloying of aluminium, plus some scrap pretreatment).

Therefore, Section 1.3 has already addressed the associated recycling flows.

[192] During secondary processing of aluminium – just as in primary routes – the molten metal naturally tends to oxidize on contact with air, forming a surface of dross. To limit oxidation and improve melting yield, salt fluxes ($NaCl$ and KCl) are added in rotary furnaces, to create a protective layer on the metal bath. This is particularly true for secondary melting, since the scrap (especially the post-consumer one) can contain more impurities, requiring more fluxing agents to separate them from alumina. However, these salts eventually mix with the formed alumina and traces of incompletely molten metal, resulting in black dross – which, as mentioned in 1.2.3, contains more salt than metal, making it hard to reuse or recycle.

2.4 Energy

According to Zore[193], energy consumption for secondary aluminium adds up to 3.8 giga joules (GJ) per ton of aluminium produced: this amount represents only 5% (5.6%, more precisely) of the 67.9 GJ required per ton of primary aluminium.

Still, some minor discrepancies could arise based on the type of scrap used, since post-consumer scrap requires more energy compared to pre-consumer industrial scrap.

2.5 Carbon Dioxide

According to the same paper by Zore (2024), CO2 emissions associated with the production of secondary aluminium are approximately 0.25 tons of CO2e per ton of aluminium. This digit represents only a minor fraction of the EU average carbon intensity, which is of 6.8 tons of CO2e per ton of aluminium produced, compared to a much higher global average of 13.1 tons of CO2e.

While secondary aluminium production, as demonstrated in this section, is considerably less carbon-intensive, it is not without its own set of concerns, most of which are associated with the difficulty in scrap selection, purification, and pre-treatment for further life cycles.

In fact, companies that choose not to engage in secondary aluminium routes justify their position based on economic feasibility constraints, which are typically linked to the high cost of acquiring pretreated scrap, the operational burden of processing untreated scrap in-house, or the capital investment required to install their own treatment facilities.

Nonetheless, the secondary route remains environmentally and strategically superior, both for broader policy objectives and companies' operational efficiency in the long run.

Findings

As shown in this chapter, the production of primary aluminium generates significant amounts of waste, which is indicated and quantified in Table 4. A materiality flow chart is also available in the Introduction.

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[193] Zore, L. (2024). Decarbonisation options for the aluminium industry. In J. A. Moya (Ed.), *European Commission's Joint Research Centre (JRC)*. European Commission's Joint Research Centre (JRC). https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://publications.jrc.ec.europa.eu/repository/bitstream/JRC136525/JRC136525_01.pdf&ved=2ahUKEwjm7dicnISMAxXD3QIHHVRnCAUQFnoECBwQAQ&usg=AOvVaw1wy2cCymISvMjc41qqIRZC.

Table 4: Primary and Secondary aluminium production waste flows

Primary aluminium production waste flows estimated quantities				
Waste Category	**Waste Type**		**Main Source**	**Quantity**
Solid Waste	Leftover Muds	Red Mud	Treatment of Bauxite	2 – 3 tons x ton of primary alumina[194]
		White Mud		2 – 10 kg x ton of primary alumina[195]
	Aluminium Dross		White Dross	2 – 5 kg x ton of primary aluminium[196]
			Black Dross	5 – 10 kg x ton of primary aluminium[197]
	Spent Pot Lining (SPL)		Hall-Héroult Electrolysis	~ 25 kg x ton of primary aluminium[198]
Liquid Waste	Caustic Soda		Treatment of Bauxite	85 kg x ton of primary aluminium[199]
Gaseous Waste	Carbon Dioxide (CO_2)		Electrolysis in the Hall–Héroult Process and Energy Consumption	More generally, 2 – 18 tons x ton of aluminium in total[200] In Europe, 6.8 tons x ton of aluminium Worldwide, 13.1 tons x ton of aluminium[201]
	Perfluorocarbons		Evaporation from molten cryolite	Hard to estimate
	Hydrogen Fluoride (HF)		Evaporation from molten cryolite	0.2 – 0.6 kg x ton of aluminium[202]
Secondary Aluminium Production Waste, Reuse, and Recycling Flows estimated quantities				
Physical waste	Black dross		Secondary remelting	200 – 500 kg x ton of secondary aluminium[203]
Liquid waste	Salt Slag		Secondary Aluminium Production	200 – 500 kg x ton of secondary aluminium

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[194] According to the European Commission's Horizon Europe's Research and Innovation Magazine (2024), « each year, about 150 million tons of red mud worldwide emerges from aluminium production – or 20 kilograms per person globally. Of that total, no more than 3% is recycled and the rest gets dumped ». McLean, A., Yang, Y., & Barati, M. (2017). Refining fluxes for metallurgical melts based on waste materials of the aluminium industry. *Research Gate*. https://doi.org/10.1080/03719553.2016.1268854.
[195] McLean *et al.* (2017)
[196] McLean *et al.* (2017)
[197] McLean *et al.* (2017)
[198] According to the International Aluminium Institute (2020), in 2019 about 1.6 million tons of SPL were produced globally; furthermore, each lining pot's lifespan typically ranges between 4 to 7 years, after which they are considered "spent".
[199] According to (ICIS Explore, 2024).
[200] Approximately 1,5 – 2,5 tons of CO2 are released due to the consumption of the carbon anodes during the Hall-Héroult electrolysis, while the remaining emissions depend massively on the energy mixed used to power the production; hydroelectric plants emit about 2 – 4 tons of CO2 per ton of aluminium, while those relying on coal can even exceed the 18 tons. However, the global carbon intensity average is between 13 and 15 tons of CO2.
[201] As mentioned above, according to Zore, 2024.
[202] Data is gathered from a Chinese study (Li et al., 2024), however it cannot be taken as a precise point of reference because the paper is based on practices of an average plant in the Yunnan province in China.
[203] According to Hu et al. (2020), building on previous research by Seng et al. (2006), Huang et al. (2014) and Tsakiridis (2012).

Chapter 5 – *Existing And Forthcoming Technologies and Processes, Decarbonization Opportunities*

Introduction

To meet the EU's emission reduction goals, a radical transformation will be needed in the aluminium industry, which, to take place, will require high capital investments.

To begin with, the most discussed solutions – for any emission-intensive activity – are carbon capture (CC), carbon capture and storage (CCS), and carbon capture, storage and utilization (CCUS).

1 Decarbonization Options for the Aluminium Industry

The entirety of Section 1 is drawn from the 2024 study on *Decarbonization Options for the Aluminium Industry* by Zore, published by the European Commission's Joint Research Centre (JRC)[204].

According to the paper, the three main strategies to decarbonize the aluminium manufacturing industry can be divided into three basic paths: Decarbonization of Indirect Emissions (Section 1.1), Decarbonization on Direct Emissions (Section 1.2) and Improved Resource Efficiency (Section 1.3).

1.1 Decarbonization of Indirect Emissions

A 55% share of the sector's emissions globally, adding up to 616 million tons of CO2e in 2022, comes from the consumption of electricity during the smelting process[205]. Only in Europe, primary production of aluminium consumed about 119 TWh of electricity, 2.5% of which was carbon-based, resulting in 688,000 tons of indirect CO_2 emissions[206].

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[204] Zore, L. (2024). Decarbonisation options for the aluminium industry. In J. A. Moya (Ed.), *European Commission's Joint Research Centre (JRC)*. European Commission's Joint Research Centre (JRC). https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://publications.jrc.ec.europa.eu/repository/bitstream/JRC136525/JRC136525_01.pdf&ved=2ahUKEwjm7dicnISMAxXD3QIHHVRnCAUQFnoECBwQAQ&usg=AOvVaw1wy2cCymISvMjc41qqIRZC.

[205] International Aluminium. (2023). *Greenhouse Gas Emissions – Aluminium Sector*. https://shorturl.at/q0ls6.

[206] *Primary Aluminium Smelting Energy Intensity*. (2024). International Aluminium. https://shorturl.at/Flo0M.

According to the International Energy Agency (IEA)'s Below 2° Scenario, projections indicate a potential reduction of emissions to near zero before the half of this century: up to 10 million tons of CO_2 could potentially be saved in the next 30 years by meeting targets set. These goals are attainable through phasing out fossil fuels in favor of renewable energy sources, or pairing fossil fuels with CCUS technologies. For smelters already integrated within power grids (those employing electricity rather than fossil fuel combustions directly in their plants), emission reductions will be facilitated by the instalment of renewables directly into the plants.

1.2 Decarbonization of Direct Emissions

These emissions come mainly from fuel combustion (required to meet the thermal needs of the productive process), anode consumption in melting furnaces, transportation, and the carbon footprint of primary raw materials. About 16% of the industry's emissions in 2022 are from direct combustion of fuels for alumina refining (Hall-Héroult electrolysis), anode production, and aluminium casting, remelting, and recycling; an additional 10% comes directly from the smelting (and refining) process, while about one last 7% come from auxiliary materials and transportation.

Specific decarbonisation options for direct emissions include:

- Inert anodes (1.2.1)
- Hydrogen as a reducing agent (1.2.2)
- Carbon capture, utilization and storage (CCUS, 1.2.3)
- Direct electrification (1.2.4)
- Other process improvements (1.2.5)

1.2.1 Inert Anodes

According to the paper, inert anodes have the potential to eliminate almost all emissions generated during the melting process.

As explained in Chapter 4 Section 1.2.2, traditional anodes release GHGs (CO2, CO, PFCs); differently, inert anodes use materials that are not consumed in the electrolytic process, releasing O_2 instead. Furthermore, inert anodes have been proven to be much more efficient, allowing the efficiency of the melting process to improve by up to 25% – hence, reducing the energy demand.

Last, implementing inert anodes would eliminate the costs associated with their consumable carbon counterpart, leading to significant reductions in operating costs.
In Europe only, in 2019, emissions from anode consumption amounted to 1.8 million tons of CO_2 equivalent in 2019[207]: in terms of emission reduction potential, carbon anodes could annul all these emissions and reduce indirect emissions through the increased energy efficacy they hold.

Despite their development, which is classified as « potentially at a tipping point », inert anodes currently have a technology readiness level (TRL) of between 4 and 5, meaning that they are not yet commercially available. Challenges include the need for the anode material to be resistant to dissolution and reactivity in the hot electrolyte, physically stable, with high mechanical strength and a low wear rate. Maintaining the purity of the aluminium produced is crucial, as corrosion can cause impurities.

Current and projected costs are uncertain due to the proprietary nature of the technology; however, it is estimated that to be competitive with carbon anodes, they would have to cost about €110 – 120 / ton of aluminium produced. The estimated investment costs for retrofitting each existing cell range from €1 to 2 million.

1.2.2 Hydrogen Use

As mentioned above, many of the processes featured in aluminium production require high temperatures. Hydrogen represents a promising solution to replace the fossil fuels burned to reach said temperatures, reducing CO_2 emissions.

Its main applications include alumina refining, secondary aluminium remelting, and anode production. In the long term, hydrogen could also serve as a reductant in primary aluminium smelting through the $Al_2O_3 + 3H_2 \rightarrow 2Al + 3H_2O$ reaction, which – theoretically – emits only water vapour. However, this concept remains at a speculative stage due to significant technical challenges and the absence of proof of concept on an industrial scale.

While hydrogen production technologies, particularly for blue and gray hydrogen, are relatively mature (TRL 7 – 9), specific applications in the aluminium sector, such as hydrogen calcination, remain in the early stages of development (TRL 5 – 6). Co-firing of hydrogen with natural gas for industrial heating is currently being explored as a transitional solution.

[207] *Aluminium*. (n.d.). Mission Possible Partnership. https://www.missionpossiblepartnership.org/action-sectors/aluminium/.

Yet, the most significant barrier is the cost of green hydrogen (varying between 3 and 5€ per kg), which is currently higher than blue hydrogen (about 2€ / kg) and grey hydrogen (about 1.5€ / kg). Although cost projections suggest that green hydrogen will become more competitive in the medium- to long term, its deployment is still hindered by the need for substantial investment in hydrogen transport, storage infrastructure, and retrofitting or redesigning existing systems for this technology – all of which must necessarily meet high safety requirements[208].

Last, the estimated cost of CO_2 abatement through hydrogen in thermal applications ranges from €450 to €781 per ton of CO_2 avoided – assuming a displacement of natural gas.

1.2.3 Carbon Capture, Utilization and Storage (CCUS)

The much-discussed CCUS[209] consists in a technology capable of capturing direct CO2 emissions from industrial operations and subsequently transporting and using or permanently storing them – primarily underground.

In the aluminium sector, CCUS can be applied to capture emissions from alumina refining – where fossil fuels are combusted to generate high-temperature heat – and from the smelting process, which emits CO_2 due to the consumption of carbon anodes. It is considered a potentially practical mid-term solution, particularly for all those who, for specific reasons, cannot switch from fossil fuels to renewables[210].

CO_2 capture technologies for flue gases have been commercially available for several years, although absorption technologies in the aluminium sector remain at a relatively low TRL (3 – 4). CO2 transport is an established practice, while storage in saline formations or depleted oil and gas fields ranges from pilot stages to commercial deployment (TRL 5 – 9).

The primary barrier is the high upfront investment required. Costs vary significantly depending on the CO_2 concentration at the source. In aluminium smelting, flue gas CO_2 concentrations are relatively low (around 1 – 1.5%), making capture costs exceed €100 per

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[208] Hydrogen is particularly problematic as it is highly inflammable and has a wide ignition range (4 – 75% in air), low ignition energy, and a tendency to leak due to its small molecular size – posing significant explosion and fire risks if not properly managed. Calabrese, M., Portarapillo, M., Di Nardo, A., Venezia, V., Turco, M., Lucani, G., & Di Benedetto, A. (2024). Hydrogen Safety Challenges: A Comprehensive Review on Production, Storage, Transport, Utilization, and CFD-Based Consequence and Risk Assessment. *Energies*, *17*(6). https://doi.org/10.3390/en17061350.

[209] *What is carbon capture, usage and storage (CCUS) and what role can it play in tackling climate change? - Grantham Research Institute on climate change and the environment*. (2024, August 16). Grantham Research Institute on Climate Change and the Environment. https://www.lse.ac.uk/granthaminstitute/explainers/what-is-carbon-capture-and-storage-and-what-role-can-it-play-in-tackling-climate-change/.

[210] This is relevant especially for those establishments located in third world delocalized areas – which comprises most upstream primary operators – where electricity grids are still either non-available, or unreliable.

ton – substantially higher than in other sectors; significant modifications to electrolytic cells would be required to reduce this cost. In contrast, in alumina refining – where CO_2 concentrations are higher – the economics are more viable, with estimated capture costs ranging between €50 and 80 per ton.

CCUS can effectively mitigate emissions from the aluminium industry, but its applicability must be tailored to specific process conditions. Financially, it is more viable for alumina refining than for electrolysis.

1.2.4 Direct Electrification

Direct electrification involves replacing combustion-based heat sources with electricity-powered heating systems.

This strategy is applicable across various stages of the aluminium value chain, particularly in low- and medium-temperature processes. In alumina refining, it can be deployed to substitute thermal operations such as crushing, conveying, digestion (via electric heating elements), and calcination (through electric kilns). Most fossil fuel used in alumina refining is concentrated in steam generation. Electrification is also viable for aluminium smelting operations, especially in secondary remelting and casting, where technologies like induction furnaces (coreless or single shot) are already being used.

A range of electric heating technologies – inductive, dielectric, and resistive – are already available and mature. Electrifying thermal processes is technically feasible, although industry-specific integration varies in readiness.

As far as effective implementation is concerned, high upfront capital costs and recent volatility in electricity prices dampen short-term implementation. Moreover, increased electricity demand may strain power grids and undermine environmental benefits if additional electricity is generated from fossil fuels.

However, direct electrification is considered to be a cornerstone of the sector's decarbonisation pathway, particularly when aligned with the overall European goals of a fully renewable power sector. The potential impact of this solution will be maximised where grid electricity is sourced from low-carbon or renewable energy.

1.2.5 Other Process Improvements

The paper also looks at further process improvements, whose scope ranges from recovery of energy via heat to other overall process innovations, all of which seek to reduce the energy intensity of the process.

More in detail:

- **Waste heat recovery (TRL 7 – 9) –** A significant portion, approximately between 30 and 45%, of the heat generated during aluminium smelting is – as of nowadays – dissipated as waste heat and carried away by exhaust gases. According to the study by JRC, the situation presents further opportunities for adopting systems for waste heat recovery aimed at lowering overall energy consumption, including – but not limited to – energy modulation technology, shell heat exchangers, and heat pipes – all of which have been successfully tested and are commercially available[211].
- **Low-Digestion Temperature (TRL** 9): This technology is already in use in some refineries (such as Hydro's Alunorte, Hydro 2023[212]). However, its applicability depends massively on the quality of the bauxite ore used: as mentioned in Chapter 4 Section 1.1.1, some qualities of bauxite allow digestion at lower temperatures (thus less emissions), while some denser others require higher temperature and pressure (resulting in more energy consumption). Yet, the impact of this technology on the sector is likely going to be limited due to the scarcity of preferable bauxite types.
- **Fluidized Bed Calciners (TRL 9) –** An alternative to rotary calciners in alumina refining, offering greater energy efficiency and potential energy efficiency improvements by up to 30 – 35%.
- **Electric Boilers for Low- and Medium-temperature Processes (TRL 4 – 5) –** An easier option for reducing emissions than fossil-fueled boilers, especially when combined with heat pumps. The limiting elements lie in the associated high capital costs and availability of affordable renewable energy
- **Mechanical Vapor Recompression, or "MVR" (TRL 7 – 8) –** This technology involves the recovery of waste heat from steam, channeling it into a compressor where its temperature and pressure are increased; this allows the reuse of steam, allowing for substantial energy savings. MVR could be employed in alumina refining (specifically

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[211] *Aluminium Industry - Etekina*. (2020, December 9). Etekina. https://www.etekina.eu/aluminium-industry/.

[212] *How a switch of energy source in world's largest alumina refinery enables low-carbon products. (2023). Hydro. https://www.hydro.com/en/global/about-hydro/stories-by-hydro/how-a-switch-of-energy-source-in-worlds-largest-alumina-refinery-enables-low-carbon-products/.*

in digestion), where renewable energy could be used to power steam production, completely displacing fossil fuel-based boiler steamers[213]. Alcoa Australia Limited has developed a pilot project to demonstrate the feasibility of MVR[214].

- **Carbothermic Reduction of Alumina (TRL 7 – 8) –** A non-electrochemical alternative to the Hall-Héroult process, using carbon as the reducing agent. The process – proposed by many studies over the last 50 years – involves the use of carbon (typically in the form of carbon or coke) as a reducing agent to extract aluminium from alumina[215]. Carbothermic technology has the potential to increase energy savings by 34 % compared to modern Hall-Héroult carbon anode technology.
- **Lower Electrolysis Temperature (TRL 7 – 8) –** Currently, electrolysis occurs at about 960°C, a temperature well above the melting point of aluminium (660°C). Bringing the temperature closer to the melting point could, in theory, decrease electricity consumption by about 1 – 1.5 MWh per ton. However, lowering the temperature and changing the composition of cryolite involve critical issues, including reduced solubility of alumina and aluminium, increased electrical resistance, and increased vapour pressure; the use of additives could mitigate these issues but would introduce new variables to be managed, such as aluminium purity, voltage in the electrolytic cells, management of the frozen insulation layer, and corrosion resistance of the coating materials[216].
- **New Smelter Technologies (TRL 7 – 9) –** New aluminium smelting technologies aim to improve economic efficiency while reducing the emission intensity of end products. Among emerging technologies is the HAL4e Ultra Cells, installed in Årdal, Norway by Hydro (2021). Progress is also being made in China with solutions such as digital twinning, distributed monitoring, constant flow regulation, heat retention, and reduced dust formation during electrolysis. These innovations improve overall efficiency, helping to decrease both emissions and operating costs[217].

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[213] Frey, R. (2025, March 25). *The importance of energy efficiency when designing process equipment systems*. RCM Technologies. https://www.rcmt.com/resources/blogs/energy-efficiency-process-equipment-systems/.
[214] Australian Renewable Energy Agency (ARENA). (2024, July 4). *Mechanical vapour recompression for low carbon alumina refining - Australian Renewable Energy Agency (ARENA)*. Australian Renewable Energy Agency. https://arena.gov.au/projects/mechanical-vapour-recompression-for-low-carbon-alumina-refining/.
[215] The reaction is as follows: $Al2O3 + 3\ C \rightarrow 2\ Al + 3\ CO$
[216] Cassayre, L., Palau, P., Chamelot, P., & Massot, L. (2021). Properties of Low-Temperature melting electrolytes for the aluminium electrolysis Process: a review. *Journal of Chemical and Engineering Data*, *55*(11), 4549–4560. https://doi.org/10.1021/JE100214X.
[217] Redaktion, A. (n.d.). *The development of China's aluminium industry and technology*. International Aluminium Journal. https://www.aluminium-journal.com/the-development-of-chinas-aluminium-industry-and-technology.

1.3 Improved Resource Efficiency – Recycling

According to the paper, and as widely argued in this whole thesis, a core strategy in decarbonizing the aluminium sector lies in recycling.

About 75% of all aluminium ever produced – which is approximately 1.4 million tons is still in use[218], and recycling best practices (meaning recycling of post-consumer scrap) have the potential to avoid up to 300 million tons of CO2e per year. However, international ambitions are very high, suggesting how adopting near-100% collection rate, improving scrap sorting, minimizing pre-consumer scrap and reducing metal losses could potentially lower the lower the need for primary aluminium by 20% by 2050[219].

In the regulatory context, the EU's Critical Raw Materials Act sets a minimum target of a 25% recycling rate[220], a target that, combined with the environmental benefits of secondary production, will encourage recycling growth.

In 2019, the EU consumed 13.2 million tons of aluminium, of which 4.7 million (35%) came from recycled material (both pre- and post-consumer scrap), 2 million (15%) from domestic primary production, and the remaining 50% was imported. In other words, 70% of ingots produced in the EU are of recycled origin[221].

Currently, a significant barrier is the cost of secondary aluminium, which is influenced by the price of primary aluminium and the cost of the recycling process. In 2019, recycling one ton of aluminium cost between 920 and 1,160€, depending on the type of scrap[222]. Scrap aluminium is sold for between 0.35 and 0.68 EUR per kilo, or about 772 to 1,500€ per ton[223],

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[218] International Aluminium Institute. (2024b, October 28). *Aluminium is infinitely recyclable - International Aluminium Institute*. https://international-aluminium.org/landing/aluminium-is-infinitely-recyclable/#:~:text=International%20Aluminium%20Institute-,Aluminium%20is%20infinitely%20recyclable,without%20changing%20its%20fundamental%20properties; European Aluminium. (2023). *Industry & market data*. https://european-aluminium.eu/about-aluminium/aluminium-industry/.

[219] European Aluminium. (2025). Aluminium Action Plan. In *European Aluminium*. https://european-aluminium.eu/wp-content/uploads/2025/02/25-01-13-An-Action-Plan-for-European-Aluminium.pdf.

[220] *Critical Raw Materials Act*. (n.d.). Internal Market, Industry, Entrepreneurship and SMEs. https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/critical-raw-materials-act_en.

[221] The International Aluminium Institute. (2025, March 5). *Global Cycle - International Aluminium Institute*. International Aluminium Institute. https://alucycle.international-aluminium.org/public-access/public-global-cycle/.

[222] Soo, V. K., Peeters, J. R., Compston, P., Doolan, M., & Duflou, J. R. (2019). Economic and Environmental Evaluation of Aluminium Recycling based on a Belgian Case Study. *Procedia Manufacturing*, *33*, 639–646. https://doi.org/10.1016/j.promfg.2019.04.080.

[223] *Pricing – Utah Metal Works*. (2023). https://umw.com/pricing/.

while the price of primary aluminium futures is currently around 2,215 EUR per ton (Trading Economics, 2023), with fluctuations between 1,447 and 2,485€ before the 2020 turmoil.

Still about resource efficiency, but specifically concerning recovery and reuse of process scrap, both solid (bauxite residue), liquid (salt slag) and gaseous (perfluorocarbons), some more technologies for recovery of resources for an overall increased efficiency can be found in Chapter 4 Sections 1.2 (Pollution Flows) and 1.3 (Recycling Flows).

Findings – Drive towards Decarbonization

To draw some conclusions on the technologies presented above, the paper analyzes the effects, costs, and potential of key decarbonization technologies in the aluminium industry, highlighting the gap between the price of carbon and the actual costs of emission reductions.

According to the Zore, in 2019, emissions from European primary aluminium production reached 4.79 mega tons of CO2e, at 6.8 tons of CO2e per ton, much higher than the 0.25 tons of CO2e associated with recycled aluminium.

Since half of the raw aluminium consumed in the EU is imported (with a higher average intensity of 13.1 tons of CO2e / ton), the weighted average intensity of total consumption (13.2 mega tons) was 7.58 tons of CO2e / ton, totaling about 100 mega tons of CO2e.

Among the technologies examined, inert anodes have the potential to eliminate 1.8 mega tons of CO2e per year but involve high costs (up to €2 million per cell).

On the other hand, CCUS, is certainly presented as more promising, but also more fitting for application in refineries rather than in smelters – because of the different concentration of CO2 in the flue gas (estimated cost between 50 – 80€ per ton in refineries and 180 – 300€ per ton in smelters).

Last, hydrogen could offset about 4 mega tons of CO2 with a cost of 450 – 78€ per ton, replacing about 75 million gigajoules (GJ) a year of thermal energy. According to current state of the art, CCUS is the technology with the best cost – reduction potential ratio: projections show how an expected decline in technology costs, combined with rising CO2 prices (around 80€ per ton as of October 2023), could accelerate the achievement of the economic tipping point for industrial decarbonisation. All of which, thanks to support mechanisms such as the EU Innovation Fund, can be covered both in costs and risks.

Still, considering the developing stage of all technologies mentioned, recycling (and circularity in general) – as of now – still stands as the most well-established and reliable decarbonisation pathway for the aluminium sector.

Chapter 6 – *Target Setting*

Introduction

This chapter outlines the methodology for setting and evaluating science-based decarbonization pathways, with a specific focus on the aluminium sector.

The reference for this Chapter is, as anticipated, the Science-Based Targets initiative's Understanding and Addressing the Barriers for Aluminum Companies to set Science-Based Targets[224].

It introduces the Sectoral Decarbonization Approach (SDA) and explains how companies (borrowers) and their lenders – including financial institutions and banks, but also individual investors – can use it to define credible emission reduction targets in line with international climate goals.

1 Pathway Setting

The primary point of reference in establishing of transition pathways is the Sectoral Decarbonisation Approach (SDA)[225]. Pointed out as the most ambitious effort of SBTI, the SDA was developed in collaboration with Carbon Disclosure Project (CDP)[226], World Resource Institute (WRI)[227], WFF[228], the United Nations Global Compact[229]and the technical support of Ecofys[230]. SDA is « a method for setting corporate emission reduction targets in line with climate science » through the use of science-based targets, defined as « targets […] to reduce GHG emissions […] in line with the level of decarbonisation required requires to

[224] Science Based Target Initative. (2020). Understanding and addressing the barriers for aluminum companies to set Science-Based Targets: Summary of findings and recommendations. In *Science Based Target Initative*. Science Based Target Initiative. https://sciencebasedtargets.org/resources/files/SBTi-Aluminum-Sector-Memo-FINAL.pdf.

[225] Science Based Target Initiative. (2015). SECTORAL DECARBONIZATION APPROACH (SDA): A method for setting corporate emission reduction targets in line with climate science. In *Science Based Target Initiative*. https://files.sciencebasedtargets.org/production/files/Sectoral-Decarbonization-Approach-Report.pdf?dm=1734357650.

[226] *CDP: Turning transparency to action*. (n.d.). CDP. https://www.cdp.net/en.

[227] *World Resources Institute - Research for People & Planet*. (2025, May 21). World Resources Institute. https://www.wri.org/.

[228] WWF. (2025, May 27). *WWF Italia | Sito Ufficiale | A tutela dell'ambiente e degli animali*. WWF Italia. https://www.wwf.it/.

[229] *Homepage | UN Global Compact*. (2025, May 23). https://unglobalcompact.org/.

[230] *Guidehouse | EcoFys*. (n.d.). https://www.ecofys.com/.

keep keeping temperature increase below 2°C compared to preindustrial temperatures, as described in the Fifth[231] (IPCC) ».

To apply the SDA, companies need to:

i. Identify a global carbon budget consistent with international targets (either 1.5°C, well below 2°C, or NDCs)
ii. Project the carbon budget in time until 2050 (where some targets aim for Net Zero)
iii. Divide the budget using Integrated Assessment Models (IAM)[232] to allocate emission reductions at the regional and sectoral level.

Through this process, companies' emission intensity pathways are established: the targets they lay out will be compared with the sector benchmark pathway to evaluate their ambitions. A bank follows the same process in budgeting its financed emissions over time, as demonstrated in Chapter 3.

2 Pathway Evaluation

After the transition pathway has been laid out, it must be compared to its respective sectoral benchmarks – and, as anticipated already, this thesis' primary scope is the aluminium sector.

To begin with, there is a recognized difference between the emission intensity of primary (integrated route) and secondary (recycling route) aluminium, with the latter requiring only 5% of the first's total energy[233]. As such, sectoral benchmarks should be chosen accordingly: because the emission intensity of the primary route is much higher than the secondary one, a combined benchmark will be excessively strict when applied to primary processing and excessively lenient when applied to secondary ones.

Therefore, when evaluating the aluminium sector, financial institutions should:

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[231] Science Based Targets Initiative. (2015). SECTORAL DECARBONIZATION APPROACH (SDA): A method for setting corporate emission reduction targets in line with climate science. In *Science Based Targets Initiative*. https://sciencebasedtargets.org/resources/files/Sectoral-Decarbonization-Approach-Report.pdf.

[232] IAMs provide a framework for companies to identify cost-effective emission reduction opportunities, considering regional technology readiness, economic feasibility, engineering constraints, and political/social factors. Emissions are normalized based on sectoral activity, through digits such as emissions per unit of output, emissions per unit of revenue, ensuring consistency and comparability for peer-to-peer considerations. United Nations Climate Change. (n.d.). *Integrated Assessment Models (IAMs) and Energy-Environment-Economy (E3) models*. Unfccc.int. https://unfccc.int/topics/mitigation/workstreams/response-measures/modelling-tools-to-assess-the-impact-of-the-implementation-of-response-measures/integrated-assessment-models-iams-and-energy-environment-economy-e3-models.

[233] International Aluminium Institute. (2024d, October 28). *Aluminium recycling saves 95% of the energy needed for primary aluminium production - International Aluminium Institute*. https://international-aluminium.org/landing/aluminium-recycling-saves-95-of-the-energy-needed-for-primary-aluminium-production/.

a) Understand which climate model companies use as a reference for their emission reduction targets and compare each with established temperature goals to ensure coherence. Tools like the Transition Arc[234] facilitate this comparison.
b) Divide the sectoral benchmark among primary, secondary, and mixed aluminium processing, depending on the production model each company engages in; the result should consist of three different emission intensity benchmarks.
c) For the first two Transition Arc models can be used, while for the third the Mission Possible Partnership's (MPP) Aluminium Sector Transition Strategy Model (ST-STSM)[235] can be used as a source of steel emission and production data. Reference data to evaluate whether a company's sectoral benchmark pathway is appropriate and sound can be found on the Transition Arc tool as well.

Comparability is key when evaluating an undertaking. It is important to assess what is the metric used by the company to benchmark its pathway against other peers.

Companies usually use the following three metrics:

i. Emission intensity – emissions per unit of aluminium produced
   This metric allows for fair comparison between companies of varying sizes; however, it is crucial to ensure consistency in measurement methodologies, and if needed, introduce adjustments for accurate comparison.
ii. Absolute emissions – total amount of GHG emissions
   This metric is particularly useful in the evaluation of a company's performance over time, serving as a historical emission chronology, underlining yearly reduction rates.
iii. Absolute emission targets – a company's goals to reduce their total GHGs (plus CO2e) within a given timeframe
   This last metric can be misleading, as it is not sensitive to the efficiency of a company: an aluminium producer can meet its emission targets by simply decreasing its output, rather than decreasing its GHG per unit of product. Furthermore, targets vary massively between companies, not allowing for fair comparisons.

The specific measure of emission intensity for the aluminium sector is Scope 1 and 2 (unless Scope 3 is greater than 40% of total GHGs, as explained below) emissions from aluminium

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[234] *TransitionArc*. (n.d.). https://transitionarc.climatearc.org/.
[235] *Sector strategies*. (n.d.). Mission Possible Partnership. https://www.missionpossiblepartnership.org/sector-transition-strategies/.

production per unit of aluminium produced in units of metric tons of CO2 equivalent per ton of aluminium.

SBTi has published a methodology for the target setting of the aluminium sector, offering a granular methodology by identifying current barriers to decarbonisation and differentiated pathways for each emission Scope[236].

These criteria and recommendations require companies to align their Scope 1 and 2 with at least well below 2°C, encouraging efforts towards 1.5°C as well.

Regardless of other popular targets, companies adopting SBTi methodology currently have three methods for setting Scope 1 and 2 targets, namely[237]:

a) Absolute contraction – « reduction of absolute emissions by a minimum of 2.5% annually to keep global temperature increase within well-below 2°C, or by a minimum of 4.2% for a 1.5°C global temperature limit ».
b) Activity-based contraction – « reduce emission intensity per physical production output with a unit that is representative of a company's portfolio (e.g. per aluminium can shipped), which, when translated into absolute emissions reduction terms, is in line with the minimum absolute contraction approach ».
c) Sector-based – « the global carbon budget is divided by sector and emission reductions are allocated to individual companies based on the sector's budget ». The SDA was developed to facilitate this division.

As per Scope 3[238], companies have four methods to choose from:

d) Absolute contraction – « reduction of absolute emissions by a minimum of 2.5% annually to keep global temperature increase within well-below 2°C, or by a minimum of 4.2% for a 1.5°C global temperature limit »
a) Economic Intensity – « reduce emission intensity per value added by at least an average of 7% year on year ».
b) Physical Intensity – « intensity reductions aligned with the aluminium sector SDA or targets that do not result in absolute emission growth and lead to linear annual intensity improvements equivalent to 2% at minimum »

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[236] Science Based Target Initative. (2020). Understanding and addressing the barriers for aluminium companies to set Science-Based Targets: Summary of findings and recommendations. In *Science Based Target Initative*. Science Based Target Initiative. https://sciencebasedtargets.org/resources/files/SBTi-Aluminium-Sector-Memo-FINAL.pdf.

[237] Science Based Target Initiative (2020), page 5.

[238] 2°C is the minimum level of ambition for Scope 3 targets, however any greater efforts by companies going beyond that will be welcomed, including efforts aiming at well below 2°C (minimum 2.5% annual linear reductions, or 1.5°C (minimum 4.2% annual linear reductions). Science Based Target Initiative (2020), page 5.

c) Supplier engagement – « commit to having a specific percentage of suppliers (as a percentage of spend or GHG emissions) with their own SBTs within five years from the date the company's target is submitted to the SBTi for validation ».

Scope 3 emissions, also known as value chain emissions, can be significant for both upstream and downstream aluminium companies: for example, the transformation of one ton of aluminium into aviation components (Scope 3, Category 10 emissions – processing of sold products) can generate amounts of emissions that surpass the sum of those associated coming from Scope 1 and 2. As such, SBTi requires companies whose Scope 3 emissions exceed 40% of their total emissions to collectively cover at least two-thirds of them in conformance with the GHG Protocol Scope 3 Standard[239].

Findings

Setting credible, science-based targets is a crucial first step in aligning the aluminium industry with international decarbonization goals. The SDA, as described in this chapter, offers a robust methodological framework for establishing emission paths that reflect both reality of climate science, industry dynamics, and operational scopes. By tailoring benchmarks for the specifics of primary, secondary, and hybrid production routes, while integrating Scope 1, 2, and – increasingly – Scope 3 emissions, companies can deliver more transparent and comparable targets that financial institutions can evaluate with precision.

Yet, setting targets alone does not equal decarbonization. The feasibility of meeting established objectives depends on the implementation of cutting-edge technology, innovations in structural processes, and systemic changes throughout the aluminium value chain – as suggested in Chapter 6.

But even so, assuming that both the target setting and deployment of all necessary innovations are carried out smoothly, how can progress be measured? It is unimaginable to detect progress only at the target year, especially for a financial institution whose responsibility is to assess the long-term viability of each deal years in advance.

The following chapter presents the ten Key Performance Indicators (KPIs) that form the foundation of this entire thesis. Their purpose is precisely to enable a forward-looking and informed assessment of an aluminium producer's exposure to climate-related risks –

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[239] Science Based Target Initiative (2020), page 6; *Corporate Value Chain (Scope 3) Standard | GHG Protocol*. (2013, May 1). https://ghgprotocol.org/corporate-value-chain-scope-3-standard.

particularly transition risks – and to evaluate each company's resilience well ahead of the target horizon.

Most importantly, these KPIs are designed to go beyond alignment and monitoring, as they seek first and foremost to capture progress, supporting the development of tailored financial strategies that stabilize and accompany companies throughout their decarbonization journey.

Chapter 7 – *KPIs*

Introduction

This section introduces a set of key performance indicators (KPIs) that have been identified as the most representative for evaluating the transition-related objectives of borrowers.

For the relevant sector, based on a comprehensive investigation of production processes, materials and fuels, KPIs have been identified by focusing on the various production inputs with a view to assess how the borrower is accelerating its transition, seeking to avoid lock-in risk, especially in a framework where circularity represents the industry's most effective response to the climate crisis.

The selected KPIs – 10 – are those that are most closely aligned with the EU's climate and sustainability goals for the aluminium industry. However, while the EU is primarily keen on emissions, other relevant institutions (ASI, European Aluminium, TPI, SBTi, etc.) shift the focus on other indicators, including recycling rate, water and energy consumption as well as origin, and overall waste generation.

The approach applied for the selection of KPIs is based on the identification of relevant materials and processes under the technical screening criteria set by the EU Taxonomy Regulation[240] that are applicable to the relevant sector. Then, KPIs and corresponding benchmarks have been identified in a way that allows their application to a potential company (borrower), its assets, and the relevant value chain level associated with it.

For each KPI, it is provided:

- N: Introduction – An outline of the underlying significance of the KPI for the assessment of a client's transition (whether in terms of emission reductions, recycling, or zero-waste practices).
- N.1: Issues – what are the issues that the KPI seeks to address
- N.2: Solution – what is the solution brought upon by this KPI to the mentioned issues and how to improve the overall effectiveness of the KPI? When easily dealt with, Sections N.1 and N.2 will be joined into one single Section, named "Issues & Solutions".
- N.3: Formula

[240] As outlined in Commission Delegated Regulation (EU) 2023/2486 of 27 June 2023.

- N.4: Benchmarks – what are the available reference benchmarks for the KPI (based on EU climate documents, coalition frameworks, and companies' best practices).

Below is a list containing a total of 10 key performance indicators (KPIs) that are pertinent to the aluminium industry: the first two (Aluminium Physical Intensity, Section 1; Scope 1 + 2 Alignment, Section 2) are more established sustainability reporting metrics, while the following three (Secondary Aluminium Production Rate, Section 3; Recycled Input Rate, Section 4; Pre- vs Post-Consumer Scrap, Section 5) are more coherent with general circularity practices; finally, the last five KPIs (Bauxite Residue, Section 6; Water Consumption, Section 7; Carbon Anodes, Section 8; Dross, Section 9 and Energy, Section 10) are industry- specific metrics to evaluate how efficiently the production of aluminium is carried out.

For each KPI, relevant benchmarks will be provided – drawing from legal standards (when available), coalition frameworks, and the reported performance of leading aluminium companies.

The companies under analysis are ALBA (Bahrein), Alcoa (USA), AMAG (Austria), Constellium (France), EGA (United Arab Emirates), Hindalco (India), Hydro (Norway), Rio Tinto (United Kingdom, Australia), RUSAL (Russia) and Vedanta (India).

All data provided is drawn from each company's sustainability and / or integrated annual reports from the financial year 2023 – 2024 – cited in Appendix 2 on Company Benchmarks along with all the data emerged from the application of the 10 proposed KPIs.

For each KPI, companies' performances are ranked from best to worst performing, where the worst performance is the non-disclosure of the digit under analysis (n/a).

For clarity, a cross-referencing table is provided in Appendix 2, summarizing all KPI-related performances of the companies, making sure to denote whether the digit under analysis is not available (n/a).

SUSTAINABILITY KPIs: Aluminium Physical Emission Intensity, Scope 1 + 2 alignment

Introduction

Within aluminium manufacturing, sustainability cannot be dissociated from decarbonization. Given the industry's energy intensity and reliance on carbon-based processes, emissions remain the most used environmental indicator for both regulators and companies.

This section introduces two key sustainability KPIs focused on quantifying GHG emissions, specifically Physical Emission Intensity (Section 1) and Scope 1 + 2 Alignment (Section 2). The first quantifies the number of emissions per unit of output produced (in this case, tons or kg of aluminium produced), while the latter assesses how closely aligned a company's emission trajectory is with science-based pathways – such as the ones outlines by the SBTi or TPI (discussed in Chapter 3).

Most importantly, these KPIs allow for comparability across companies – regardless of their size or production scale – by anchoring emissions' disclosures to physical units of output. Plus, linking emissions to units allows efficiency improvements not to go unnoticed despite any increases in production volumes.

1 Aluminium Physical Emission Intensity

Reporting emissions using intensity metrics enables a relative comparison of the environmental impact across different elements of the aluminium industry's pathway to Net Zero. By measuring emissions per unit of output, intensity metrics account for both production scale and efficiency, allowing for benchmarking among different production phases, technologies, and companies. Unlike absolute emissions, they do not penalize increases in production if they are coupled with efficiency gains or cleaner energy uses. This makes intensity metrics particularly valuable during transition phases, as they reveal the proportion between aluminium produced and emissions associated: the lower the ratio between emissions and produce, the more the efficiency (hence sustainability) of the production process. Key stakeholders in the aluminium sector mandate calculation and disclosure of emission intensities, including the ASI, European Aluminium, and all entities working on decarbonization plans for the sector (such as SBTI); furthermore, given the wide availability of this data, financial actors often refer to these metrics in the assessment of a producer's Net Zero alignment.

1.1 Issue

Assessing a company (hence, a borrower)'s performance only through emission intensity metrics may cause misalignment with their carbon budget. If, on the one hand, intensity metrics are useful for showing how efficiently a company produces—especially when emissions per unit decrease even as production grows (as explained just above)—on the other, they may shift the focus away from established emission caps: a company might appear aligned with climate targets based on intensity yet still increase its total emissions by scaling up production. In other words, meeting intensity targets does not give producers a free pass to raise output to levels that push them beyond their overall carbon budget.

1.2 Solution

Emission intensity metrics are essential for financial institutions to evaluate a borrower's alignment with carbon budget targets and to understand transition activities. While an absolute emissions metric shows the total amount of GHG emitted, an emissions intensity metric offers a fairer comparison between steelmakers. The issue discussed above can be easily solved by normalizing emissions based on output, allowing lenders to compare borrowers directly, regardless of their size.

1.3 Formula

$$Emission\ Intensity = \frac{Tons\ of\ CO_2}{Mass\ of\ aluminium\ produced\ (in\ tons)}$$

1.4 Benchmarks

For this KPI, several emission caps and benchmarks will be provided, specifically: the European Taxonomy Framework emission and energy caps (Section 1.4.1), emission intensities from some of the major players in the industry (Section 1.4.2), and last, emission limits drafted by voluntary coalition frameworks according to different climate scenarios (Section 1.4.3).

1.4.1 EU Taxonomy

According to the European Taxonomy, any aluminium producer must meet or stay below the following carbon intensity benchmarks, which correspond to the current best performances (BATs).

Until 2025, from a climate mitigation perspective, primary aluminium manufacturing[241] must comply with at least two of the following criteria[242]:

i. GHGs[243] ≤ 1,484 tons of CO2e / ton of aluminium manufactured[244]

ii. Average carbon intensity for indirect GHGs[245] ≤ 100 g CO2e/kWh

Additionally, the Taxonomy associates the established carbon intensities with an electricity consumption, adding a third criterion, namely

iii. Electricity consumption for the manufacturing of primary aluminium ≤ 15.5 MWh / ton of aluminium manufactured

After 2025, the manufacture of primary aluminium must comply with all three of the criteria above.

1.4.2 Industry

Below are presented the emission intensities (expressed as ton of CO2e / ton of aluminium manufactured) of some of the major aluminium producers over the year 2023 – 2024:

1) AMAG (Austria) – 0.163 tons of of CO2e / ton of aluminium
2) Constellium (France) – 0.66 tons of CO2e / ton of aluminium
3) Hydro (Norway) – 1.54 tons of CO2e / ton of aluminium

[241] According to the European Commission (2023), this activity is « associated with NACE code C24.42, C24.53 in accordance with the statistical classification of economic activities established by Regulation (EC) No 1893/2006 ». European Commission. (2023). *Manufacture of aluminium*. https://ec.europa.eu/sustainable-finance-taxonomy/activities/activity/273/view.

[242] Which are « combined to a single threshold resulting in the sum of direct and indirect emissions, calculated as the average value of the top 10% of installations based on the data collected in the context of establishing the EU ETS industrial benchmarks for the period of 2021 – 2026 and calculated in accordance with the methodology for setting the benchmarks set out in Directive 2003/87/EC plus the substantial contribution to climate change mitigation criterion for electricity generation (100gCO2e/kWh) multiplied by the average energy efficiency of aluminium manufacturing (15.5 MWh/t Al) ». European Commission. (2023). *Manufacture of aluminium*. https://ec.europa.eu/sustainable-finance-taxonomy/activities/activity/273/view.

[243] Calculated in accordance with Regulation (EU) 2019/331. *Delegated regulation - 2019/331 - EN - EUR-Lex*. (n.d.). https://eur-lex.europa.eu/eli/reg_del/2019/331/oj/eng.

[244] Defined as « The aluminium manufactured is the unwrought non alloy liquid aluminium produced from electrolysis ». European Commission. (2023). *Manufacture of aluminium*. https://ec.europa.eu/sustainable-finance-taxonomy/activities/activity/273/view.

[245] Defined as « the life-cycle greenhouse gas emissions produced from the generation of the electricity used for the manufacturing of primary aluminium ». European Commission. (2023). *Manufacture of aluminium*. https://ec.europa.eu/sustainable-finance-taxonomy/activities/activity/273/view.

1.4.3 Coalition Frameworks

The Transition Pathway Initiative (TPI) uses projections of emissions and expected aluminium production to calculate its average emissions intensity benchmarks under the below 2°C scenario, reporting:

- By 2014 ≤ 6.34 tons of CO2e / ton of aluminium
- By 2020 ≤ 5.07 tons of CO2e / ton of aluminium
- By 2025 ≤ 4.00 tons of CO2e / ton of aluminium
- By 2030 ≤ 3.07 tons of CO2e / ton of aluminium

Last, the International Aluminium Institute does the same, going further in time (2050), and differentiating between more scenarios (including below 2°C and 1.5°C) and primary and secondary aluminium manufacturing – as shown below in Table 5.

Table 5: International Aluminium Institute climate-aligned benchmark

Year	Scenario	Primary Intensity (t of CO2e / t of Al)	Secondary Intensity (t of CO2e / t of Al)	Total Emissions (millions of t of CO2e)
2025	Below 2°C	15	0.55	840
	1.5°C	12.5	0.5	640
2030	Below 2°C	14.5	0.5	440
	1.5°C	11.5	0.45	200
2050	Below 2°C	2.5	0.2	250
	1.5°C	0.5	0.1	53

2 Scope 1 + 2 Alignment

The direct emissions from activities within the operational boundaries of the company and the emissions from the use of electricity are known as Scope 1 and 2 of a borrower. When assessing a company's (hence a borrower's) climate strategy, financial institutions consider the alignment of their Scope 1 and 2 emission reduction targets. As explained in Chapter 3, Scope 1 emissions are the direct emissions from a company's operations, while Scope 2 emissions result from the electricity consumption associated with them. The coherence between a company's emission targets and broader climate objectives is a crucial factor to consider in its transition plan: since Scope 1 and 2 emissions fall under the direct control of the company, they are considered the most immediate and measurable indicators of its decarbonization efforts.

2.1 Issue

Because these emissions are largely influenced by a company's management decisions, financial institutions (or lenders in general) must ensure coherence between targets and objectives to evaluate the alignment between emission reduction targets and climate objectives. This is because if a borrower fails to meet its emissions reduction goals, it can lead to legal, reputational, and financial problems for both the borrower and the lender: assessing these risks is crucial for credit evaluation, as not meeting targets could indicate poor management or unpreparedness for climate-related rules – and a greater chance of default.

2.2 Solution

The metric reflecting the near- and long-term alignment between emission reduction targets and climate goals is known as the commitment gap: it is quantified as the difference between the company's *Scope 1 + 2 targets* ($T_{S1,2}$) and the *company specific decarbonization benchmark* ($CB_{S1,2}$) that is chosen as a reference. The pathways are expressed in kg of CO2 per unit of activity (such as tons of aluminium produced). The difference obtained between the two is the commitment gap. In other words, the metric evaluates how far the company's actual path is from a science-based (SBTI) or sector-specific (TPI) decarbonization pathway.

To evaluate the obtained digit, the commitment gap is compared to the maximum gap possible, which is the *business-as-usual* pathway, representing potential operations without emission reductions – to provide context. Business-as-usual is defined as an unchanged (horizontal) intensity pathway, where emissions do not diminish at all.

This approach aligns with the United Nations Environment Program's (UNEP) methodology for assessing the global commitment gap under the United Nations Framework Convention on Climate Change (UNFCCC) Climate Agreements.

2.3 Formula

$$Commitment\ gap = \frac{T_{S1,2} - CB_{S1,2}}{BAU_{S1,2} - CB_{S1,2}}$$

where,

$T_{S1,2}$ =the

$CB_{S1,2}$ = the company's Scope 1 + 2 benchmarks at the target year, also defined as the *reference decarbonization pathway*

$BAU_{S1,2}$ = the maximum commitment gap possible, defined as the *business-as-usual* scenario for the company

The lower the commitment gap, the stronger the alignment between the company's climate targets and the science-based pathway required to meet the reference temperature goal[246].

2.4 Benchmarks

The Commitment Gap can be interpreted according to ranges, where:

- Gap = 0 – the company's target ($T_{S1,2}$) is perfectly aligned with the decarbonization benchmark ($CB_{S1,2}$): the company is committed to doing exactly what is required by the selected decarbonization pathway.
- 0 < Gap < 1 – the company's target ($T_{S1,2}$) is less ambitious than the benchmark ($CB_{S1,2}$), but still represents an improvement compared to the business-as usual-scenario ($BAU_{S1,2}$): the company is going in the right direction, but non fast or deep enough to align with the pathway, where the commitment gap indicates the quantification of effort lacking.
- Gap = 1 – the company's target ($T_{S1,2}$) is identical to the business-as-usual scenario ($BAU_{S1,2}$), meaning that there is no effort was made to align with the decarbonization pathway ($CB_{S1,2}$).
- Gap > 1- the company's target ($T_{S1,2}$) is worse than the business-as-usual scenario ($BAU_{S1,2}$) when both are compared to the reference benchmark ($CB_{S1,2}$) – assuming that $CB_{S1,2}$; this would imply that the company foresees an emission intensity even greater than what it would have had without doing anything (an extremely unlikely scenario, especially if a company declares reduction targets)[247].

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[246] For example, TPI identifies three target scenarios: one for the Paris Agreement pledges, one for Below 2° and one below 1.5°. It is widely known that the first one is too permissive, and would not hinder climate change, while the second and the third are more effective; however, due to delays in implementation of decarbonization efforts, the most credible one is the 1.5° scenario.

[247] Or, if the target ($T_{S1,2}$) was between the $BAU_{S1,2}$ and the benchmark, but the benchmark was higher than the $BAU_{S1,2}$ (an anomalous situation where "improving" means emitting more than the $BAU_{S1,2}$ to achieve a less stringent benchmark), one could have values > 1. But in the typical configuration ($BAU_{S1,2} > T_{S1,2} \geq CB_{S1,2}$ or $BAU_{S1,2} > CB_{S1,2} > T_{S1,2}$), a Gap > 1 occurs if $T_{S1,2} > BAU_{S1,2}$ (assuming $BAU_{S1,2} = CB_{S1,2}$). In simpler terms, if $BAU_{S1,2} > CB_{S1,2}$, a Gap > 1 implies that $T_{S1,2} > BAU_{S1,2}$ meaning that the firm plans to deteriorate relative to BAU.

- Gap < 0 (negative value) – the company's target ($T_{S1,2}$) is more ambitious that the reference decarbonisation pathway ($CB_{S1,2}$), hence it is committed to doing better than what is required.

Unfortunately, the determination of this indicator turned out to be particularly time-consuming, primarily due to the extensive research required to obtain necessary data. While companies willingly share the climate goals they are aiming for, they are more unlikely to provide data compatible with benchmarks (discussed in Chapter 2): this is because they often communicate targets in terms of percentage reductions (both achieved and targeted), rather than as clean digits.

Consequently, within the scope of this analysis, the "Scope 1 + 2 alignment" has not been calculated for every company under review, as evident in Appendix 2.

Nevertheless, to illustrate its practical application and underlying methodology, a clear example of this calculation is provided for Alcoa (the first company looked at in Appendix 2): this example sees a practical application of the formula presented just above.

As such, the best possible benchmark this section can offer is a reference to Chapter 2 (Section 3, "Benchmarking: where to next?"), where entire pages are dedicated to aluminium industry-specific emission targets.

CIRCULARITY KPIs: Secondary Aluminium Production Rate, Recycled Input Rate, End of Life (EoL) Recycling Input Rate

Introduction

The manufacturing of primary aluminium is a highly energy-intensive and GHG-emitting process responsible for about 1 % of global GHG emissions[248]: its processing – especially the smelting – is responsible for about 8 % of the global electricity use in the global industrial sector[249]. Plus, given its high performability, the demand for aluminium is expected to grow by 81% by 2050, reaching nearly 120 million tons annually[250]. At the same time, aluminium

[248] Kermeli, K., Ter Weer, P., Crijns-Graus, W., & Worrell, E. (2024). Energy efficiency improvement and GHG abatement in the global production of primary aluminium. *Energy Efficiency*, *8*(4), 629–666. https://doi.org/10.1007/s12053-014-9301-7.

[249] Pedneault, J., Majeau-Bettez, G., Krey, V., & Margni, M. (2021). What future for primary aluminium production in a decarbonizing economy? *Global Environmental Change*, *69*, 102316. https://doi.org/10.1016/j.gloenvcha.2021.102316.

[250] European Aluminium. (2022, October 22). *Our vision 2050 for the aluminium industry: A vision for circular, low carbon, and competitive aluminium*. https://european-aluminium.eu/blog/vision2050/.

is infinitely recyclable, and its secondary processing is 95.5% more efficient than primary one[251].

Therefore, the most effective solution to mitigate the environmental impact of the growing aluminium demand is to gradually phase out from primary production and prioritize secondary production routes.

It follows that a judicious assessment of an aluminium producer as a potential borrower, must consider – in addition to emissions – the company's circularity, as it represents the only possibly successful pathway towards a decarbonized yet increased aluminium production.

Accordingly, the following section proposes other 3 different KPIs for the assessment of the extent to which a company is "doing more with less", trying to detect a tendency towards circularity. The KPIs in question are Share of Secondary Aluminium (Section 3), Recycled Input Rate ("RIR", Section 4), and Pre-Consumer Scrap vs Post-Consumer Scrap Rate (Section 5).

3 Share of Secondary Aluminium

When it comes to assessing the circularity of an aluminium producer, a key KPI is the *share of secondary aluminium* produced over the total amount.

As explained above, the best way to meet the growing demand for aluminium in light of limited resources and sustainability concerns, is to increase the production of secondary aluminium – which being on its second processing cycle, requires (as mentioned just above) less energy, energy whose associated emissions have already been accounted for by the primary producer.

The share of secondary aluminium over the total amount is expressed as a percentage, allowing for an immediate comparison between secondary and primary aluminium production volumes.

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[251] International Aluminium Institute. (2024d, October 28). *Aluminium recycling saves 95% of the energy needed for primary aluminium production - International Aluminium Institute*. https://international-aluminium.org/landing/aluminium-recycling-saves-95-of-the-energy-needed-for-primary-aluminium-production/; International Aluminium Institute. (2024e, December 20). *Primary aluminium smelting energy intensity - International Aluminium Institute*. International Aluminium Institute. (2024e, December 20). *Primary aluminium smelting energy intensity - International Aluminium Institute*. https://shorturl.at/Flo0M.

3.1 Issues & Solutions

Despite its relevance, the share of secondary aluminium has several limitations that must be addressed to ensure robustness and comparability.

Most notably, current reporting often fails to distinguish between *pre-consumer* (industrial scrap) and *post-consumer* recycled aluminium, despite the latter having a significantly higher environmental value. However, since this behavior is shared by most of the industry's best practices, it can be overlooked for the time being; this issue, however, will most certainly be solved within the next few years, as a new and more ambitious doctrine emerges more prominently. Not to mention that the necessary distinction between pre- and post-consumer scrap will be considered as a KPI of its own (see Section 5), to test whether and to what extent companies measure and disclose this digit.

Additionally, some manufacturers only process aluminium without controlling the entirety of its upstream sourcing, which may distort the indicator's significance.

Integrating third-party verification and aligning definitions with international standards, such as ISO 14021[252] and GRI 301-2[253] can further enhance reliability and cross-sector comparability.

3.2 Formula

$$Share\ of\ Secondary\ Aluminim\ (\%) = \left(\frac{Secondary\ Al\ produced\ (tons)}{Total\ Al\ produced\ (tons)}\right) \times\ 100$$

3.3 Benchmarks

Currently, recycled aluminium meets about 36% of the global demand, however, this data is expected to grow significantly, driven by circular economy efforts[254].

Globally, the average recycled aluminium input rate in 2018 was 32%[255].

As for the large aluminium producers, their performance in this regard is as follows.

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[252] *ISO 14021:2016. (2016). ISO.* https://www.iso.org/standard/66652.html.

[253] Global Reporting Initiative. (2016a). GRI 301: Materials 2016. In *Global Reporting Initiative*. https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://www.globalreporting.org/pdf.ashx%3Fid%3D12456&ved=2ahUKEwisqfCnn_OMAxVD_rsIHZGEORAQFnoECCEQAQ&usg=AOvVaw1YTAI5dgDOmgzGdajnaI2q.

[254] *The growing demand for recycled aluminium in the circular economy: a sustainable revolution*. (2007). https://www.alcirclebiz.com/blogs/the-growing-demand-for-recycled-aluminium-in-the-circular-economy?utm_source.

[255] The International Aluminium Institute (IAI). (2024). ALUMINIUM RECYCLING. In *The International Aluminium Institute (IAI)*. https://international-aluminium.org/wp-content/uploads/2024/03/wa_factsheet_final.pdf.

1) AMAG (Austria) – 76.1%
2) Hindalco (India), but in its "sustainable" branch named Novelis – 63%
3) Hydro (Norway) – n/a as a net digit, shares that it processed 444'000 tons of secondary post-consumer aluminium, which is among the highest numbers.

4 Recycled Input Rate (per product)

Key considerations about a company's transition to circular economy can be drawn from its *recycled input rate* (RIR), which is defined as « an indicator of the proportion of recycled from new (pre-consumer scrap) and old (post-consumer) scrap contained in the metal produced »[256]. Declined at the company level, the RIR becomes very similar to the share of secondary aluminium, causing an overlap with the previous KPI – mentioned just above in Section 3[257].

As such, to provide a broader picture, this section will instead interpret RIR as the percentage of secondary aluminium contained in the final products, rather than the total amount used by the company. The aim is to highlight the products with the highest recycled content.

4.1 Issues & Solutions

As noted for the previous KPI (Section 3.1), whenever recycled material is mentioned, there hardly ever is a uniform approach to what counts as "secondary" (since the term itself can indicate both *pre-consumer* ("new", industrial scrap) and *post-consumer* ("old") recycled aluminium.

In any case, and as concluded just above, given the lack of more precise reporting on the sourcing of secondary aluminium, for this KPI both definitions are welcomed, so long as there is a clearly quantifiable total secondary input. The differentiation between pre- and post-consumer scarp will be carried out through a dedicated KPI (see Section 5).

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[256] The International Aluminium Institute (IAI), (2024).

[257] While both indicators relate to the role of secondary aluminium in a company's operations, they capture slightly different aspects of circularity. The first KPI – the share of secondary aluminium produced over the total amount – measures a company's overall reliance on recycled material in its production processes. Differently, the recycled input rate (RIR) – in an application coherent with the aim of the KPIs proposed – focuses on the proportion of recycled content specifically embedded in final products, underlining which products are more advanced in terms of recycled composition. While there is some overlap, the RIR provides a more granular, product-level insight, allowing to identify which product lines contribute most effectively to circular economy goals, aim where the overall company's material sourcing falls short on.

4.2 Formula

$$Recycled\ Input\ Rate = \frac{Recycled\ Al\ (New\ Scrap + Old\ Scrap)}{Total\ Output}$$

4.3 Benchmarks

Several key players in the aluminium industry offer very high performances in terms of recycled content, the most ambitious ones including:

1) Hydro (Norway) – 75% of Hydro Circal 75R[258], with a RIR of at least 75% (and a CO2 footprint of 1.9 kg / kg of Al); plus, this product only uses post-consumer scrap.
2) AMAG (Austria) – ≥ 70% of AMAG AL4®ever[259].
3) Alcoa (USA) – 50% corresponding to Alcoa EcoDura[260].

5 Pre- vs Post-Consumer Scrap Rate

As mentioned in Section 3.1, while the most looked at digit is the amount of recycled content in a product, or the amount of recycled (hence secondary) material a producer is involved with, there is so much more behind what qualifies as *recycled*.

In fact, recycled matter can be both pre- and post-consumer material, where the former consists of industrial scrap (such as leftovers from castings, or aluminium recovered from dross) that never went past the gates of the company it was produced at, while the latter is scrap recovered after a first life cycle (hence, post-consumer) and treated accordingly to be reused again.

Naturally, pre-consumer scarp is easier to work with, since it is much like primary aluminium in the first place. Differently, post-consumer scrap is more complex to work with, since it often is mixed with other metals, layered with additional coatings (such as paint), and

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[258] *Hydro REDUXA*. (n.d.). Hydro. https://www.hydro.com/it/global/Alluminio/products/alluminio-a-basso-tenore-di-carbonio-e-riciclato/alluminio-a-bassa-impronta-di-carbonio/reduxa/. Hydro is also developing a REDUXA 3.0 line and another CIRCAL called 100R, both with a RIR of near 100% and an almost inexistent carbon footprint, however it is not on the market yet. *Hydro CIRCAL*. (n.d.). Hydro. https://www.hydro.com/it/global/Alluminio/products/alluminio-a-basso-tenore-di-carbonio-e-riciclato/alluminio-a-bassa-impronta-di-carbonio/circal/.

[259] *Sustainability at every step: AMAG AL4® ever now also offers certified, low carbon primary aluminium | AMAG*. (n.d.). https://www.amag-al4u.com/en/media/press-releases/press-detail/nachhaltigkeit-in-jedem-schritt-amag-al4r-ever-bietet-jetzt-auch-zertifiziertes-co2-armes-primaeraluminium.

[260] *Alcoa -- Sustana*. (n.d.). https://www.alcoa.com/products/sustana.

might require removal of dross caused by natural oxidation of materials; more simply, to work with it once again, post-consumer scarp must be freed from any trace of its past life.

For this reason, companies would rather focus on using what internal pre-consumer scrap they produce than engage in complex processing of post-consumer scrap, or purchase it from someone processing it for them.

It follows that post-consumer thus holds more environmental value, since it essentially was snatched from landfilling.

Therefore, a granular assessment of a company's circularity must consider the difference between the two.

5.1 Issues & Solutions

While this KPI seeks to solve superficial reporting on recycling practices, it still comes with some inherent shortcomings of its own.

First of all, and most importantly, there is limited disclosure on whether the recycled content used is pre- or post-consumer, causing this metric to have limited applicability due to lack of data.

Second, regardless of the type of scrap used, a further dimension adding to the environmental performance of a company is whether the recycled content ends up in a downcycling or an upcycling route[261].

Lastly, it is also critical to understand if recycled aluminium (regardless of whether it is pre- or post-consumer) is displacing primary aluminium, or merely adding to its overall production.

Still, given how forward-looking this KPI is, all the issues associated with it may as well be overlooked or evaluated qualitatively, since – given current practices – data about scrap sporting is to be appreciated.

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[261] When a recycled material is transformed into a product of lower quality or value, less durable or no longer recyclable at the end of its life, it is called downcycling; its exact opposite is upcycling, which is when the material is transformed into a product of greater value or with a different and lasting function, maintaining or increasing its value. For example, many automotive parts are made out of recycled aluminium, which, while initially sounding sustainability-aligned, implies that such recycling will likely be the last for said aluminium, since automotive parts are rarely ever recycled due to dismantlement difficulties. Veracura. (2021, September 8). *Recycling, upcycling, downcycling: quali sono le differenze?* Veracura. https://veracura.network/recycling-upcycling-downcycling/.

5.2 Formula

$$Pre - Consumer\ Scrap = \frac{Pre - Consumer\ Scrap\ used}{Total\ Scrap\ used} \times 100$$

$$Post - Consumer\ Scrap = \frac{Post - Consumer\ Scrap\ used}{Total\ Scrap\ used} \times 100$$

5.3 Benchmarks

While many companies engage in operations with recycled material, few of them have clear reporting of its pre- or post-consumer nature. The best performances in this regard are:

1) Hydro (Norway) – 59.9% of pre-consumer scarp (443,760 tons), and 40.1% of post-consumer scrap (662,280 tons)
2) Constellium (France) – 61.9% pre-consumer scrap (396,760 tons), and 38.1% of post-consumer scrap (244,160 tons)
3) Alcoa (USA) – n/a as a clear cut number, only shared that out of the scrap they use, 42% (237,720 tons) is internal pre-consumer scrap, but there are no specifics on the composition of the remaining 58% (328,280 tons) they purchase from external entities.

RESOURCE EFFICIENCY KPIs

Introduction

Among the most critical aspects to monitor is the ability of a company to optimize resource use – particularly through recycling and closed-loop systems: given growing resource constraints – especially for precious materials such as aluminium – poor management of material flows not only weakens operational efficiency but also exposes firms to a range of financial risks: these include regulatory penalties, litigations over improper waste disposal or land use, and all relative reputational damage. Furthermore, inefficient resource usage may hinder access to specific funds, financing, and investment opportunities. Accordingly, it is natural for financial institutions to be concerned with a company's resource circularity, as it is a predictor of long-term financial stability and legal resilience.

In fact, and as discussed in Chapter 4, the aluminium production chain implies the consumption of precious resources (like water and energy), as well as the generation of several byproducts, the main ones of which are bauxite residue, carbon anodes, and aluminium dross.

Accordingly, this chapter concludes by proposing other five KPIs to evaluate how efficiently the largest aluminium producers on the global market use their resources. The KPIs proposed are Bauxite Residue (Section 6), Water Consumption (Section 7), Carbon Anodes (Section 8), Aluminium Dross (Section 9), and Energy (Section 10): the last section on energy is divided in Total Energy Consumption (10.1), Share of Renewable Energy (10.2), and Energy used in the Electrolysis (10.3).

6 Bauxite Residue (per ton of aluminium produced)

Bauxite residue, commonly known as red mud (which, however, as shown in Chapter X can also be white) is one of the most voluminous and problematic waste streams in the aluminium industry.

On average, for every ton of alumina produced 2 or 3 tons of this highly alkaline byproduct are generated[262] – creating massive environmental liabilities for producers. However, there are many potential ways to reintroduce bauxite residues in the production cycle – whether it be the within the production of aluminium itself, or a whole new product: this aspect is analyzed more closely as shown in Chapter 5, Section 1.3 (1.3 Recycling Flows).

6.1 Issues & Solutions

To begin with, the amount of bauxite residue is far from being a standardized metric, causing it to be almost rare to spot in sustainability reports. This is mainly because many aluminium producers are not directly responsible for the mining of bauxite, which is often purchased from a delocalized third-party miner, leading to the immediate consequence of hardly ever finding data – since it does not fall under the company's direct operations.

Second, bauxite is produced only in the manufacturing of primary aluminium, while companies usually disclose the amount of bauxite residue over the total amount of aluminium produced – both primary and secondary one – causing the digit to be "watered down" by secondary aluminium manufacturing.

[262] McLean *et al.* (2017).

Yet, given the growing diffusion of certification schemes like the ASI Chain of Custody Standard (analyzed in Chapter 2), finding data about bauxite residue is becoming increasingly easier.

6.2 Formula

$$Bauxite\ Residue\ (\frac{tons}{tons}) = \frac{Total\ Amount\ of\ Bauxite\ Waste\ Generated}{Total\ Amount\ of\ Al\ Manufactured}$$

6.3 Benchmarks

Before presenting benchmarks, it is important to note that many of the analyzed companies do not engage in upstream operations, meaning that they lack data about mining and relative resources, since they rely on third parties providing already refined alumina; specifications about each company's role along the aluminium value chain are provided in Appendix 1 on Company Benchmarks.

Still, two companies managed to provide accurate data on bauxite residue, and they are:

1) Century Aluminium – 1.65 metric tons / metric ton of alumina produced
2) Alcoa (USA) – 1.79 metric tons / ton of alumina produced

7 Water (per ton of aluminium produced)

Water is a critical input throughout the aluminium production chain, from bauxite mining and alumina refining to smelting and casting: the industry relies on large volumes of water for ore washing, cooling, slurry transportation, electrolysis cell maintenance, and residue storage systems.

On average, between 9.8 (without China, whose energy mix at the time of the study had a significant impact on the indirect water footprint) and 18 m^3 of H2Oe are consumed per ton of aluminium produced[263]. However, we can further explore this indicator by breaking it down into the following categories:

a) Direct water consumption – the freshwater used directly in bauxite mining, alumina refining, and aluminium smelting

[263] Buxmann, K., Koehler, A., & Thylmann, D. (2016). Water scarcity footprint of primary aluminium. *The International Journal of Life Cycle Assessment*, *21*(11), 1605–1615. https://doi.org/10.1007/s11367-015-0997-1.

b) Indirect water consumption – water used in the production of electricity consumed by the aluminium industry, particularly evaporation from hydropower reservoirs (which in the study cited above was identified as a significant contributor)

And by adding

c) Water scarcity index – a measure assessing the potential negative impact of water usage in a specific area by considering both the amount of water consumed and the local availability of water resources, highlighting potential stress on limited water supplies.

7.1 Issues & Solutions

While apparently straightforward, water consumption also comes with several pitfalls.

First and foremost, the more the details – such as direct and indirect consumption and water scarcity index – the better the picture: net consumption only fails to represent important aspects including the sourcing of water, its quality and whether it is later on reused / recycled.

However, all of the above can be solved by detailing the water consumption figure into its relevant dimensions, making sure they cover all parts of the supply chain. Coherent with this view is ISO 14046:2014 (Environmental management – Water footprint – Principles, requirements and guidelines)[264], providing a recognized framework for a cradle-to-gate (or cradle-to-grave) assessment of water footprint.

7.2 Formula

$$Water\ Consumption\ (\frac{m^3}{tons}) = \frac{Total\ Amount\ of\ Water\ Consumed}{Total\ Amount\ of\ Al\ Manufactured}$$

7.3 Benchmark

The best- performing companies in terms of water consumption are:

1) Century Aluminium – 2.35 m^3 / ton of aluminium
2) AMAG (Austria) – 5.7 m^3 / ton of aluminium
3) Constellium (France) – 1.4 m^3 / ton of aluminium shipped (however, Constellium is put in third place since such a low digit is likely due to the downstream operations of the company, hence “aluminium shipped” rather than “produced”)

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[264] *ISO 14046:2014*. (n.d.). ISO. https://www.iso.org/standard/43263.html.

8 Carbon Anodes

Consumption of carbon anodes can be an insightful KPI, as it is a direct proxy for the efficiency and sustainability of the electrolysis process, which uses the most electricity.

8.1 Issues & Solutions

The issue related to carbon anodes' consumption is one and one only: the limited availability of this digit.

On the one hand, this tendency is due to the lack of standardised reporting on such a number. While inherently easy to obtain as a digit – especially compared to more difficult metrics such as emissions – the consumption of carbon anodes is rarely mentioned in reports, and this is most likely because it does not fall under mandatory reporting.

On the other hand, not all aluminium producers – and especially EU based ones – are involved with the entirety of the value chain: this means that carbon anodes are not processed, and therefore any kind of reporting by upstream manufacturers is entirely optional.

Yet, while whole supply chain reporting is optional for waste materials such as carbon anodes, the same is not true for emissions. So, in a sense, to fill the lack of data on carbon anodes, companies can report the emissions deriving from the Hall-Héroult electrolysis (in which carbon anodes are consumed). More specifically, this process emits perfluorocarbons (PFCs, as mentioned in Chapter 5) whose global warming potential is much greater than that of C02; as such, a CO2e emission accounting will be able to better grasp the impact of what remains the most energy-intensive step in the whole aluminium chain.

8.2 Formula

$$Anode\ Consumption\ (\frac{kg}{tons}) = \frac{Total\ Amount\ of\ Anodes\ Consumed}{Total\ Amount\ of\ Al\ Manufactured}$$

8.3 Benchmarks

As anticipated, unfortunately, there is very limited reporting on the consumption of carbon anodes, and of the few companies that did report on the subject, none managed to provide any numerical data.

9 Aluminium Dross

Aluminium dross is a byproduct generated during primary smelting and secondary remelting processes of aluminium: it mainly consists of aluminium oxides, entrapped metals and other impurities.

Depending on each company's operational efficiency, between 9 and 91% of aluminium input can be lost as dross[265].

While historically labelled as a waste requiring disposal, dross has progressively been recognized as a potential input for further production rounds, allowing for recovery of substantial amounts of oxidized aluminium otherwise permanently lost.

9.1 Issues

The main issue with regards to aluminium dross lies in the lack of harmonized measurement standards: companies often fail to disclose it separately in sustainability reports, either merging it into broader "waste" categories or omitting it entirely.

Further major complications arise because the amount of dross generated depends on the specific type of operation: remelting of secondary aluminium tends to be more dross-intensive compared to primary smelting – yet, many companies aggregate the overall dross digit, masking actual operational efficiency.

Moreover, inconsistencies arise from different practices in dross treatment, while some producers reprocess dross internally, others externalize it to specialized recyclers, which may lead to underreporting or double counting – depending on the scope of the company's report.

9.2 Solutions

Leaving aside all considerations related to the accuracy of measurements for the time being, mere reporting of a single (even of aggregated) dross digit still stands as the industry's best practice.

Nevertheless, the growing attention to material circularity – encouraged by standards

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[265] Taylor, J. A., Prakash, M., Pereira, G., Rohan, P., Lee, M., & Rinderer, B. (2009). Predicting DROSs formation in aluminium melt transfer operations. *Materials Science Forum*, *630*, 37–44. https://doi.org/10.4028/www.scientific.net/msf.630.37; Kelly, S., Apelian, D., Center for Resource Recovery and Recycling (CR3), Metal Processing Institute, & Worcester Polytechnic Institute. (2021). Automotive Aluminium recycling at End of Life: A grave-to-gate analysis. In *Aluminium.org*. https://www.aluminium.org/sites/default/files/2021-10/Final-Report-Automotive-Aluminium-Recycling-at-End-of-Life-A-Grave-to-Gate-Analysis.pdf?.

such as the ASI Performance Standard and growing CSRD requirements – is gradually pushing aluminium producers towards more transparent and granular waste reporting, including more specific figures for dross generation and recovery.

Until a uniform dross reporting approach emerges (ideally one that is differentiated per product and operation type, to respond to the issues presented just above), reporting of a single number will be more than enough to satisfy current requirements.

9.3 Formula

$$Aluminium\ Dross\ (\frac{kg}{tons}) = \frac{Total\ Amount\ of\ Dross\ Generated}{Total\ Amount\ of\ Al\ Manufactured}$$

9.4 Benchmarks

Unfortunately, data on dross generation is very limited, and when available, it is presented in many ways based on the information the company has. Nonetheless, three of the ten examined companies presented data about it, and they share the following information:

1) Vedanta (India) – claims the highest reuse rate, reporting that 98% of their dross is reused. This indicates a strong commitment to minimizing waste and maximizing resource efficiency
2) Hindalco (India) – reports a 91% utilization rate of dross.
3) ALBA (Bahrein) – reports 20.7 kg of dross per metric ton of molten aluminium, with 98% of dross recycled or recovered internally; while the recovery rate is high, the kg / ton metric makes it less directly comparable to the utilization rates of the other two.

10 Energy

As mentioned already in Chapter 5 Section 1.4 on 1.4 Energy, aluminium production is among the most energy-intensive industrial activities; the major driver of this tendency is the Hall-Héroult electrolysis, in which alumina is transformed in aluminium (as shown in Chapter 5 Section 1.1.2 on Electrolytic Reduction – the Hall-Héroult Process).

On average, producing one ton of primary aluminium requires between 13 and 17 MWh[266]. However, this hard-to-abate sector still holds significant potential for reducing its environmental impact. To do so, two main strategies emerge: first, by increasing the share of

[266] Brough, D., & Jouhara, H. (2020). The Aluminium Industry: A review on state-of-the-art technologies, environmental impacts and possibilities for waste heat recovery. *Science Direct*, *1–2*. https://www.sciencedirect.com/science/article/pii/S2666202719300072.

secondary (recycled) aluminium[267] (as discussed in Section 3 of this Chapter), and second, by shifting the energy supply used from fossil fuels to renewable energy sources[268].

Accordingly, in the following section, three energy KPIs are proposed: the first focuses on Total Energy Consumption (10.1), while the second looks at the Share of Renewable Energy (10.2); lastly, the third underlines the Energy Consumption of the Hall-Héroult Electrolysis only (10.3), to allow considerations of companies' efficiency in their most energy-demanding step.

10.1 Total Energy Consumption

Total energy consumption measures the overall energy input required to produce one ton of aluminium, encompassing all stages from alumina refining to smelting and casting.

10.1.1 Issues & Solutions

A major challenge in using total energy consumption as a KPI lies in the inconsistency of data boundaries: some companies report only direct energy used in smelting, while others include upstream activities such as mining and alumina refining.

Additionally, energy source differentiation (renewable vs fossil-based) is often unclear, limiting the KPI's ability to fully reflect sustainability performance – as discussed in the following section.

To address these issues, companies should adopt standardized reporting frameworks like GRI 302-1[269] and clearly disclose both the operational boundaries and the energy mix associated with their consumption figures.

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[267] This could lower the energy consumption to only 0.8 MWh according to The International Aluminium Institute. International Aluminium Institute. (2024, September 19). *1.5 degrees scenario: A model to drive emissions reduction - International Aluminium Institute*. https://international-aluminium.org/resources/1-5-degrees-scenario-a-model-to-drive-emissions-reduction/.

[268] Such as hydropower, which currently powers a large share of global aluminium production and 92.7% of European smelting operations. Svendsen, A. (2023b, March 8). *The shift toward renewable power in aluminium smelting - Light Metal Age Magazine*. Light Metal Age Magazine. https://www.lightmetalage.com/news/industry-news/smelting/the-shift-toward-renewable-power-in-aluminium-smelting/.

[269] Global Reporting Initiative. (2016). GRI 302: Energy 2016. In *Global Reporting Initiative*. https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://globalreporting.org/pdf.ashx%3Fid%3D12467%26page%3D8&ved=2ahUKEwiz5OvPsfiMAxWQhv0HHawkFAwQFnoECCcQAQ&usg=AOvVaw2fQ4FkU7kGPFJ0C-o7f0QN.

10.1.2 Formula

$$Energy\ Consumtion(\frac{MWh}{tons}) = \frac{Total\ Energy\ Consumed}{Total\ Amount\ of\ Al\ Manufactured}$$

10.1.3 Benchmarks

Among the ten companies analyzed, the three best performing ones in terms of total energy consumption are:

1) AMAG (Austria) – 4.26 GJ / ton of aluminium (1.184 MWh / ton of aluminium)
2) Constellium (France) – 12.7 GJ / ton of aluminium produced (3.53 MWh / ton of aluminium)
3) Hydro (Norway) – 50.5 GJ / ton of aluminium (14.03 MWh / ton of aluminium)

10.2 Renewable Energy Share

Renewable Energy Share tracks the proportion of a company's total energy consumption that comes from renewable sources, such as hydroelectric, solar, and wind energy.

10.2.1 Issues & Solutions

A key limitation of the renewable energy share is the lack of uniform definitions: companies may inconsistently categorize what constitutes "renewable" (like including biomass or large-scale hydro without transparency).

Furthermore, some entities report purchased renewable energy certificates (RECs) without proving physical energy consumption changes, creating a gap between reporting and reality.

To mitigate these risks, firms should align their disclosures with standards such as the GHG Protocol's Scope 2 Guidance[270], and prioritize traceable, verifiable renewable energy sourcing over market-based-only instruments.

10.2.2 Formula

$$Renewable\ Energy\ Share\ (\%) = \frac{Renewable\ Energy\ Purchased}{Total\ Energy\ Purchased}$$

[270] *Scope 2 Guidance | GHG Protocol*. (2015, January 1). https://ghgprotocol.org/scope-2-guidance.

10.2.3 Benchmarks

The three best performing companies respective to renewable energy share are:

1) RUSAL (Russia) – ≥ 99% thanks to proximity to hydropower installations
2) Alcoa (USA) – 87%
3) Rio Tinto (UK, Australia) – 78%

10.3 Energy for Electrolysis

Energy consumed in electrolysis quantifies the electrical energy required to separate alumina into aluminium and oxygen within the electrolytic cells (Hall-Héroult process); this KPI's relevance lies in the fact that the electrolysis is the most energy-intensive stage in aluminium production, accounting for the largest share of the industry's overall energy demand and associated greenhouse gas emissions.

10.3.1 Issues & Solutions

A key challenge in comparing energy consumed in electrolysis data arises from variations in reporting boundaries and methodologies.

Discrepancies primarily occur when companies include or exclude energy consumed by ancillary processes, when they use different cell technologies, or when they have different anode types, such as carbon vs inert anodes.

Furthermore, the lack of granularity in reporting (averaging across plants with varying efficiencies) can obscure best practices and hinder accurate benchmarking.

To enhance comparability and transparency, companies should provide detailed breakdowns of energy consumption by smelting technology, production line and plant, aside from adhering to standardized reporting protocols – replicating the reporting practices in place for energy consumption in general would be more than enough for appropriate benchmarking.

10.3.2 Formula

$$Energy\ for\ Electrolysis = \frac{Total\ Energy\ Consumed\ for\ Electrolysis}{Total\ Aluminium\ Produced}$$

10.3.3 Benchmarks

Lastly, the three best performances in terms of energy consumption during the electrolysis process are:

1) Hydro (Norway) – 14.03 MWh / ton of alumina (identical to total energy consumption, since Hydro is only a smelter)
2) Rusal (Russia) – ≤ 12.8 MWh / ton of alumina
3) AMAG (Austria) – ≤ 15.5 MWh / ton of alumina (via Alouette, its smelter)

Findings

This chapter aimed to identify metrics (KPIs, in fact), which could dig deep into the business practices of aluminium manufacturers. The goal is surely most certainly that of identifying greenwashing-proof metrics capable of capturing the exposure to climate change related risks of companies, especially in terms of transition risks due to policy misalignment or failure to meet pledges undertaken.

Where companies disclose their emission reductions as percentages, or targets, physical emission intensities and Scope 1 + 2 alignment (KPIs 1 and 2) are needed to ensure comparability and context, since the former, by themselves, say little: a meaningful emission-related disclosure needs to be anchored to sectoral benchmarks, physical output units and science-based trajectories.

Where companies claim their engagement in secondary aluminium production, differentiating between overall share of secondary metal produced, recycled input rate in its products, and specifications about whether the material used is pre- or post-consumer scrap (respectively, KPIs 3, 4, and 5) is essential to ensure circularity claims are grounded, and not just in semantics.

Lastly, there are a variety of parameters that are rarely looked at (bauxite residue, water, dross, carbon anodes, and energy consumption) that reflect the materiality of the aluminium value chain far beyond carbon accounting. These indicators (KPIs 6 to 10) capture the environmental intensity of production processes, highlighting potential hotspots of pollution, inefficiency, or resource depletion.

Subject to a third-party analysis by industrial experts, based ton available literature, the identified KPIs could constitute a fair assessment of an aluminium manufacturer's performance. The real issue is that for an average manufacturer, measurement – and much less disclosure – of these quantitative indicators would be an exception rather than a rule.

As noted several times in this chapter, and as shown by the company benchmarks in the Appendix, any thorough evaluation that goes beyond emission reporting inevitably runs into the issue of the quality and potential "sweetening" of data published by companies. In fact, on the one hand, established metrics are often inflated or manipulated to overstate actual performances[271], while on the other, there is a limited amount of data regarding more niche digits (especially "physical" ones like material flows of waste).

However, there are entities entirely dedicated to the debunking of environmental claims by large "committed" companies, such as BankTrack[272], whose focus is exposing banks' financial support towards unsustainable solutions.

While limited, incomplete, or inflated reporting is legitimate, it is not the central focus of this analysis; that is – rather – to delineate the boundaries of what is climate-aligned yet technically, operationally and economically feasible; for the transition to happen, companies must remain capable of meeting market demand. In other words, becoming sustainable does not deny operational efficiency, as aluminium producers must go beyond feasibility margins to reinvest in technological and progress innovation.

The KPIs developed, as well as their benchmarks and identified risk thresholds, aim exactly at this purpose, that is, identify what a company can afford to aspire to.

In addition to this, inflated claims are not – at this stage – a determining issue: if anything, having companies compete over who can present the most ambitious environmental narrative may even be beneficial in terms of "raising the bar" – of course, when the narrative is also matched by the company's numbers. Plus, external control and standardisation mechanisms exist and are being strengthened – from initiatives such as TPI and SBTi, to certifications such as ASI, to the role of independent auditors – and lack of adherence to a recognized science-based framework, is in itself an answer.

Fundamentally, this thesis asserts that financial institutions exert a significant, albeit indirect, influence on the environmental performance of companies, as they are obligated to maintain their support. And regardless of the quality of the reported baseline, it will be banks bringing their customers into line, because they are crucially exposed to the sum of all their risks.

More simply, firms – fully aware of the growing importance of sustainability in their financial exposure – are incentivised to present increasingly ambitious transition plans, and while some of these statements might be too optimistic, they still contribute to collectively raising the bar.

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[271] One might observe, for example, the Indian group Hindalco "dilutes" its environmental impact with the great performance of its subsidiary Novelis, sharing averaged data whose impact is lowered by a recycling specialist.
[272] *home*. (n.d.). Banktrack. https://www.banktrack.org/.

And while this may generate scepticism about the immediate feasibility of commitments made, this dynamic – as a side effect – subjects the entire industry to a greater level of attention and expectations; this, in the medium to long term, can catalyse real improvements.

Chapter 8 – *Sustainable Banking and Finance*

Introduction

As discussed in the previous two chapters, despite clear international and European targets guiding businesses' responses to the climate crisis, companies remain focused on short-term value, delaying the necessary transformations for long-term resilience to tomorrow. This phenomenon is also known as short-termism[273].

What is needed is a driver other than simple "legality" (given the limits imposed by jurisprudence) that can stimulate in companies the compulsion to stop procrastinating the transition to tomorrow. It is no surprise that money can really change the tradeoff between present and future value.

However, companies' need for liquidity is only superficial, for underneath these dynamics lie the commitments of financial institutions to ensure the stability of the entire system and its resilience to climate change and the risks that come with it.

In fact, the delay in implementing credible transition strategies – by both regulators and companies – exposes the financial system to significant systemic risks[274].

In 2015, Bank of England governor Mark Carney stated that climate change can profoundly affect asset prices and financial stability[275], and the lack of early preventive action increases the likelihood of abrupt and disorderly adjustments. These can manifest through the sudden repricing of carbon-intensive assets[276], regulatory clampdowns, or loss of market

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[273] Defined as « an excessive focus on short-term results at the expense of long-term interest » (CFA Institute Research and Policy Center, 2019). This word indicates the overall tendency to overestimate the value of now compared to that of the future, as if our future scenarios are an entirely different matter we are not concerned with. This phenomenon is also known as present bias in behavioral sciences. *Short-Termism*. (2019, October 29). CFA Institute Research and Policy Center. https://rpc.cfainstitute.org/policy/positions/short-termism.

[274] « Physical and transition risks [explained in Sections 3.2 and 3.3] can adversely affect financial institutions through, for example, losses in the value of financial portfolios, increases in claims paid by insurers, or decreases in the creditworthiness of borrowers. These shocks can pose a threat to financial stability if they occur simultaneously or if an extreme shock is transmitted to other institutions through the network of financial interconnections. We refer to these threats to the financial system emanating from climate risks as "systemic climate risks". Jourde, T., & Moreau, Q. (2022). Systemic climate risk. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.4300469.

[275] *Breaking the tragedy of the horizon - climate change and financial stability - speech by Mark Carney*. (2025, March 25). Bank of England. https://www.bankofengland.co.uk/speech/2015/breaking-the-tragedy-of-the-horizon-climate-change-and-financial-stability.

[276] Gitterman Asset Management & entelligent. (2023). *The Great Repricing: Financial advice in the age of climate change*. One Earth Community. https://assets.takeshape.io/86ce9525-f5f2-4e97-81ba-54e8ce933da7/dev/9879741e-9edd-433c-b03c-5152b2c75c8b/Great-Repricing-Report.pdf.

confidence, all of which can trigger cascading effects across financial institutions, portfolios, and markets.

Furthermore, the "opacity" of corporate transition plans and the absence of harmonized disclosure standards hinder proper risk assessment, leading to potential misallocation of capital and underestimation of climate-related exposures[277].

This is what prevents sustainable banking, embedding climate models, data, and regulatory clarity to anticipate and absorb transition shocks well before they escalate into systemic crises.

1 Sustainable Banking

Sustainable banking can be defined as "*a decision by banks to provide products and services only to customers who consider the environmental and social impacts of their activities*"[278]: building onto this definition, sustainable banking basically enables financial transactions whose credit decision is based on the environmental and social performance of customers. However, committing to sustainable banking requires more than just offering tailored financial products – it demands concrete efforts to align portfolios with sustainability targets. « Committing to align portfolios with net zero by 2050 is a welcome market signal – but the material question remains where banks intend to be 1, 5, or 10 years toward that goal. In other words, you've announced where you're going, but how will you get there? The interim details matter, because turning ambition into action […] means translating long-term 2050 targets into near-term milestones relevant for financial decision-making today. Further, staying within the bounds of our global carbon budget over time requires meeting certain emissions reduction milestones at certain times on our way to zero. Interim targets are therefore essential for assessing the shape of banks' emissions trajectories » [279]: this is where the Net Zero Banking Alliance steps in.

As the world-leading coalition in sustainable banking, the Net Zero Banking Alliance (NZBA)[280] provides a comprehensive framework to guide banks in aligning their operational

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[277] Directory, S. (2025b, April 24). *Financial opacity → term*. Sustainability Directory. https://sustainability-directory.com/term/financial-opacity/.
[278] Bouma, J. J., Jeucken, M. H., & Klinkers, L. (1999). Introduction: Sustainable Banking: The Greening of Finance. *Greener Management International*, *1999*(27), 5–6. https://doi.org/10.9774/gleaf.3062.1999.au.00003.
[279] Slanger, D., Mann, W., & Bhat, S. (2022, March 2). *How the Net-Zero Banking Alliance Helps Banks Set Interim Emissions Targets*. RMI. https://rmi.org/how-the-net-zero-banking-alliance-helps-banks-set-interim-emissions-targets/.
[280] *Net-Zero Banking Alliance*. (n.d.). https://www.unepfi.org/net-zero-banking/.

and attributable emissions with the goal of achieving Net Zero emissions by 2050. However, in April 2025, the NZBA revised its core principles, softening its commitment to 1.5° C-aligned lending and capital investments for 2050 from mandatory to encouraged ("banks are recommended to")[281].

To do so, the NZBA establishes four guidelines[282]:

i. Banks shall individually and independently set and publicly disclose long-term (2050) and intermediate (2030) targets to support meeting a Net Zero by 2050
ii. Banks shall establish an emission baseline and annually measure and report the emissions profile of their lending, investment and capital market activities
iii. Banks shall use widely accepted science-based decarbonization scenarios to set both long-term and intermediate targets that are aligned with a Net Zero scenario by 2050 goal
iv. Banks shall regularly review targets to ensure consistency with current climate science.

In other words, aside from internal management of their Scope 1 and 2 emissions, the main contribution banks can make to achieving Net Zero is the gradual reduction of their financed or attributable emissions (Scope 3)—explained in Table 6 and in the following section.

Table 6: Unpacking the concept of the total emissions of a bank among its Scope 1, 2 and 3[283]

Emission Type	Definition	Example
Scope 1 (Direct Emissions)	Covers emissions from sources that an organization owns or controls directly	Office heating and cooling
		Company owned vehicles
Scope 2 (Indirect Emissions)	Indirect emissions caused by the energy the bank buys	Emissions caused by the production of electricity

[281] Segal, M., & Segal, M. (2025, April 16). *Net Zero Banking Alliance Drops Requirement to Align Financing with 1.5°C*. ESG Today. https://www.esgtoday.com/net-zero-banking-alliance-drops-requirement-to-align-financing-with-1-5c/; United Nations Environmnt Programme & Net Zero Banking Alliance. (2025). Guidance for Climate Target. In *Version 3*. United Nations Environment Programme. https://www.unepfi.org/wordpress/wp-content/uploads/2025/04/Guidance-for-Climate-Change-Target-Setting-Version-3.pdf.
[282] United Nations Environmental Programme (UNEP) & Net Zero Banking Alliance (NZBA). (2024). Guidelines for Climate Target. In *United Nations Environmental Programme*. United Nations Environmental Programme. https://www.unepfi.org/wordpress/wp-content/uploads/2024/03/Guidelines-for-Climate-Target-Setting-for-Banks-Version-2.pdf.
[283] *What are scope 1, 2 and 3 carbon emissions? | National Grid*. (n.d.). https://www.nationalgrid.com/stories/energy-explained/what-are-scope-1-2-3-carbon-emissions.

Scope 3 (Value Chain Emissions)	Indirect emissions from business operations, including investment	Employees work-related movement
		Financed (or attributable) Emissions

1.1 Financed Emissions

To operationalize and quantify the environmental impact of their financial relationships, banks use “financed emissions”, which represents the portion of emissions by client companies attributable to the financing received from the bank.

The Financed Emissions of a bank are calculated according to the formula

$$Financed\ Emissions = \sum_i attribution\ factor_i \times emissions_i$$

$$\text{where } attribution\ factor_i = \frac{Outstanding\ amount_i}{Total\ equity + debt_i}$$

which refers to the borrower’s or investee’s share of total emissions allocated to the loan or investment, specific to that asset class[284].
Another interesting figure for banks building their Net Zero pathway is the Carbon Intensity of a Loan (CLI), calculated according to the formula[285]

$$LCI_{s,t} = \frac{E_{s,t}}{L_{s,t}}$$

$$\text{where } E_{s,t} = emissions\ of\ sector\ s\ at\ time\ t$$

$$\text{and } L_{s,t} = outstanding\ loans\ of\ sector\ s\ at\ time\ t$$

But once these data are obtained, what should a bank do with them? What should – practically speaking – be the agenda of a bank seeking to align its portfolios with decarbonization targets? The McKinsey paper “Managing financed emissions: How banks can support the net-zero transition” discussed in the following section provides an operational

[284] Partnership for Carbon Accounting Financials (PCAF). (2022). Financed emissions: The Global GHG Accounting and Reporting Standard Part A: Financed Emissions. Second edition. In *Partnership for Carbon Accounting Fianancials (PCAF)*. https://carbonaccountingfinancials.com/files/downloads/PCAF-Global-GHG-Standard.pdf.
[285] *Carbon footprint of bank loans*. (n.d.). https://climatedata.imf.org/datasets/596f11fea29d429ba6c5507e3756a751_0/about.

framework responding to this question, outlining a six-step process to turn emission baselines and targets into everyday business actions.

2 What should a bank do?

According to the paper by Mc Kinsey[286], banks can support Net Zero by following a six-step process (Chart 11 below).

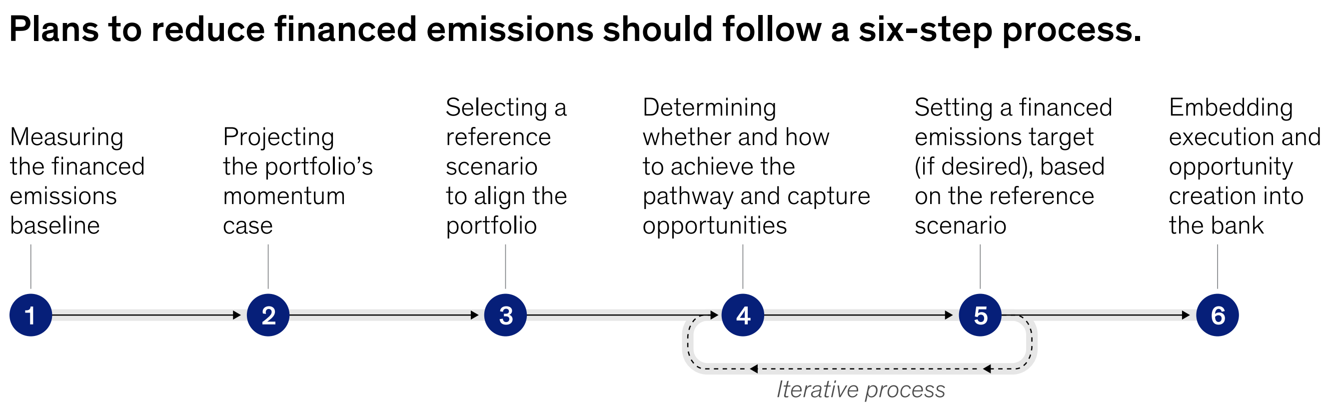

Chart 12: The six-step process to manage financed emissions[287]

Upon closer examination of the image above, a bank aligned with Net Zero should follow these steps.

2.1 Step 1: Measuring the financed emissions baseline

The first step for a bank is to establish a clear baseline of its financed emissions – explained just above in Section 1.1. This practically implies the unpacking of the portfolio into the different sectors the bank is involved with, calculating how much each one is emitting by combining the reports of each company operating within it. This step needs to be carried our considering:

i. All parts of the value chain
ii. All GHGs, not only CO_2, quantifying other emissions as CO_2e
iii. All three emission scopes

[286] Azoulay, M., Casoli, A., Kansy, T., Mikkelsen, D., Muvezwa, M., Stephens, D., Underwood, S., & Venugopal, S. (2022, November 24). *Managing financed emissions: How banks can support the net-zero transition*. McKinsey & Company. https://www.mckinsey.com/industries/financial-services/our-insights/managing-financed-emissions-how-banks-can-support-the-net-zero-transition.
[287] See Note 69.

iv. All asset coverages, which as of now have been identified by the Partnership for Carbon Accounting Financials (PCAF)[288]. However, a bank's coverages may extend further, so each partnership should be considered closely.

Furthermore, all the above should be done using the most accurate and latest available data (signaling specific trends, such as the pandemic or the 2022 energy crisis), considering the legal entity to which the emissions are attributed along the whole supply chain (as suppliers often are delocalized).

However, financed emissions as a metric must face an inevitable limit: they belong to the financial economy, and as such, they do not necessarily grasp real-economy dynamics. To be more specific, since they are calculated based on the money involved (in €) instead of the actual amount of emissions from activities, they can easily be affected by inflation, changes in value, and fluctuations in carbon prices under systems like the EU ETS. As a result, from a risk management and prudential perspective, banks cannot trust this metric blindly to assess a client's climate alignment: financed emissions need to be complemented with additional metrics and sector-specific KPIs that can capture the actual technological, operational, and transition-readiness profile of each counterparty.

2.2 Step 2: Projecting the Portfolio's Momentum Case

Secondly, « banks should build […] a view about what will happen to a given sector or given counterparty […]. The momentum case is essentially the unmanaged outcome: if the bank continued to finance its current counterparties at the current rate, what would its financed emissions be next year, in 2025, and in 2030? The momentum case is based on counterparties' announced targets and aspirations, industry and asset-level forecasts, and announced government policies and targets. Banks can also create bespoke scenarios and simulate sensitivities within the portfolio (for example, counterparties drawing on their lending facility, or counterparties missing their announced targets)»[289]. Most evidently, banks need to consider:

i. Realistic changes to the trajectory, especially when announced transition pathways are not credible

[288] Partnerships for Carbon Accounting Financials has identified the following asset classes: listed equities and corporate bonds, business loans and unlisted equities, project finance, commercial real estate, mortgages, and motor vehicle loans; draft methods have also been published for green bonds, sovereign bonds, and emissions removals. New guidance and methods for public consultation. (2024). In *Partnerships for Carbon Accounting Financials (PCAF)*. Partnerships for Carbon Accounting Financials (PCAF). https://carbonaccountingfinancials.com/files/2024-consultation/PartA-Methods2024-Master-01-1.pdf.
[289] See Note 69.

ii. Technological advancements specific to the sector (for example, in the aluminium industry inert anodes are scored as TRL 4 – 5, meaning that they are likely going to be available on the broader market in 2030)

iii. Governmental policies that could affect the trajectory, such as reducing EU ETS emission caps, increasing carbon prices and enforcement of announced policies.

To properly incorporate these variables into a robust momentum case, banks must act on three levels.

First, by updating both the emissions baseline and the portfolio trajectory according to the chosen climate scenario – typically the IEA Net Zero by 2050 scenario.

Second, by embedding in their risk and governance structure a set of climate-aligned KPIs that reflect sector-specific technological readiness and the alignment (or misalignment) of counterparties with evolving policy frameworks – this, specifically, is the precise focus of this thesis and is discussed in Chapter 8 where the sector chosen, as anticipated, is aluminium manufacturing.

Last, and most critically, banks must integrate these dynamic considerations into their actual risk modelling and decision-making processes – again, the primary question this thesis seeks to address, which is dealt with in Chapter 9.

2.3 Step 3: Selecting a Reference Scenario to Align the Portfolio

Once the momentum case is settled, the bank can understand what it would take to align each sector in the portfolio with the Paris Agreement temperature goals. However, there is more than one Paris-aligned reference scenario (as shown in Chapter 2), each corresponding to a more or less ambitious pathway: for instance, targets often either aim at well below 2°C or at 1.5°C, with this half degree making a huge difference in terms of a bank's portfolio transition speed. Based on the temperature ambition selected, the banks should choose sector-specific reference scenarios from organizations to guide their target setting. Since standard scenarios may lack sectoral or geographic detail, some banks "augment" these models by incorporating more specific data that aligns with their portfolio and strategic priorities.

Within this context, the most widely recognised reference is the IEA Net Zero Emissions by 2050 (NZE) scenario, which has already been mentioned several times. As outlined in the EBA's Implementing Technical Standards, financial institutions operating in the EU are expected to adopt this scenario as their main benchmark for climate alignment.

More in detail, these documents offer a detailed pathway across sectors and regions, including emission intensity reduction curves that can be translated into client-level targets and KPIs.

2.4 Step 4: Determine whether and how to achieve the pathway and capture opportunities

Once a bank has established its financed emissions baseline, developed a momentum case, and selected a reference scenario, it must determine whether and how to align with that scenario for each sector. This decision-making process requires a realistic feasibility assessment, considering business constraints and strategic trade-offs. A successful transition pathway requires:

i. A deep understanding of targets' potential impact on the business that also considers the weight of financial measures – on both the bank and its clients
ii. Involvement of the business and risk-evaluation, ensuring leading figures from each sector provide explanation of trade-offs between transition speed and business constraints
iii. Identification of purpose-aligned growth opportunities: according to McKinsey Global Institute, the achievement of Net Zero will require about $9 trillion per year of capital expenditure until 2050 in a variety of sectors. Embedding Net Zero into business as usual will allow banks and their clients to capture this market share, and key strategies to do that go beyond renewables lending and green bonds: decarbonization finance will play a critical role in aligning portfolios with emissions targets while maintaining profitability.

In the aluminium sector, for example, financing the shift from primary to recycled production – which is much more convenient – offers both environmental benefits (reduced energy consumption, less emissions to account for, reduced waste management) and strategic returns (cheaper input materials and less dependency on raw materials procurers). Within this same context, banks can also support emerging technologies like inert anodes and other promising innovations (discussed in Chapter 6) to align portfolios and support hard-to-abate, enabling real-economy transformation.

2.5 Step 5: Setting a financed emissions target based on the reference scenario

Banks are encouraged to determine the most suitable method for measuring Net Zero alignment on the path to 2050. This involves choosing the best metric or target or KPI for each sector. According to UNEP[290], the four most used metrics to determine financed emissions are:

i. Absolute emissions – reduction in total sector-level financed emissions
ii. Physical intensity – reduction in emissions per unit of activity, such as ton of aluminium produced
iii. Economic intensity – reduction in emissions per unit of revenue
iv. Absolute financing – reduction in exposure to a sector over time

Banks should consider the metrics' potential impact on the ability to finance clients and grow the portfolio, positive environmental impact robustness, easiness of tracking and measurement, levers available to meet the target and relevance to the sector's decarbonization pathway. Granularity is key: while targets are often set at the sector level, internal breakdowns ensure they are actionable. Most importantly, sustainable banking is not (only) financing of sustainable activities but rather the financing of hard-to- abate sectors in transitioning to their more sustainable self[291]: a successful strategy requires both reducing high-carbon investments and actively funding decarbonization to drive real[292].

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290 Net Zero Banking Alliance & Oliver Wyman. (2023). Developing Metrics for Transition Finance. In *United Nations Environmental Programme*. United Nations Environmental Programme. https://www.unepfi.org/wordpress/wp-content/uploads/2023/12/Developing-Metrics-for-Transition-Finance.pdf

291 Generali, B. (2025, May 21). *What does it mean to invest in the real economy?* https://www.bancagenerali.com/en/blog/investire-in-economia-reale#:~:text=Unlike%20the%20real%20economy%2C%20the,production%20of%20goods%20and%20services.

292 More specifically, banks must go beyond cutting financed emissions, and carry the burden of supporting the transition of high-emission sectors, as doing otherwise would ignore the problem, rather than solving it; this is particularly true when considering the risk of stranded assets. According to the London School of Economics (LSE), « containing global temperature rise to well below 2°C would require the world to keep […] an estimated 60% of oil and gas reserves and 90% of known coal reserves […] unused in order to limit global warming to 1.5°C […]. In this scenario, we would be left with fossil fuel resources that cannot be burned and fossil fuel infrastructure (e.g. pipelines, power plants) that is no longer used and may end up as a liability before the end of its anticipated economic lifetime – these are […] "stranded assets". Companies extracting oil, gas, and coal could be affected by stranded assets as a result of the low-carbon transition, but […] other sectors that use fossil fuels as inputs for production, or are otherwise energy- or carbon-intensive, could also be impacted […]. As the world transitions away from high-carbon activities, all technologies and investments that cannot be adapted to low-carbon and zero-emission modes could face stranding ». Therefore, rather than abandoning these sectors, banks have a strategic interest in financing their transformation to avoid both environmental failure and financial instability. *What are stranded assets? - Grantham Research Institute on climate change and the environment.* (2023, December 11). Grantham Research Institute on Climate Change and the Environment. https://www.lse.ac.uk/granthaminstitute/explainers/what-are-stranded-assets/.

2.6 Step 6: Embedding execution and opportunity creation into the business

Last, banks must embed their Net Zero commitment into daily operations, balancing it with their financial requirements and the overall regulatory framework. This implies:

i. Embedding targets into credit policies, data and incentives, and creating a single (ideally automated) scheme that aligns lending decisions with climate goals and emissions tracking to motivate bankers to prioritise sustainability.
ii. Measure, report, disclose, and adjust targets based on investors' requirements and credibility
iii. Optimize the emissions' balance sheet to underline the trade-off between emissions and financial objectives (including exposure to risks, as explained in more detail in Section 3.1)
iv. Exercise sectoral leadership in must-win (hard to abate) sectors
v. Involve the board and management, ensuring Net Zero commitments are matched with real economy scenarios for better understanding by companies
vi. Acquire and retain talent and expertise by upskilling and hiring
vii. Build client engagement by involving bankers and credit teams along with emission calculation teams.

As a wrap, a Net Zero aligned bank should establish a clear timeline of its financed emissions, one that essentially works as an ever-decreasing budget. Naturally, this timeline can be investigated more closely as a range of yearly budgets: the closer to 2050, the lower the budget, until zero is hit in said year. Year after year, the bank must allocate its emissions budget in an efficient way, one
that stimulates financed sectors to reduce their emissions, without the limits imposed being overly stringent – causing potential loss of confidence (the[293] "screw it" logic) and / or disruptions at the sector level.

To better understand how emission budget allocation works, Table 7 (see below) depicts a hypothetical and very simplistic Net Zero commitment for a bank involved with aluminium manufacturing.

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[293] According to what one could call "screw it" logic, being assigned an overly challenging objective turns out to backfire on individuals' confidence in pursuing it, leading them to give up due to the perceived unrealistic expectations. *Why goal setting can lead to disaster*. (2009, February 19).
Forbes. https://www.forbes.com/2009/02/19/setting-goals-wharton-entrepreneurs-management_wharton/?.

However, a bank's financed emissions serve merely as a tool for financial institutions to monitor their clients' operations and provide leverage in those dealings. What banks care about is not the emissions per se, but the potential impact the latter – as anticipated earlier in this chapter – has on a company's resilience to climate change.

More simply, banks need to adjust financial transactions based on their clients' exposure to physical and transition risks brought on by climate change.

Table 7: Simplification of a bank's financed emissions budgeting

/	**Total Emissions (Today, $MtCO_2e$)**	**2030 Target ($MtCO_2e$)**	**2050 Target ($MtCO_2e$)**
Bank's Total Financed Emissions	**100**	**40**	**0**
↓ Alumina Production	**35**	**15**	**0**
→ Company A (Bauxite Mining)	10	4	0
→ Company B (Bauxite Refining)	10	5	0
→ Company C (Alumina Production)	15	6	0
↓ Primary Aluminium Production	**45**	**20**	**0**
→ Company D (Aluminium Smelter)	30	13	0
→ Company E (Aluminium Casting)	15	7	0
↓ Secondary Aluminium Production	**20**	**5**	**0**
→ Company F (Recycling Foundry)	12	3	0
→ Company G (Secondary Casting)	8	2	0

3 Risk Assessment

Geopolitical tensions, scarcity of rare earth metals, and depletion of oil reserves: these are macro trends that can potentially impact the profitability of a business. Climate change has been a recent addition to this list.

The primary factor in determining the value of a financial asset is the risk it carries. This risk – mapped and categorised through the institution's risk inventory[294] – guides the setting of an interest rate: the higher the perceived risk, the higher the rate applied to compensate for potential losses in case of default[295]. However, banks do not evaluate risk in isolation. Banks operate within a broader strategic framework, defined by their Risk Appetite Statement (RAS)[296] and Risk Appetite Framework (RAF)[297], which outline the types and levels of risk they are willing to accept: these tools ensure that pricing decisions are consistent with the institution's overall risk tolerance and regulatory obligations.

We should now consider the line of reasoning raised in the previous chapter's Findings (Section 4). A company with a retroactive – rather than proactive – approach to climate alignment and compliance is most certainly more exposed to default compared to a resilient peer[298].

Suppose company A is a severe case of short-termism: it addresses compliance with a day-by-day approach, deviating from its business as usual only when failure to do so results in operational impacts.

This scenario is where sustainable finance, banking, and investing considerations play crucial roles.

When companies seek funding, banks can – and should – assess the resilience and credibility of the company's climate-related targets and actions both from a transition and a physical risk perspective. A financially and environmentally sound company is more likely to secure the

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[294] An institution's risk inventory is a comprehensive list of potential threats and / or vulnerabilities that could impact its operations, finances, or reputation. Pazornik, M. (2024, February 27). *Risk inventories drive effective compliance Risk management - Treliant*. Treliant. https://www.treliant.com/knowledge-center/risk-inventories-drive-effective-compliance-risk-management/?.

[295] Gorton, D. (2024, November 26). *A quick guide to the Risk-Adjusted discount rate*. Investopedia. https://www.investopedia.com/articles/budgeting-savings/083116/guide-riskadjusted-discount-rate.asp.

[296] « The Risk Appetite Statement (RAS) indicates the level and type of risk a financial institution is willing to assume coherently with its long-term strategic objectives – in other words, it defines the risk boundaries within which the institution aims to operate, or to avoid » *CRIF Academy: Le metriche del Risk Appetite Framework*. (n.d.). https://www.crif.it/ricerche-e-academy/formazione/crif-academy/crif-academy-risk-appetite-framework-25-3-2020/.

[297] « The Risk Appetite Framework is the overall approach, including policies, processes, controls, and systems through which Risk Appetite is established, communicated and monitored. It includes a risk appetite statement, risk limits, and an outline of the roles and responsibilities of those overseeing the implementation and monitoring of the RAF, [which] should consider material risks to the financial institution, as well as to the institution's reputation vis-à-vis policyholders, depositors, investors and customers. […]. *Risk Appetite Framework - Open Risk Manual*. (n.d.). https://www.openriskmanual.org/wiki/index.php/Risk_Appetite_Framework?

[298] Paxton, C. (2025, January 27). *The proactive approach to regulations compliance*. Akeneo. https://www.akeneo.com/blog/the-proactive-approach-to-regulations-compliance/.

necessary funding, while riskier firms may face higher borrowing costs or be denied financing altogether.

In the example mentioned, company A is exposed to *transition risks*, defined as those climate-related risks that arise from the transition to a low-carbon and climate-resilient economy. Suppose instead that company A is forward-looking enough not to delay meaningful mitigation compliance but not enough to choose an equally appropriate location for its manufacturing facility, which, for the sake of this example, will be in an area subject to flooding. If company A were to look for funding for its 10-year expansion plan, any lender would hardly ever do so since the site, based on climate scenarios, is at high risk of being entirely flooded in the forthcoming years.

In this scenario, the physical effects of climate change expose company A to risks that a prospective lender would find unacceptable due to the high probability of the borrower defaulting on the bank's loan.

3.1 Transition Risks

According to the European Central Bank (ECB) « transition risk refers to an institution's financial loss that can result, directly or indirectly, from the process of adjustment towards a lower-carbon and more environmentally sustainable economy. This could be triggered, for example, by a relatively abrupt adoption of climate and environmental policies, technological progress or changes in market sentiment and preferences» [299]. The transition to a low-carbon and resilient economy will result in an interplay between policy, legal, technological, and market forces. Organizations' responses to these forces are going to determine their level of financial and reputational risk: fast learners will earn their share in newborn markets, while those that do not meet newborn requirements will lag behind.
Table 8 below depicts the different transition risk categories.

[299] European Central Bank [Banking Supervision]. (2020). Guide on climate-related and environmental risks: Supervisory expectations relating to risk management and disclosure.
In *BankingSupervision.Europa.EU*. https://www.bankingsupervision.europa.eu/ecb/pub/pdf/ssm.202011finalguideonclimate-relatedandenvironmentalrisks~58213f6564.en.pdf.

Table 8: Categories of transition risks with examples and their potential financial impacts[300]

Transition risk categories	Examples	Potential Financial Impacts
Policy and Legal	Increased GHG emission pricing	Higher operational costs (compliance and insurance costs)
	More stringent reporting obligations	Write-offs and early retirement of assets due to new policies
	Exposure to litigation	
Technology	Obsolescence of existing products and services and substitution with more emission efficient options	Write-offs and early retirement of assets
	Unsuccessful investment in new technologies	Research and development expenditures in new and alternative technologies
	Transition costs to lower emissions	Capital investments in technology development
Market	Shift in consumers' behavior	Reduced demand for goods and services
		Re-pricing of assets
	Increased cost of raw materials	Higher production costs (energy, water) and output requirements (waste treatment)
Reputation	Shift in consumers' beliefs	Reduced revenue from reduced goods and services demand
	Stigmatization of sector	Reduced revenue from negative impacts on workforce management and planning
		Reduction in capital availability
	Increased stakeholder concern or negative stakeholder feedback	Reduced production capacity (delayed planning approvals, supply chain interruptions)

3.2 Physical Risks

According to the European Central Bank (ECB), « Physical risk refers to the financial impact of a changing climate, including more frequent extreme weather events and gradual changes

[300] *Climate Risks and opportunities defined | US EPA*. (2025, March 3). US EPA. https://www.epa.gov/climateleadership/climate-risks-and-opportunities-defined#:~:text=Transition%20risks%20are%20those%20associated,and%20transition%20to%20renewable%20energy.

in climate, as well as of environmental degradation, such as air, water and land pollution, water stress, biodiversity loss and deforestation. Physical risk is therefore categorized as "acute" when it arises from extreme events, such as droughts, floods and storms, and "chronic" when it arises from progressive shifts, such as increasing temperatures, sea-level rises, water stress, biodiversity loss, land use change, habitat destruction and resource scarcity. This can directly result in, for example, damage to property or reduced productivity, or indirectly lead to subsequent events, such as the disruption of supply chains »[301].

Physical risks are exemplified in Table 9 below.

Table 9: Categories of physical risks with examples and their potential financial impacts[302]

Physical Risks	Examples	Potential Financial Impacts
Acute physical risks *Risks that are event-driven, including increased severity of extreme weather events*	Cyclones, hurricanes, heat or cold waves, floods and weather patterns	Reduced revenue from decreased productivity (supply chain interruptions)
	Rising sea-levels	Reduced productivity from negative impacts on workforce (excessive heat, safety)
		Increased capital costs (damage to facilities)
Chronic physical risks *Risks reflected in longer-term shifts in climate patterns that may cause chronic events*	Sustained changes in climate, including temperature and precipitations	Increased insurance premiums and potential for reduced liquidity for assets in "high-risk" locations
		Write-offs and early retirement of existing assets (damage to property and assets in "high-risk" locations)

[301] European Central Bank [Banking Supervision]. (2020). Guide on climate-related and environmental risks: Supervisory expectations relating to risk management and disclosure. In *BankingSupervision.Europa.EU*. https://www.bankingsupervision.europa.eu/ecb/pub/pdf/ssm.202011finalguideonclimate-relatedandenvironmentalrisks~58213f6564.en.pdf.

[302] *Climate Risks and opportunities defined | US EPA*. (2025, March 3). US EPA. https://www.epa.gov/climateleadership/climate-risks-and-opportunities-defined#:~:text=Transition%20risks%20are%20those%20associated,and%20transition%20to%20renewable%20energy.

3.3 Mitigation & Adaptation – finding the right balance

Closely related to physical and transition risk is the concept of climate change adaptation and mitigation.

As anticipated in Chapter 2 – *adaptation* refers to « the process of adjustment to actual and expected climate change and its impacts », while *mitigation* is defined as « means the process of holding the increase in the global average temperature to well below 2 °C and pursuing efforts to limit it to 1,5 °C above pre-industrial levels, as laid down in the Paris Agreement »[303].

Building on the risks defined above, it is possible to conclude that physical risks (e.g. extreme weather events) require adaptation strategies (e.g. building resilient infrastructure), while transition risks (e.g. regulatory requirements) are more coherently associated with mitigation strategies (e.g. cutting emissions).

However, a successful transition to Net Zero should feature the right mix of both adaptation and mitigation efforts – which, to be evaluated meaningfully, should be projected over time to obtain a potential future scenario (as explained in Chapter 3 Section 5).

4. Transition Risk and Decarbonization Dynamics in the Aluminium Sector: Implications for Banking Portfolios

At the core of banks' portfolio decarbonisation strategies lie their relationships with hard-to-abate sectors – which, according to the OECD, include aluminium[304].

While being electricity- and resource-intensive, this industry is essential to many value chains, including automotive, software and IT, packaging and renewable energy – all of which are fundamental for the transition to happen.

Given the indispensable role of aluminium, financial institutions face the strategic imperative to engage in transition finance. This involves not only divesting from non-green activities but also leveraging the power of financial institutions to support their

[303] *European Union. (2020, June 6). REGULATION (EU) 2020/852 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL. Eur-Lex.Europa.Eu. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32020R0852&from=EN.*

[304] Teusch, J., D'Arcangelo, F. M., Kruse, T., Pisu, M., & OECD - Economics Department Working Papers. (2024). Carbon prices, emissions and international trade in sectors at risk of carbon leakage: Evidence from 140 countries. In *OECD.com*. https://doi.org/10.1787/116248f5-en; Mission Possible Partnerships. (2022). MAKING NET-ZERO ALUMINIUM POSSIBLE: An industry-backed, 1.5°C-aligned transition strategy. In *EnergyTransition.org*. https://www.energy-transitions.org/wp-content/uploads/2022/10/MPP-Aluminium-Full-Report-101722-final-digital.pdf?.

transformation. The goal is that of meeting the growing aluminium global demand, while progressively decoupling it from intensive resource extraction and pollution.

However, like Damocles' sword, the risks linked to failing to transition are characterised by cascading effects which, to complete this transition pathway, grow heavier by the day, threatening not only individual firms' resilience but also the long-term stability of the financial system they depend on.

4.1 Transition Risks of the Aluminium Sector

The transition risks of the aluminium stem primarily from its extreme energy intensity – most of which, to date, still rely on fossil fuels. As such, aluminium producers are among the hardest hit by policies designed to internalise the cost of carbon emissions. These include the progressive phase-out of free allowances under the EU ETS and implementing the CBAM. Both instruments essentially act as cost amplifiers, increasing operational expenditure (OpEx) and narrowing the economic viability of older, carbon-intensive production plants.

At the same time, decarbonising aluminium production demands significant capital expenditures (CapEx). Technologies such as inert anodes or hydrogen-based reduction remain at low Technology Readiness Levels (TRLs) – respectively of between 4 – 5 and 5 – 6[305] – and require substantial R&D investment and industrial scaling. This requires strong liquidity and availability of capital, which is specifically aimed at the technological advancements needed to ac achieve climate transition objectives. Financial institutions, on the other side, need to be able to understand the technological needs of the client and introduce those technology considerations in their product origination policies. The introduction of technology KPIs in origination policies for banking product creation allows a sectoral understanding of the technology needs of the client for its transition and to deliver tailored financing.

In addition to this, market dynamics are transforming. Consumers' expectations, regulatory demands, and procurement criteria established by downstream industries[306] are

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[305] Zore, L. (2024). Decarbonisation options for the aluminium industry. In J. A. Moya (Ed.), *European Commission's Joint Research Centre (JRC)*. European Commission's Joint Research Centre (JRC). https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://publications.jrc.ec.europa.eu/repository/bitstream/JRC136525/JRC136525_01.pdf&ved=2ahUKEwjm7dicnISMAxXD3QIHHVRnCAUQFnoECBwQAQ&usg=AOvVaw1wy2cCymISvMjc41qqIRZC.

[306] In any industry there is a clear distinction between downstream and upstream operators. "Downstream" refers to those companies whose activities are carried out on semi-finished or even finished products, which they turn into end-use goods: within the context of aluminium, these include automotive, aerospace, construction, packaging, electronics, consumer goods, and specific energy or IT-related components. In other words,

driving an increase in the demand for low-carbon aluminium. Producers run the danger of losing market share, getting shut out of supply chains, and having their brand damaged if they don't have clear, credible transition pathways.

Three main transmission channels allow the transmission of these risks to financial institutions and markets:

1. Credit Risk – businesses that are unable to obtain financing for clean technology improvements, or that do not have viable decarbonization plans may be at increased risk of default; balance sheets are weakened, and credit risk exposure is increased when capital expenditure requirements and financing capabilities are not aligned.
2. Market Risk – asset devaluation, poorer collateral quality, or write-downs or -offs in banks' equity exposures to the industry might result from misalignment with climate trajectories, whether they are technological or reputational.
3. Operational Risk – misjudgement is more likely when customers' actual transition capabilities are unknown and ESG data is inconsistent or lacking; evaluating the materiality of decarbonization plans – energy mix shifts, recycling strategies, carbon capture, or digitalization of smelting processes – requires sector-specific expertise and forward-looking analysis tools.

Findings

Banks need to move beyond ESG ratings to reduce these risks and capitalise on possible opportunities, which requires assessing clients' readiness in a granular way. How ambitious is

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downstream producers rely on the physical properties of aluminium – such as lightness, durability, conductivity, and recyclability – to incorporate it into their final products. Differently, "upstream" producers are those who operate on the raw material itself, whether it be its mining, refining and casting into both generic-use products (such as pure aluminium foils, ingots, or sheets) or ready-for-assembling specific components (like ready-made cans, bars, or automotive components). Generally speaking, the global south is more active along the upstream part of the value chain, while the global north operates in the downstream section instead. This is, unfortunately, oftentimes an escamotage to delocalise and export externalities, or to have access to cheaper inputs associated with downstream activities – which are more energy and resource intensive. As a response to these perverse logics, the EU has in fact introduced measures such as the CBAM and the EU ETS, to even out the level of costs between those who produce inside and outside of its economic zone, as well as to internalise the externalities (for the time being, emissions only) resulting from manufacturing processes. *HULAMIN | The Aluminium Value Chain*. (n.d.). https://www.hulamin.com/iar2017/business/the-aluminium-value-chain.php; European Aluminium. (2025a). *A STRONG, SUSTAINABLE & COMPLETE EUROPEAN VALUE CHAIN*. https://european-aluminium.eu/about-aluminium/aluminium-industry/; United States Congress. (2022, October 26). *Congressional Research Service – R47294: Summary*. Congress.gov. https://www.congress.gov/crs_external_products/R/HTML/R47294.web.html; *The competitiveness of the aluminium industrial chain in Italy and Europe | Italpres*. (n.d.). https://www.italpres.com/aluminium-die-casting-news/competitiveness-aluminium-industrial-chain-italy-and-europe.

the decarbonisation target? Is it feasible? What technologies are going to be used to achieve it, and what is their Technology Readiness Level? How are CapEx and OpEx projected to evolve under different policy and market scenarios? And in what format, and with how much specificity, is the client providing all this data? Is it percentages, clear- cut numbers, or qualitative analysis only?

This level of understanding is crucial for both opportunity identification and risk management, which are ultimately interrelated.

Chapter 9 – *From Climate to Finance: a Quantitative Tool to assess Transition Risks of the Aluminium Sector*

Introduction

The previous chapter introduced the design and structure of ten KPIs designed to measure the environmental impact of aluminium producers. Yet, their scope goes beyond mere reporting: in fact, the broader purpose the indicators aim to fulfil is capture the aluminium sector's exposure to climate-related risks – especially transition ones. Therefore, contextualising them within the broader framework of transition finance and risk management unlocks their full potential.

But why are these KPIs so necessary? Why do banks need to internalise environmental impacts if there already are established structures, such as the EU ETS? And how are these KPIs incorporated into financial institutions' decisions? These are the guiding questions of the present chapter. These are the guiding questions of the present chapter.

1. Climate Risk Materiality

As explained in Chapter 3, climate-related risks are not confined to the firms that generate them: once materialised – whether through physical events or transition dynamics – they propagate across the financial system via interlocking channels. Particular attention should be given to the choice of wording, where "materialised" is used with its more technical meaning: in financial terms, materiality is a concept that determines whether the omission or misstatement of information in a financial report would impact a reasonable user's decision making - in other words, a risk is material if it has the potential to alter credit decisions, risk assessments, or capital allocations within financial institutions.

1.1 Prudential Plans

Following the establishment of the Task Force on Climate-related Financial Disclosures (TCFD) by the Financial Stability Board in 2015, the concept of "financially material climate-related risks" was recognised as formally relevant for the stability of the financial system as a whole. Since then, more and more regulators, banks, and oversight groups have started to recognise this idea, leading to the need for banks to include climate change -related risk factors in their management and planning.

Accordingly, in 2022 the Basel Committee on Banking Supervision, released the *Principles for the Effective Management and Supervision of Climate-Related Financial Risks*[307] in which it states that prudential regulation of banks is structured around three main Pillars:

1. Pillar I – setting the minimum capital requirements that banks must maintain to cover standard risks (including credit, market, and operational risk), based on either standardised or internal risk models.
2. Pillar II – defining the supervisory review process under which banks are required to identify and manage all material risks (including ESG-related risks) through internal assessment frameworks such as the ICAAP (Internal Capital Adequacy Assessment Process).
3. Pillar III – promoting market discipline by mandating public disclosure of risk exposures, risk management practices, and governance structures, ensuring transparency for both investors and regulators.

These principles, designed to strengthen banking supervision and financial stability, have since then been embedded into binding regulatory instruments within the EU: specifically, the Capital Requirements Regulation (CRR2/CRR3) and the Capital Requirements Directive (CRD V/VI) – adopted between 2019 and 2024 – introduced this framework, with the European Banking Authority (EBA) explicitly mentioning mandatory ESG-related risks' disclosure under Pillar III.

What the EBA introduces is the need to identify, quantify, and internalise the degree to which a given economic activity is exposed to environmental, social, or governance risks that are financially significant. Plus, when it comes to environmental risks, materiality is not evenly distributed: certain sectors are disproportionately affected due to their carbon-intensive and polluting nature, reliance on highly energy- [308]￼.

[307] *Principles for the effective management and supervision of climate-related financial risks*. (2022, June 15). https://www.bis.org/bcbs/publ/d532.htm; Caswell, G. (2022, June 15). *Basel Committee releases climate risk principles*. Green Central Banking. https://greencentralbanking.com/2022/06/15/basel-climate-risk-principles/.

[308] As such, banks should carefully monitor the share of their clients operating in hard-to-abate sectors with whom they engage in financial relationships — whether through lending, investment, or credit exposure — in order to ensure that their capital requirements are properly adjusted. In addition, they must closely track the evolving risk profile of these clients: either diversifying their exposures, capping their concentration, or

The aluminium industry is one of them: with above-average structural emissions intensity, high energy dependence, and strategic economic importance, aluminium production is particularly exposed to transition risks.

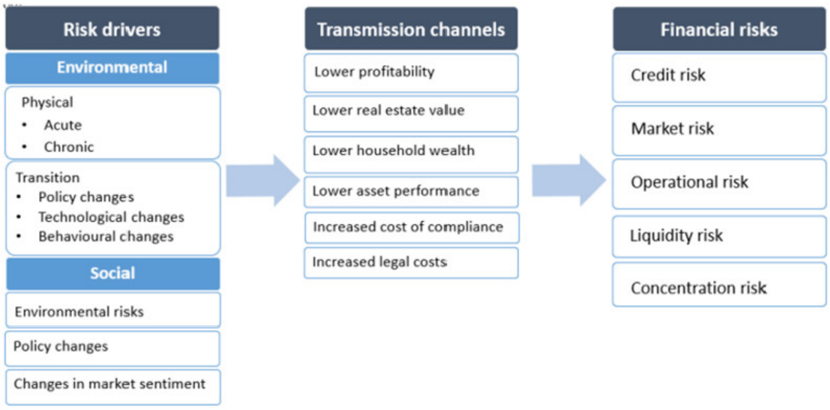

Chart 14: How environmental and social risks translate into financial risks[309].

2. Transmission Channels: Linking KPIs to Financial Risk Types

As shown in Chapter 5, producing aluminium – especially throughout the primary production route – is one of the most impactful industrial processes globally. The bulk of this sector's emissions derives from two primary sources:

- Process emissions (direct processing emissions, such as those from electrolysis in the Hall-Héroult process);
- Energy use, especially electricity, accounts for more than 60% of production costs in certain regions.

Because of this, the aluminium sector is highly exposed to transition risks, which, based on the framework from Bannier & Auzepy[310], materialise in four main areas:

1. Regulatory Risk – introduction of regulatory bottlenecks such as carbon taxes (CBAM), carbon markets or mandatory emissions thresholds (EU ETS); the main

embedding sector-specific limits directly into their Risk Appetite Framework (RAF) or Risk Appetite Statement (RAS). Farias, P. H. F. V. L. (2025, February 12). *Final EBA Guidelines on ESG Risk Management – Implications for Governance and Risk Management*. https://www.bdo.de/en-gb/insights/updates/assurance-en/final-eba-guidelines-on-esg-risk-management-implications-for-governance-and-risk-management?.

[309] ABN AMRO Bank. (n.d.). *EBA shelves inclusion of environmental and social risks into Pillar 1*. https://www.abnamro.com/research/en/our-research/eba-shelves-inclusion-of-environmental-and-social-risks-into-pillar-1.

[310] Auzepy, A., & Bannier, C. E. (2025). Integrating climate risks in bank risk management and capital requirements. In *Springer eBooks*. https://doi.org/10.1007/978-3-658-47061-6.

impact of these risks are increased production costs, risk of obsolescence and stranded assets, pressure of competitiveness margins.

2. Market Risk (Demand Side) – shifting of demand from downstream operators (such as aluminium smelters and casters) seeking for low-carbon products; the impact is a loss of market share and a price differentiation between high-carbon and low-carbon producers, which ultimately leads to revenue loss.
3. Technological and Operational Risk – need for liquidity to invest in low-carbon alternatives (such as inert anodes), whose main impact is higher Capex requirements, exposure to innovation risk and potential execution failures.
4. Reputational and Disclosure Risk – increased scrutiny from investors, financial institutions, regulators and clients; the impacts of these risks are potential barriers to access to capital, higher cost of financing, and even exclusion from green portfolios.

To address these risks, financial institutions must be able to trace the sources, methods, and channels through which these risks emerge in order to respond appropriately.

As follows, this chapter seeks to bridge the KPIs proposed in the previous chapter with the financial impacts they are meant to help banks anticipate, absorb, and internalise.

3. KPI-Risk Mapping Framework

As anticipated, the following section's purpose is to link the ten KPIs developed to the specific risk exposures within the aluminium sector. They are intended to capture – tracing the channels through which they propagate and the financial impact they ultimately can potentially trigger.

Each KPI, when underperforming, reveals a specific vulnerability that propagates through a distinct pathway, eventually affecting one or more prudential risks faced by banks – credit, market or operational. For example, if a company has a high physical emission intensity (KPI 1), it might lead to higher costs for meeting regulations, which can impact cash flow predictions, increase the chance of default (PD), and create credit risk. On the other hand, KPIs related to circularity may expose firms to market risks, as clients shift toward more sustainable supply chains.

Each KPI listed in the table below is mapped against a specific transition risk category, a transmission channel describing how that risk materialises, and the corresponding type of financial risk, as classified by the EBA[311].

Additionally, for each KPI, financial impacts are identified through key indicators of credit and investment analysis to express how poor performance on a given KPI can directly affect a firm's financial health and, by extension, its credit profile. They are:

- PD (Probability of Default) is defined as the likelihood that a borrower will fail to meet its debt obligations; it is a core input in credit risk modelling and capital requirement calculations and is potentially directly linked to poor environmental performance and low transition plan credibility.
- Cost of Capital[312] – corresponding to the minimum return demanded by lenders to compensate for perceived risk; it increases along with PD (hence, client's repayment uncertainty).
- Access to Capital[313] – ability to secure financing on favourable terms; deteriorates due to poor environmental performance and low transition plan credibility.
- EBITDA (Earnings Before Interest, Taxes, Depreciation and Amortisation)[314] – measuring a company's core operational profitability. This digit reflects how much profit a company generates from its operations before accounting for financial decisions (interest), tax obligations, or accounting practices related to asset depreciation and amortisation; it is widely used in credit and investment analysis to assess a firm's ability to generate cash flow from its core activities – regardless of its capital structure or fiscal environment. A declining EBITDA typically signals deteriorating operating performance, whether it is due to rising input costs or falling sales volumes, and if sustained over time, it indicates financial vulnerability.

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[311] European Banking Authority (EBA). (2025). *Financial report: Guidelines on the management of environmental, social and governance (ESG) risks*. https://www.eba.europa.eu/sites/default/files/2025-01/fb22982a-d69d-42cc-9d62-1023497ad58a/Final%20Guidelines%20on%20the%20management%20of%20ESG%20risks.pdf.
[312] *Cost of capital*. (n.d.). Morgan Stanley Investment Management. https://www.morganstanley.com/im/it-it/intermediary-investor/insights/articles/cost-of-capital.html.
[313] EU Platform on Sustainable Finance (PSF). (2025). Financing a Clean and Competitive Transition: Monitoring Capital Flows to Sustainable Investments: final report. In *EU Platform on Sustainable Finance (PSF)*. https://finance.ec.europa.eu/document/download/87c48ab4-34d2-4cd7-997e-efc1310e62c5_en?filename=250311-sustainable-finance-platform-report-capital-flows_en.pdf.
[314] Team, C. (2024, December 6). *EBITDA*. Corporate Finance Institute. https://corporatefinanceinstitute.com/resources/valuation/what-is-ebitda/.

- Opex (Operating Expenditures)[315] – all those recurring costs incurred through day-to-day operations, such as energy, raw materials' inputs and maintenance; rising Opex can reduce profitability and cash flow resilience – defined below.
- CapEx (Capital Expenditures)[316] – investments in long-term assets like equipment, infrastructure, or low-carbon technologies; a high Capex reflects adaptation or growth, but can also strain liquidity.
- Free Cash Flow (FCF)[317] – the cash remaining after a company covers its operating expenses and capital investments: it represents the firm's capacity to finance its obligations or invest without needing external funding.

Table 10: KPI-risk mapping framework

KPI		**Transition Risk**	**Transmission Channel**	**Financial Impact**	**Financial Risk**
Sustainability KPIs					
1	Physicial Emission Intensity	Regulatory (ETS, CBAM) + Market & Reputational and Disclosure Risk	**High emission intensity =**	↑ **PD**	Credit Risk
			↑ emissions to account for	↓ EBITDA	
			↓ environmental performance	↑ Opex	
2	Scope 1 + 2 Alignment		**Misalignment with climate targets =**	↑ **PD**	Market Risk
			↑ investor / lender pressure	↑ Cost of capital	
			↓ client retention	↓ Access to capital	

315 *Operating Expenditure | CFO Coalition for the SDGs*. (n.d.). https://www.cfocoalition.org/blueprints/p2-2-2-operating-expenditure.
316 *Capital expenditure | CFO Coalition for the SDGs*. (n.d.). https://www.cfocoalition.org/blueprints/p2-2-1-capital-expenditure.
317 Vipond, T. (2024, May 13). *Free Cash flow (FCF) formula*. Corporate Finance Institute. https://corporatefinanceinstitute.com/resources/valuation/fcf-formula-free-cash-flow/.

Circularity KPIs					
3	Share of Secondary Aluminium	Tech and Operational + Regulatory (CEAP) + Market & Reputational and Disclosure Risk	**Not enough secondary production =**	↑ **PD**	Credit Risk
			↑ energy consumption	↓ EBITDA	
			↑ emissions to account for	↑ Opex	
4	Recycled Input Rate (per product)		**Low recycled content =**	↑ **PD**	Market Risk
			↓ enviornmental performance	↓ Revenue	
			↑ emissions to account for	↓ EBITDA	
			↓ client retention	↑ Cost of capital	
5	Pre- vs Post-Consumer Scrap		**Low post-consumer scrap =**	↑ **PD**	Operational Risk
			↑ raw material volatility exposure	↓ Free Cash Flow	
			↓ environmental performance	↑ Opex	
			↑ emissions to account for	↑ Cost of capital	
Resource Efficiency KPIs					
6	Bauxite Residue (red mud)	Regulatory + Reputational and Disclosure Risk	**More bauxite residue =**	↑ **PD**	Operational Risk
			↑ litigation risk	↑ Capex	
			↑ management costs	↑ Opex	

7	Water Consumption		Regulatory + Operational Risk	**Intense wate usage =**	↑ **PD**	Operational Risk
				↑ litigation risk	↓ Free Cash Flow	
				↑ vulnerability and price volatility exposure	↑ Opex	
8	Carbon Anodes Consumption		Tech and Operational Risk	**Continued reliance on carbon anodes =**	↑ **PD**	Credit Risk
				↑ management cost	↑ Opex	
				↑ risk of obsolescence	↓ Free Cash Flow	
9	Dross (Slag) Management		Regulatory + Reputational and Disclosure Risk	**Increased dross production & poor recovery =**	↑ **PD**	Operational Risk
				↑ litigation risk	↑ Cost of capital	
				↑ management cost	↑ Opex	
10	Energy	10.1 Total Energy Consumption	Regulatory + Reputational and Disclosure Risk	**Intense energy intensity =**	↑ **PD**	Credit Risk
				↑ exposure to price volatility	↓ EBITDA	
				↑ emissions to account for	↑ Opex	
		10.2 Renewable Energy Share	Regulatory + Reputational and Disclosure Risk	**Low renewable energy share =**	↑ **PD**	Market Risk
				↓ environmental performance	↑ Cost of capital	
				↓ client retention	↓ Access to capital	
		10.3 Electrolysis Energy Use	Tech and Operational Risk	↑ energy consumption	↑ **PD**	Credit Risk
				↑ emissions to account for	↓ EBITDA Margin	

4. Integrating KPIs into Risk Appetite and Governance Structures

As explained just above, the integration of climate-related KPIs into a bank's risk governance system allows for a structured and operational response to environmental risks – especially transition risk. Within the Risk Appetite Framework (RAF), these KPIs contribute to defining the overall strategic stance of the bank regarding environmental exposure: for example, by establishing a general orientation toward limiting credit exposure to clients with high carbon intensity or low levels of circularity.

Before going into more detail about quantifications of what counts as "acceptable" in terms of risk associated to KPI performances, few definitions are needed.

- Risk Inventory – a bank's Risk Inventory is a comprehensive and structured list of all material risks to which a bank is – or could be – exposed; typically categorized by risk type, the inventory supports the development of all other financial instruments discussed below.
- Risk Appetite Framework (RAF) – the RAF defines the both the levels and types of risk a bank is willing to accept in pursuit of its strategic objectives: more simply, it serves as a quantitative and qualitative reference point for aligning decision-making processes in a way that matches the institution's capacity (especially in terms of capital requirements) and long-term goals.
- Risk Appetite Statement – what the RAF mandates, the RAS specifies: this document translates the principles outlined in the RAF into concrete, sector-specific and measurable risk thresholds.

Having clarified this, it becomes evident how, the RAS turns the RAF into actionable and measurable thresholds, providing a decision-making criterion of what is an acceptable risk according to the bank's Risk Inventory. Naturally, all these elements rely substantially on the bank's identity: there cannot be a single value that fits the RAS of both the European Central Bank, and Silicon Valley Bank – as the two have very different risk appetite.

Nonetheless, the analysis of the aluminium sector conducted in Chapters 5 and 6 allows for – to the very least – a definition of:

- Minimum Risk – the base boundary of the "acceptable risk area", hence what fully aligns with the bank's strategy

- Risk Tolerance – the upper boundary of the "acceptable risk area", that requires close monitoring and eventual trigger of preventive action
- Risk Limit – the exact line dividing the "acceptable risk area" from what the bank is not willing to deal with, must raise alerts and trigger corrective actions
- Maximum Risk – an unacceptable level of risk that requires immediate intervention such as override, credit denial or client exclusion
- Risk Capacity – the overall level of risk the bank can absorb based on its capital, liquidity, and strategic objectives; it is defined at portfolio or sector level.

Accordingly, the following table presents a practical translation of these risk levels into environmental performance thresholds, applied to the aluminium sector. Each KPI is matched with specific performance ranges that correspond to Minimum Risk, Risk Tolerance, Risk Limit, Maximum Risk, and overall Risk Capacity. These benchmarks serve as a decision-making tool for integrating environmental risk into the bank's RAF and RAS.

KPI	Minimum Risk	Risk Tolerance	Risk Limit	Maximum Risk
Sustainability KPIs				
Aluminium Physical Intensity (tons of CO2e / ton of aluminium)	< 2	2 – 3	3 – 4	≥ 4
Scope 1 + 2 Alignment (0 ≤ 1)	< 0.1	0.1 – 0.3	0.3 – 0.6	≥ 0.6
Circularity KPIs				
Share of Secondary Aluminium (%)	> 60%	40% – 60%	20% – 40%	≤ 20%
Recycled Input Rate (per product) (%)	> 65%	45% – 65%	25% – 45%	≤ 25%
Pre- vs Post-Consumer Scrap Rate (%)	Post-consumer ≥ 50%	Post-consumer 35 – 50%	Post-consumer 20 – 35%	Post-consumer < 20%
	Pre-consumer ≤ 50%	Pre-consumer dominant but declining	No roadmap for growth	Pre-consumer untracked or > 80%
Resource Efficiency KPIs				
Bauxite Residue (tons / tons of alumina produced)	< 1.5	1.5 – 2.0	2.0 – 2.5	≥ 2.5 or unreported
Water Consumption (m³ / ton of aluminium)	**< 7**	7 – 12	12 – 18	≥ 18
Carbon Anodes Consumption (kg / ton of aluminium)	< 400	400 – 450	450 – 500	≥ 500

Dross	< 10	10 – 20	20 – 30	≥ 30
Energy				
Total Energy Consumption (MWh / ton)	> 13	13 ≤ 15	15 ≤ 17	< 17
Renewable Energy Share	> 80%	50 ≤ 80%	50 ≤ 30%	< 30%
Energy Consumed in Electrolysis	< 13.5	13.5 ≤ 15	15 ≤ 16	> 16

Table 11: risk-integrated KPI performances

Findings

At last, this chapter proposed a practical taxonomy of transition-related KPIs tailored to the aluminium sector, divided into three macro-categories: sustainability, circularity, and resource Efficiency.

For each KPI, quantitative risk thresholds were developed – building on information presented in Chapters 5, 6, 7, 8 and Appendix 2 – to align performance ranges with levels of banking risk governance, namely Minimum Risk, Risk Tolerance, Risk Limit, and Maximum Risk. As mentioned already, these thresholds seek to bridge environmental data, credit decision-making tools (such as the RAF, RAS and the ICAAP).

Before concluding, it is important to highlight that not all KPIs share the same level of maturity, and this affects how strictly their thresholds can be defined – a factor one could call "forgiveness".

In the case of Sustainability KPIs (Physical Emission Intensity and Scope 1 + 2 Alignment, respectively KPIs 1 and 2), the thresholds are intentionally tighter, as these metrics are now part of standardised reporting practices, supported by international frameworks including the EU Taxonomy, SBTi, and TPI: their methodological clarity justifies higher expectations.

Differently, Circularity KPIs (Share of Secondary Aluminium, Recycled Content Rate (per product) and Pre- vs Post-Consumer Scrap Rate, respectively KPIs 3, 4 and 5) are voluntarily treated with slightly softer thresholds, as their formal recognition is still evolving. Yet, the Recycled Input Rate (RIR) per product is deliberately more stringent: achieving high recycled content in a specific product line is often feasible and commercially strategic (especially when producers use their own pre-consumer scrap), even while a company's overall use of secondary aluminium remains limited.

Lastly, Resource Efficiency KPIs lie somewhere in between: indicators such as Water and Energy Consumption (KPIs 7 and 10) benefit from a fair degree of disclosure and comparability, while others – like Bauxite Residue, Carbon Anodes' Consumption, and Dross Generation (KPIs 6, 8 and 9) – are more forward-looking and still lack uniform reporting practices. As such, again, thresholds were set accordingly. However, that said, the three less-established Resource Efficiency KPIs are linked to serious environmental liabilities, where total non-disclosure cannot be accepted. Despite the lack of formal standards, the risks associated with improper waste management (including potential radioactivity or groundwater contamination caused by bauxite residue and carbon anodes respectively) are severe enough to require – at least basic – transparency. Thus, in these cases, forgiveness does not imply tolerance of omission, but rather a proportional risk-weighted expectation that still mandates disclosure and mitigation.

To conclude, this chapter has demonstrated how sector-specific environmental KPIs can be operationalised within banking risk governance. How? By aligning performance thresholds with tools such as the Risk Appetite Framework (RAF), the Risk Appetite Statement (RAS), and ICAAP, ESG criteria are no longer treated as symbolic or separate, but fully embedded into the core of credit evaluation and portfolio risk management.

In contrast to sustainability-labelled products like Sustainability-Linked Loans (SLLs) and Transition-Linked Loans (TLLs) – where loan pricing is tied to predefined environmental performance targets – the proposed approach aims to be broader, as well as sector-specific and structurally integrated. While SLLs and TLLs play an important signalling role, their real-economy impact remains limited: they mainly stem from voluntary and non-standardised KPIs and cover only a small portion of banks' lending books, frequently less than 5%.

As such, rather than designing yet another green-labelled instrument, the goal of this chapter – and in broader terms, of this thesis – is to make transition metrics become the new ESG, making their application to financial risk mainstream, from individual investors, to a bank's portfolios: this enables banks to account for transition risk, not only in products designed to signal sustainability, but in their ordinary use of proceeds, their pricing decisions, and their capital allocation choices.

In short, while SLLs and TLLs reward the “tip of the iceberg” the framework proposed targets the broader mass below the surface – all those clients, sectors and exposures that may not be green yet, but may plan on becoming so.

Chapter 10 – *Conclusions*

The core aim of this thesis was to provide a set of performance indicators (KPIs) capable of evaluating, in a concrete, comparable, and credible way, the progress of aluminium producers towards a low-carbon transition – particularly regarding climate risk mitigation and alignment with sustainability goals. The research path followed throughout has highlighted the need for metrics that go beyond the narrow narrative of emissions in favour – instead – of capturing broader dimensions such as circularity and resource efficiency.

From the analysis conducted, a clear picture emerges, where environmental reporting in the aluminium industry is still highly fragmented – overly standardised for some metrics, whose impact does not go beyond the financial economy and incomplete in other more reality-bound areas.

This underscores the growing need for analytical tools that can surpass declarative sustainability claims, providing measurable, objective, and verifiable evaluations of production processes, material usage, and environmental impact.

The ten KPIs proposed in this work address this need. Divided according to what emerged as the three key strategies to achieve resilience in the aluminium sector – namely, sustainability, circularity and resource efficiency – they not only evaluate how a company reduces its emissions (KPIs 1 and 2), but also how it adopts circular practices (KPIs 3 to 5), and, ultimately, how efficiently it manages its resources and material waste flows (KPIs 6 to 10). In this sense, what is argued for is not simply a list of metrics but a methodological framework designed to bridge the gap between stated commitments and actual performance.

Another critical point that emerged is the pivotal role of financial institutions, which serve as unintended yet powerful enforcers of transition dynamics. As they are exposed to the aggregated risks of their clients, they are increasingly compelled to demand transparency, consistency, and credibility from the companies they finance. In this context, adopting the KPIs identified in this thesis could represent a concrete step toward aligning business practices with broader climate and sustainability imperatives.

In conclusion, this thesis contributes to the industrial decarbonisation debate by showing that effective change cannot occur without effective measurement. Change begins with what we choose to measure—and measurement itself must no longer be partial, vague, or self-serving. For the climate transition to succeed, it must be based on clear, detailed, and actionable data

Appendix 1: Policies activated under the Circular Economy Action Plan

New Circular Economy Action Plan of 2020				
Objective	**Year**	**Policy**	**Targets**	**Enforcement**
SUSTAINABLE PRODUCT POLICY INITIATIVE	2022	Eco-design for Sustainable Products Regulation (ESPR)	Improving EU products' circularity, energy performance, recyclability, durability and tracking with digital product passports (DPP)	In force since 18/07/2024
	2024	Empowering Consumers in the Green Transition Directive	A Directive amending Directives 2005/29/EC and 2011/83/EU to provide consumers with better information on product sustainability and protection against greenwashing.	In force on 27/09/2026
	2023	Right to Repair Directive	Makes it easier and more affordable for consumers to repair their e-products, fostering more sustainable consumption and reducing e-waste	In force on 30/07/2024
	2023	Green Claims Directive	Requires companies to back up their environmental claims with solid scientific evidence and standardized methodologies.	Proposal under review
	2022	Mandatory Green Public Procurement (GPP) criteria and targets in sectoral legislation	Encourages MS to support sustainable products	(non chiaro)
KEY PRODUCT VALUE CHAINS	2023	Review of the Rules on ELV	Reduce waste by: a) Compulsorily improve design to allow b) Mandatory recovery and reuse of CRMs	Proposal
	2022	Revision of the IED	Further reduces pollution from industries by expanding the IED's scope (e.g., inclusion of battery manufacturing) and strengthening emission permits (based on BAT).	In force since 04/08/2024
	2021	Review of the RoHS Directive in EEE and guidance to clarify its links with REACH and Eco-design requirements	Proposal under review	
	2023	Mandatory requirements on recycled plastic content and plastic waste reduction measures vehicles	Mandates reductions of plastic waste and promotes a circularity within the automotive by mandating ≥ 25% recycled plastic content in new vehicles by 2030.	Proposal under review

LESS WASTE, MORE VALUE	2023	Review of the 2018 Waste Framework Directive	a) ≥ 60% of municipal waste generated should be prepared for reuse or recycled: a binding obligation that has to be met by each MS individually b) Residual (non-recycled) municipal waste should be reduced by half (CEAP and zero pollution action plan) — a non-binding commitment that should be achieved at EU level. c) Introduced Extended Producer Responsibility (EPR) requiring producers to cover waste management.	Newest version under proposal
	2022	Tracking & restricting hazardous substances (Soc) in recyclables	Enhances safety and quality of recycled materials, thereby promoting their reuse by: a) introducing a harmonized information system b) develop methodologies to track, monitor and minimize SoC	Proposal under review
	2020	Scoping the development of further EU-wide end-of-waste and by-product criteria	Seeks to identify priority EU waste streams for developing further EU-wide EoW[318] by-products	Active since 2020, upgrades ongoing
	2021	Revision of the rules on waste shipments	Strengthens controls on waste exports and promotes recycling within the EU	2022
CROSSCUTTING ACTIONS	2020	Circular Cities and Regions Initiative	"Aims to increase synergies among projects and initiatives, disseminate relevant knowledge, and give greater visibility to best practices" (*Circular Cities and Regions Initiative | Circular Cities and Regions Initiative*, 2024)	2021
	2021	Global Alliance on Circular Economy and Resource Efficiency GACERE	Proposing a Global Circular Economy Alliance and initiating discussions on an international agreement on the management of natural resources	Active since 2022
MONITORING	2021	"Updating the Circular Economy Monitoring Framework to match new policy priorities and develop further indicators on resource use, including consumption and material footprints"[319]	Sets the development of a Circular Economy Monitoring Database on Eurostat	Established in 2018, updated in compliance with the New CEAP of 2020 in 2021

Appendix 2: Company Benchmarks

[318] End-of-Waste criteria specifying when certain waste ceases to be waste and becomes a product, or a secondary raw material (*Waste Framework Directive*, 2020).
Environment. https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en#:~:text=End%2Dof%2Dwaste%20criteria%20specify,or%20a%20secondary%20raw%20material.&text=This%20criteria%20for%20specific%20materials,through%20the%20%E2%80%9Ccomitology%E2%80%9D%20procedure.

[319] *EUR-LEX - 52020DC0098 - EN - EUR-LEX*. (2020). https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN.

/			Company									
KPI		Unit of measure	Alcoa (USA)	AMAG (AUT)	Century Aluminium (USA)	Constellium (FRA)	EGA (ARE)	HINDALCO (IND)	HYDRO (NOR)	Rio Tinto (GBR/AUS)	RUSAL (RUS)	Vedanta (IND)
1		tons of CO2e / ton of al	5.17	0.163	n/a	0.66	8.12	19.39	1.54	6.21	< 2.2	16.8
3		%	n/a	76.1%	n/a	42%	n/a	n/a	n/a	n/a	n/a	n/a
4		%	50%	≥ 70%	n/a	n/a	n/a	n/a	> 75%	n/a	n/a	n/a
5		%	42% pre-c	n/a	n/a	61% pre-c 38.1% post-c	n/a	n/a	59.9%	100%	n/a	n/a
6		tons / ton of Al	1.79	n/a	1.65	n/a	n/a	n/a	n/a	n/a	n/a	n/a
7		m^3 / ton of Al	n/a	5.7	2.13	18.2	n/a	50.07	n/a	n/a	n/a	41.99
8			n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
9		tons / ton of Al	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
10	10.1	MWh / ton of Al	n/a	1.184	n/a	3.20	n/a	19.39	14.03	n/a	n/a	52.62
	10.2	%	87%	35%	n/a	n/a		0.66%	70%	78%	99%	3.7%
	10.3	MWh / ton of alumina	n/a	< 15.5	n/a	n/a		n/a	14.03	n/a	n/a	n/a

Introduction

This Appendix seeks to ground the KPI thresholds proposed in Chapter 9 into existing, real-world conditions that fall within the context of feasibility.

For this purpose, the ten KPIs developed were applied to ten major aluminium producers to assess what can realistically be achieved in terms of business practices. This is because, while scientific literature provides important theoretical insights, the outcomes observed in a controlled setting often differ significantly from what is attainable within an actual company. For this reason – and to test the robustness of the KPIs – this analysis was carried out to gain a clearer picture of how companies can perform within the established thresholds, without them compromising their operational efficiency.

ALCOA (United States): KPI Performance

Alcoa Corporation is a USA-based company and one of the major players globally involved in the aluminium sector, active along the entire supply chain: from bauxite mining, to refining into alumina, to primary and secondary aluminium production. In terms of sustainability, being USA based, the company is not under CSRD or other obligations, allowing it not to be entirely transparent in terms of disclosure – explaining the limited availability of data presented below. The sources used for the following KPI assessment are the Alcola 2023 Sustainability Report[320], and the 2023 Alcoa Data Book[321], used to complement data provided by the reporting and allow necessary calculations.

SUSTAINABILITY KPIs

1 **Aluminium Physical Emission Intensity –** 5.17 metric tons of CO2e / metric ton of aluminium

2 **Scope 1 + 2 Alignment –** 0.119 = 11.9%

To obtain the Commitment Gap of Alcoa, the data presented below are needed:

- Target year – Alcoa's objectives are set on both 2030 and 2050, however for a more accurate comparison, 2030 will serve as target year.

[320] Alcoa. (2023). Alcoa 2023 Sustainability Report. In *Alcoa*. https://www.alcoa.com/sustainability.
[321] Alcoa. (2023). 2023 Alcoa Data Book. In *Alcoa*. Aloca. https://www.alcoa.com/sustainability/pdf/2023-Sustainability-Data-Book.xlsx.

- Company target – Scope 1 + 2 emission targets set by the company, in Alcoa's case a 50% reduction by 2030 compared to 2015, year that serves as a baseline (where the company emitted ≈ 7.10 tons of CO_2e / ton of aluminium), hence 7.10 divided by 2, which equals 3.55 tons of CO_2e / ton of aluminium.
- Business as usual (BAU) scenario – corresponding to a horizontal projection over time of emissions the year before decarbonisation efforts began, hence 2015 with its ≈ 7.10 tons of CO_2e / ton of aluminium
- Decarbonisation benchmark – according to TPI (and as shown in Chapter 2), the average aluminium intensity of an aluminium producer aligned with a Below 2° Scenario is 3.07 tons of CO_2e / ton of aluminium.

Meaning that, according to the formula

$$Commitment\ gap = \frac{T_{S1,2} - CB_{S1,2}}{BAU_{S1,2} - CB_{S1,2}}$$

that applied in Alcoa's case becomes

$$Commitment\ gap\ (Alcoa) = \frac{3.55 - 3.07}{7.10 - 3.07} = \frac{0.48}{4.03} = 0.119$$

In percentage terms, this means that Alcoa is 100% – 11.9% aligned with climate targets, hence it has fulfilled 88.1% of the gap. In other words, Alcoa is aligned, but there still is little room for improvement.

CIRCULARITY KPIs

3 **Share of Secondary Aluminium –** n/a

4 **Recycled Input Rate (RIR) per Product –** 50%, represented by Alcoa EcoDura, which only uses pre-consumer scrap[322]

5 **Pre- vs Post-Consumer Scrap –** 42% pre-consumer scrap (internal to Alcoa's operations) and 58% (corresponding to 328'280 tons) is external, but there is no information about the composition of the latter. Thus, the only certain claim is that Alcoa's scrap composition is made of at least 42% (corresponding to 237'720 tons) of pre-consumer scrap[323].

RESOURCE EFFICIENCY KPIs

6 **Bauxite Residue –** 1.79 metric tons / ton of alumina, an increase compared to the 1.69 metric tons of the previous year; however, Alcoa's long-term goal is a 15% reduction in bauxite residue land storage requirements per 1000 metric tons of alumina produced by 2030, against the 2015 baseline. In 2023, a 15.5% reduction was achieved relative to this baseline[324].

7 **Water Consumption –** n/a, but Alcoa shares that the intensity of total water use from company-defined water-scarce locations (primarily Western Australia) saw a 2.1% increase in 2023 compared to the 2015 baseline. Still, the company's long-term commitment is to reduce this intensity by 5% by 2025 and 10% by 2030 from the same baseline[325].

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[322] *Alcoa -- Sustana*. (n.d.). https://www.alcoa.com/products/sustana.
[323] Alcoa. (2023). 2023 Alcoa Data Book. In *Alcoa*. Aloca. https://www.alcoa.com/sustainability/pdf/2023-Sustainability-Data-Book.xlsx.
[324] Alcoa (2023), page 99.
[325] Alcoa (2023), page 89, 93, 95.

8 **Carbon Anodes Consumption –** n/a, however, Alcoa, in partnership with Rio Tinto, is developing the ELYSIS™ zero-carbon aluminium smelting technology, which aims to eliminate all direct GHG emissions from the smelting process, including those resulting from the consumption of traditional carbon anodes[326].

9 **Dross –** n/a, but Alcoa shares its commitment to a Dross-to-Pots initiative, designed to recycle dross directly back into the aluminium smelting process; in 2023, stable alloyed dross recycling was achieved at the Baie-Comeau smelter (Canada, Quebec), and pure dross recycling capabilities were fully deployed at the Alumar smelter (Brazil, São Luís) [327].

10 **Energy**[328]

10.1 Total Energy – n/a, but the company shares that its overall energy consumption decreased by 0.7% in 2023 compared to the previous year; however, the energy intensity increased by 1.5% over the same period.

10.2 Renewable Energy Share – 87%, surpassing the company's goal of sourcing 85% of its global smelting electricity from renewables by 2025.

10.3 Energy Consumed in Electrolysis – n/a

AMAG (Austria): KPI Performance

AMAG Austria Metall AG, is an Austrian aluminium company focused on recycling secondary aluminium from pre- and post-consumer waste: this approach explains their reduced environmental footprint – shown below; plus, AMAG uses only purchases renewable energy. However, some data such as Scope 3 emissions, are less accurate because of the dependency on external suppliers for upstream steps (bauxite mining and primary aluminium production), the most relevant one being Alouette. Sources used for this evaluation are AMAG's 2024 Financial Report[329], complemented by additional data on AMAG's sustainability page[330].

[326] Alcoa (2023), page 30.
[327] Alcoa (2023), page 97.
[328] Alcoa (2023), page 72.
[329] AMAG. (2024). FINANCIAL REPORT 2024: Competence in Aluminium. In *AMAG*. https://www.amag-al4u.com/fileadmin/user_upload/amag/Investor_Relations/Publikationen/2024/AMAG_GJ2024_Finanzbericht_en.pdf.
[330] *Publications | AMAG*. (n.d.). https://www.amag-al4u.com/en/media/publikationen.

SUSTAINABILITY KPIs

1 **Aluminium Physical Emission Intensity –** 0.163 tons of CO2 / ton of aluminium from Scope 1 + 2 emissions only, and 3.17 counting Scope 3 as well (calculated via personal elaboration of available data)[331]. However, all energy AMAG purchases is renewable, making Scope 2 emissions equal to 0[332]: this means that the 0.163 digit corresponds to Scope 1 emissions only. Furthermore, AMAG plans to reduce its Scope 1 + 2 emissions by 40% before 2030[333] and to achieve climate neutrality between 2040 and 2050[334].

2 **Scope 1 + 2 Alignment –** not calculated

CIRCULARITY KPIs

3 **Share of Secondary Aluminium –** 76.1%, coherent with AMAG's internal plans on keeping this digit between 75 and 80%[335].

4 **Recycled Input Rate (RIR) per Product –** ≥ 70%, corresponding to AMAG AL4®ever, which is AMAG's most circular product, with a CO2 footprint of below 4 tons / ton of aluminium – its recycled content is consistent with the company's share of secondary aluminium presented just above (75 – 80%)[336].

5 **Pre- vs Post-Consumer Scrap –** n/a, however it is shared that the overall scrap processed in 2024 is of 294'700 tons – coming from both pre- and post-consumer sourcing[337].

RESOURCE EFFICIENCY KPIs

6 **Bauxite Residue –** n/a, since this KPI is not directly applicable to AMAG's own operations at its Ranshofen site (Austria), because the company does not procure bauxite or alumina for this facility: this operation is dealt with by Alouette (Canada, Quebec), which however fails to provide numbers[338].

7 **Water Consumption –** 5.7 m^3 / ton of aluminium, well below the internal goal of 6 m^3[339].

8 **Carbon Anodes Consumption –** n/a, as, again, this step is dealt with by Alouette.

9 **Dross –** n/a, primary dross falls under Alouette's operations.

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331 AMAG (2024), page 2
332 AMAG (2024), page 48
333 AMAG (2024), page 25
334 AMAG (2024), page 46
335 AMAG (2024), page 6, 71
336 *AMAG AL4® ever | AMAG*. (n.d.). https://www.amag-al4u.com/en/products/amag-al4-ever.
337 AMAG (2024), page 2
338 AMAG (2024), page 6
339 AMAG (2024), page 2, 26

10 Energy

10.1 Total Energy – 1.184 MWh / ton of aluminium[340]

10.2 Renewable Energy Share – 35% for AMAG global[341], but installments in Germany, reach up to 86%. AMAG maintains a commitment to purchase 100% renewable electricity at all its production sites; he 35% figure for total energy indicates that while electricity sourcing is fully renewable, other energy requirements (e.g., for thermal processes, fuels) still rely partly on non-renewable sources, a common challenge for industrial manufacturers[342].

10.3 Energy Consumed in Electrolysis – n/a, but lower than Alouette's internal limit of 15.5 MWh / ton of aluminium[343].

CENTURY ALUMINIUM COMPANY (USA): KPIs Performance

Century Aluminium Company ("Century") is an integrated producer of primary aluminium, operating aluminium reduction facilities (smelters) in the United States and Iceland. They also have a 55% joint venture interest in the Jamalco bauxite mining operation and alumina refinery in Jamaica, acquired in 2023, which supplies alumina to their Iceland smelter. Century also owns a carbon anode production facility in the Netherlands. The company aims to provide reliable aluminium products, a safe and sustainable workplace, and compelling value for stakeholders, conducting business with a focus on sustainability and the health and safety of their people and communities. Century has set ambitious carbon reduction goals, including a 30% reduction in emissions from primary production by 2030 (from a 2021 baseline) and achieving carbon neutrality by 2050. They offer a low-carbon aluminium product line, Natur-Al™[344].

SUSTAINABILITY KPIs

1 **Aluminium Physical Emission Intensity (Scope 1 + 2)** – Century Aluminium reports Scope 1 emissions intensity for its individual sites[345]. For 2023, these are:

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[340] AMAG (2024), page 48

[341] While AMAG reports that only 35 – 36% of the total energy used comes from renewable sources, it still claims zero Scope 2 emissions. This is because all purchased electricity (the component considered in Scope 2, mentioned in Point 1 of AMAG's performance report) is certified as renewable. In contrast, the remaining energy requirements, related to internal thermal processes such as smelting, are covered by fossil fuels, thus falling under Scope 1. This distinction is common in the industrial sector, where full electrification of high-temperature processes remains an open challenge.

[342] AMAG (2024), page 47

[343] AMAG (2024), page 31

[344] Century Aluminium (2023), page 19

[345] Century Aluminium. (2023). *A Green Path to a New Century: 2023 ESG report.* Page 4 – 9

- Norðurál & Vlissingen: 1.84 MT CO2e / MT Al.
- Sebree: 2.62 MT CO2e / MT Al.
- Mt Holly: 2.36 MT CO2e / MT Al. The company states that Scope 2 emissions are their largest source. A consolidated Scope 1 + 2 emission intensity for the entire company's aluminium production is not explicitly provided in the provided excerpts.

The Natur-Al™ product from Norðurál is reported to have a total carbon footprint (Scope 1, 2, and 3 combined) of less than four tons of carbon dioxide equivalents per ton of aluminium[346].

2 **Scope 1 + 2 Alignment** – not calculated. Century has set targets to reduce carbon emissions from primary production by 30% by 2030 (from a 2021 baseline) and to be carbon neutral by 2050[347]. They are developing enterprise-wide initiatives to achieve these. However, the provided sources do not contain information that allows for calculating the alignment with specific science-based pathways or sector-specific decarbonization trajectories.

CIRCULARITY KPIs

3 **Share of Secondary Aluminium – n/a**. The report highlights increasing the amount of scrap reused in production[348] and exploring avenues to reprocess and reintegrate scrap aluminium into production processes[349]. They also mention expanding recycling capacity[350]. However, a specific percentage representing the overall share of secondary aluminium produced compared to the total amount is not disclosed in the provided excerpts.

4 **Recycled Input Rate (RIR) per product – n/a**. The Century report mentions their Natur-Al™ low-carbon product and generally increasing the use of scrap[351]. However, it does not provide specific data or percentages for the recycled input rate for individual products.

5 **Pre- vs Post-Consumer Scrap – n/a**. The report discusses reusing scrap and managing aluminium scrap as part of waste management[352]. It does not provide a quantitative breakdown or percentage share differentiating pre-consumer from post-consumer scrap used in their operations.

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346 Century Aluminium (2023), page 9
347 Century Aluminium (2023), page 11
348 Century Aluminium (2023), page 9
349 Century Aluminium (2023), page 26
350 Century Aluminium (2023), page 9
351 Century Aluminium (2023), page 9, 17
352 Century Aluminium (2023), page 9, 26

RESOURCE EFFICIENCY KPIs

6 **Bauxite Residue** – Century Aluminium acquired a 55% interest in the Jamalco bauxite mining and alumina refining operation in Jamaica in 2023[353]. The report lists "Red mud" as a type of waste generated, amounting to 1,139,141 metric tons in 2023[354]. This waste is associated with bauxite refining. With a total aluminium production of 690,962 metric tons in 2023[355], this corresponds to an intensity of approximately 1.65 metric tons of red mud per metric ton of aluminium produced (1,139,141 MT Red Mud / 690,962 MT Al) based on reported totals, although red mud is a byproduct of alumina, not aluminium production directly. The report notes the importance of effective waste management for bauxite mining and refining.

7 **Water Consumption** – The report lists "Municipal / potable water" usage. For 2023, this amounted to 1,623,648,420 liters[356]. With a total aluminium production of 690,962 metric tons in 2023, this corresponds to approximately 2.35 m^3 per metric ton of aluminium produced (1,623,648,420 L / 690,962 MT Al, converted from liters to m^3). The figure provided in the source specifically refers to municipal/potable water and may not represent total water withdrawal for all industrial uses (e.g., cooling).

8 **Carbon Anodes Consumption** – n/a. Century operates a carbon anode production facility in the Netherlands and produces anodes on-site at its US smelters, as carbon anodes are consumed in the production of primary aluminium[357]. While this is a relevant material input for their primary production, the report does not provide a quantitative figure for carbon anodes consumption or consumption intensity (kg per ton of aluminium).

9 **Dross – n/a**. The report discusses managing waste streams and reprocessing "aluminium scrap and other byproducts of the aluminium production process"[358], but the specific term "dross" is not used, nor is a quantitative figure for dross generation or management provided in the provided excerpts.

10 **Energy**

10.1 Total Energy Total Energy – n/a. The report highlights electricity as a primary resource and lists total electricity consumption as 10,579,462 GWh in 2023[359]. It also lists other energy sources used at Jamalco (Diesel/fuel oil, Gasoline, Natural gas)

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[353] Century Aluminium (2023), page 4,5
[354] Century Aluminium (2024), page 26
[355] Century Aluminium (2023), page 8
[356] Century Aluminium (2023), page 25
[357] Century Aluminium (2023), page 4
[358] Century Aluminium (2023), page 26
[359] Century Aluminium (2023), page 23

with quantitative data[360]. However, a consolidated figure for total energy consumption across all Century operations (including electricity and other fuels) is not provided in the excerpts, nor is a total energy intensity per ton of aluminium produced.

10.2 **Renewable Energy Share** – Century states that their total consumption of electricity in 2023 was 10,579,462 GWh, with almost 50% from renewable sources[361]. They primarily use hydroelectric power where available and look to geothermal, wind, and solar[362]. A solar rooftop project at Vlissingen is expected to generate over 3 GWh, fulfilling 20% of that plant's annual energy demand[363].

10.3 **Energy Consumed in Electrolysis** – n/a. While the report provides total electricity consumption, it does not break down the portion consumed specifically by the electrolysis process across all smelters, nor provide an intensity figure for this step.

CONSTELLIUM (France): KPI Performance

Constellium is a French-based company specialized in the processing and recycling of aluminium, operating only in the downstream end of the supply chain: it purchases primary and secondary aluminium to produce rolled products, extrusions, and components for the automotive, aerospace, and packaging industries. By not handling upstream steps (such as bauxite mining or electrolysis), its environmental footprint is reduced, both in terms of energy (thus CO2) consumption, and residual waste flows (bauxite mining, carbon anodes, etc.). With an annual recycling capacity of more than 750,000 tons, it plays a key role in aluminium circularity[364]. All the information provided below is drawn from Constellium’s 2024 Sustainability Report[365].

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[360] Century Aluminium (2023), page 25
[361] Century Aluminium (2023), page 23
[362] Century Aluminium (2023), page 21
[363] Century Aluminium (2023), page 21
[364] *Constellium recycled feedstock rate holds steady in 2024: Global aluminium producer says it relied on 42 percent recycled materials for the second year in a row.* (2025, March 7). Recycling Today. https://www.recyclingtoday.com/news/constellium-aluminium-recycling-usa-france-added-capacity-sustainability-2024/.
[365] Constellium. (2024). Constellium Sustainability Report 2024: Advancing a Sustainable Economy Together. In *Constellium*. https://res.cloudinary.com/constellium/image/upload/v1743515313/PDF%20documents/Brochures%20and%20Reports/Business%20and%20Sustainability%20Reports/2025%20-%20Sustainability%20Report%202024/EN_2024_Sustainability_Report_xgvy6v.pdf.

SUSTAINABILITY KPIs

1 **Aluminium Physical Emission Intensity (Scope 1 + 2) –** 0.66 mt of CO2e / ton of aluminium shipped. Adding Scope 3 emissions, intensity is 5.42 mt of CO2e / ton shipped. Constellium aims to reduce Scope 1 + 2 emission intensity by 30% by 2030 compared to 2021 (0.70 mt of CO2e / ton of aluminium shipped).

2 **Scope 1 + 2 Alignment –** not calculated

CIRCULARITY KPIs

3 **Share of Secondary Aluminium –** 42% (total for 2024, of which 16% is post-consumer and is 26% pre-consumer)[366]. The short-term goal is to increase the recycled input to 750'000 mt by 2026, while the long term one is to sourcing 50% of all aluminium input from recycled scrap by 2030[367]**.**

4 **Recycled Input Rate (RIR) –** n/a, since no data are available on the percentage of recycled material for specific products beyond the overall average shown above.

5 **Pre- vs Post-Consumer Scrap –** 61% of pre-consumer scrap (corresponding to 396.760 tons of aluminium) and 38.1% of post-consumer scrap (corresponding to 244.160 tons of aluminium).

RESURCE EFFICIENCY KPIs

6 **Bauxite Residue –** n/a, as Constellium is a downstream operator that thus, does not engage in bauxite mining and alumina refining.

7 **Water Consumption –** 18. 2 m³ / ton of aluminium shipped (water withdrawal intensity)[368].

8 **Carbon Anodes Consumption –** n/a, for the same reasons of point 6 just above.

9 **Dross –** n/a, as Constellium does not engage in primary aluminium production; however, all dross generated by secondary maltings and castings is reused internally.

10 **Energy**

10.1 Total Energy – 12.7 GJ / mt of aluminium shipped.

10.2 Renewable Energy Share – n/a

10.3 Energy Consumed in Electrolysis – n/a, as Constellium is a downstream operator

[366] Constellium (2024), page 37
[367] Constellium (2024), page 23
[368] Constellium (2024), page 44

EGA (United Arab Emirates): KPIs Performance

Emirates Global Aluminium (EGA), based in the United Arab Emirates, is one the world's largest producers of "premium aluminium" and a key player in the Middle Eastern economy[369]. Formed through the merger of DUBAL and EMAL, it also produces value-added aluminium. It aims for climate neutrality by 2050 by promoting the CelestiAL solar brand[370], alongside substantial investment in expanding its recycling capacity. Notably, EGA's emissions profile is its reported as having zero Scope 2 emissions for 2023, which implies that all its electricity is either self-generated (with emissions accounted for under Scope 1) or procured through arrangements that ensure zero reportable market-based Scope 2 emissions, such as direct Power Purchase Agreements (PPAs) for solar energy[371]. All data shown below is drawn from EGA's 2023 Sustainability Report[372].

SUSTAINABILITY KPIs

1. **Aluminium Physical Emission Intensity (Scope 1 + 2) –** 8.12 tons / ton of aluminium
2. **Scope 1 + 2 Alignment –** not calculated

CIRCULARITY KPIs

3. **Share of Secondary Aluminium –** While the 2023 sustainability report does not specify the percentage share of secondary aluminium for 2024, it confirms major acquisitions in the recycling sector (Spectro Alloys and Leichtmetall) that occurred in 2024, whose initiatives and data will be included in the next annual report, indicating a strategy to grow EGA's recycling business[373].
4. **Recycled Input Rate (RIR) –** n/a, since EGA does not disclose specific data on the percentage of recycled aluminium in its product. There is, however, a reference to CelestiAL – R, stating that in 2023, almost all the CelestiAL supplied to BMW Group was "solar aluminium further softened with recycled metal"[374]: however, the exact percentage of recycled content is not specified, nor is the total volume of CelestiAL-R compared to total

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[369] Emirates Global Aluminium. (2025, May 29). *Emirates Global Aluminium Sustainability Report*. DitchCarbon. https://ditchcarbon.com/organizations/emirates-global-aluminium.
[370] *CelestiAL solar aluminium | EGA*. (n.d.). https://www.ega.ae/en/products/celestial.
[371] *Net zero FAQs | EGA*. (n.d.). https://www.ega.ae/en/sustainability/net-zero/net-zero-faqs.
[372] EGA (Emirates Global Aluminium). (2023). EGA 2023 Sustainability Report. In *EGA (Emirates Global Aluminium)*. https://www.ega.ae/en/sustainability/sustainability-reports.
[373] EGA (2023), page 15
[374] Ega. (2023, June 15). *BMW Group first to source CelestiAL-R, solar aluminium with recycled metal, from EGA*. BMW Group First to Source CelestiAL-R, Solar Aluminium With Recycled Metal, From EGA. https://media.ega.ae/bmw-group-first-to-source-celestial-r-solar-aluminium-with-recycled-metal-from-ega/.

production (which could answer to KPI 3). Still, reports specify that Spectro Alloys (acquired in September 2024) used 70% post-consumer scrap as raw material for its production (25.4 kt). This figure sets the bar for future expected results but does not allow an average recycled input rate to be calculated for all 2.74 million tons of EGA output in 2024[375].

5 **Pre- vs Post-Consumer Scrap –** n/a, but the company shares that it could recover 60% of its internal dross, for a total of 36'000 tons of aluminium. As mentioned above in Point 4, there is no information on the exact quantities of post-consumer scrap used, neither there is a clear quantification of the total pre-consumer scrap.

RESOURCE EFFICIENCY KPIs

6 **Bauxite Residue –** n/a, there only is reference to the installation of a pilot implant to convert this residue to manufactured soil ("Turba"). Aside from this, only generic industry data are cited (~ 4 tons of residue per ton of aluminium globally or 120 – 150 Mt annually globally)[376].

7 **Water Consumption –** n/a, EGA only shares its 2019 consumption of 54'938 mega liters and pledges to monitoring of its water discharges in UAE[377].

8 **Carbon Anodes Consumption –** n/a

9 **Dross –** n/a,

10 **Energy**

10.1 Total Energy – n/a, EGA shares only that its fusion and melting operations consumed about 116.9 GJ / ton of aluminium produced[378].

10.2 Renewable Energy Share – n/a, EGA only claims that its sale of solar energy increased by 54.7% compared to 2022 to support CelestiAL-R production[379].

10.3 Energy Consumed in Electrolysis – n/a

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375 EGA (2023), page 21
376 EGA (2023), page 33, 67
377 EGA (2023), page 59
378 EGA (2023), page 51
379 EGA (2023), page 9, 31, 52

HINDALCO (India): KPIs Performance

Hindalco Industries Limited is a flagship company of the Aditya Birla Group and a leading integrated aluminium producer based in India. Its operations span the entire aluminium value chain, from bauxite mining, alumina refining, and coal mining to captive power plants, aluminium smelting, and downstream manufacturing of rolled products, extrusions, and foils. Hindalco's wholly-owned subsidiary, Novelis, is a global leader in aluminium rolling and recycling. Hindalco has established ambitious ESG goals, aiming for net-zero carbon emissions, water positivity, no net loss to biodiversity, and zero waste to landfill by 2050. In terms of sustainability, Hindalco presents a dual nature: its Indian primary operations have historically been carbon and resource-intensive due to reliance on coal-based power (however, there is an ongoing transition for a 100 MW round-the-clock carbon-free power project for its Odisha smelter); in contrast, its subsidiary Novelis is a global frontrunner in aluminium recycling, significantly enhancing the Group's overall sustainability performance. This dichotomy means that consolidated KPIs for Hindalco are influenced heavily by Novelis, and that a clear distinction between the two is often necessary for accurate benchmarking. The information presented below is mainly shared by the company in its 2023 – 2024 Annual Report[380].

SUSTAINABILITY KPIs

1 **Aluminium Physical Emission Intensity (Scope 1 + 2) –** 19.39 tons of CO2e / ton of aluminium produced, which – however – may be heavily influenced by the Novelis performances' acting as "offsetting"[381].

2 **Scope 1 + 2 Alignment –** not calculated

CIRCULARITY KPIs

3 **Share of Secondary Aluminium –** while specific share of secondary aluminium is not available from Hindalco, there is data from its subsidiary Novelis, with an average recycled content of 63% (61% in the previous year)[382]. The aim is reaching a solid 75% by 2030.

4 **Recycled Input Rate (RIR) –** n/a

5 **Pre- vs Post-Consumer Scrap –** n/a

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[380] Hindalco. (2024). INTEGRATED ANNUAL REPORT 2023-24 HINDALCO INDUSTRIES LIMITED: A force for good. In *Hindalco*. https://www.hindalco.com/upload/pdf/hindalco-annual-report-2023-24.pdf.
[381] Hindalco (2024), page 151
[382] Hindalco (2024), page 21, 163

RESOURCE EFFICIENCY KPIs

6 **Bauxite Residue –** n/a, but Hindalco shares that it exceeded the goal of reusing 100% of it (hitting a 109% reusage rate)[383], and is actively working towards a long term goal of zero waste to landfill by 2050; key bauxite applications Hindalco is pushing for include backfilling and road construction.

7 **Water Consumption –** 50.07 m^3 / mt of aluminium; Hindalco also claims it seeks to achieve water positivity by the end of 2025 for its minerary sites[384].

8 **Carbon Anodes Consumption –** n/a

9 **Dross –** n/a

10 **Energy**

  10.1 Total Energy – 69.81 GJ / mt of aluminium produced[385]

  10.2 Renewable Energy Share – 0.66%, corresponding to the declared 320.91 million of GJ in 2024[386]

  10.3 Energy Consumed in Electrolysis – n/a

HYDRO (Norway): KPIs Performance

Norsk Hydro is a Norwegian-based, fully integrated aluminium company with a global presence, with its operations starting from bauxite mining (Paragominas, Brazil) and alumina refining (Alunorte, Brazil), to primary aluminium production – which is almost entirely hydropower-based, particularly in Norway. Hydro has committed to achieving net-zero emissions by 2050 or earlier and plans to do so the following two ways: decarbonizing its primary production through renewable energy (and relative process innovations), while aggressively expanding its aluminium recycling capacity along with the market for its recycled-content products; in other words, where emissions cannot be cut any further, secondary material can be used instead. Hydro's operations in Brazil for bauxite and alumina are accompanied with environmental and social considerations, such as bauxite residue management and biodiversity impacts, which differ from those associated with its smelting operations, particularly in Norway: this signals due diligence and disclosure along the entire value chain.

[383] Hindalco (2024), page 169
[384] Hindalco (2024), page 159, page 53, 156
[385] Hindalco (2024), page 147
[386] Hindalco (2024), page 21, 147

SUSTAINABILITY KPIs

1 **Aluminium Physical Emission Intensity (Scope 1 + 2) –** 1.54 tons of CO2e / ton of aluminium produced; This figure excludes Slovalco in 2022 due to curtailment and Albras from 2019 due to extraordinary start-up emissions.

2 **Scope 1 + 2 Alignment –** not calculated

CIRCULARITY KPIs

3 **Share of Secondary Aluminium –** n/a as a net share, but Hydro shares that the exact quantity of post-consumer recycled material is 444’000 tons (a massive 38% increase compared to the previous year). Plus, the company has a strategic internal target to increase its post-consumer scrap recycling capacity to between 850’000 and 1’200’000 tons per year by 2030.

4 **Recycled Input Rate (RIR) –** ≥ 75%, represented by the Hydro CIRCAL line; however, there also is a Hydro CIRCAL 100R, corresponding to a 100% RIR, but since it seems to be less common, this product is likely not commercial yet.

5 **Pre- vs Post-Consumer Scrap –** 59.9% of pre-consumer scrap (corresponding to 662’280 tons of aluminium) and 40.1 of post-consumer scrap (corresponding to 443’760 tons of aluminium).

RESOURCE EFFICIENCY KPIs

6 **Bauxite Residue –** n/a, but Hydro shares that it is actively working on solutions for bauxite residue valorisation; this includes a partnership with WAVE Aluminium to explore reuse possibilities and the construction of a processing plant at Alunorte, designed to initially process 50,000 tons per year of bauxite residue to produce pig iron. Furthermore, Hydro aims to eliminate the need for new bauxite residue storage areas by 2050 and to utilize 10% of its bauxite residue (generated from its Alunorte refinery) from 2030 onwards.

7 **Water Consumption –** n/a

8 **Carbon Anodes Consumption –** n/a, Hydro only mentions that 25 – 30% of the cash costs associated with its primary aluminium production are due to the consumption of carbon anodes.

9 **Dross** – n/a

10 **Energy**

10.1Total Energy – 14.03 MWh / ton of aluminium produced.

10.2 Renewable Energy Share – ≥ 70%.

10.3 Energy Consumed in Electrolysis – 14.03 MWh / ton of aluminium produced, corresponding to the overall energy consumption of the company since it is primarily a smelter.

RIO TINTO (United Kingdom, Australia): KPI Performance

Rio Tinto is a large global mining company, engaged in research, mining and processing of a wide range of mineral resources: its main products include iron ore, aluminium, copper, industrial minerals (borates, titanium dioxide and salt) and diamonds[387]. Its operations extend worldwide, with a strong presence in Australia and North America, however, its legal headquarters are in Australia (Rio Tinto Limited) and United Kingdom (Rio Tinto plc). Due to the large scale of its operations, and the aggregate nature of its reports, Rio Tinto fails to provide detailed metrics on its aluminium production.

SUSTAINABILITY KPIs

1 **Aluminium Physical Emission Intensity (Scope 1 + 2)** – Rio Tinto declares a total of 30.7 Mt of CO2e[388], of which "approximately two-thirds" derive from their Aluminium business[389] (so around 20.5 Mt of CO2e). The resulting KPI hence is 6,21 t of CO2e per t of Aluminium.

2 **Scope 1 + 2 Alignment** – not calculated.

CIRCULARITY KPIs

3 **Share of Secondary Aluminium** – In 2024, Matalco's recycled aluminium production was 528 thousand tons, with Rio Tinto's 50% share amounting to 264 thousand tons[390] furthermore, Rio Tinto acquired a 50% stake in Matalco, a leading North American

[387] Rio Tinto. (n.d.). *Rio Tinto*. Rio Tinto Global. Retrieved May 29, 2025, from https://www.riotinto.com/en.
[388] Rio Tinto. (2024). *Rio Tinto Annual Report 2024*. Retrieved May 29, 2025, from https://cdn-rio.dataweavers.io/-/media/content/documents/invest/reports/annual-reports/2024-annual-report.pdf.
[389] Rio Tinto (2024), page 47
[390] Rio Tinto (2024), page 275

aluminium recycler, in 2023, to support “the growing demand for low-carbon and recycled products” [391] and invested USD 1.1 billions investment in expanding the AP technology AP60 aluminium smelter in Quebec[392].

4 **Recycled Input Rate (RIR)** – n/a

5 **Pre- vs Post-Consumer Scrap** – 100% pre-consumer waste (corresponding to 17’000 tons of aluminium), and thus, no post-consumer scrap at all.

RESURCE EFFICIENCY KPIs

6 **Bauxite Residue** – n/a

7 **Water Consumption** – n/a

8 **Carbon Anodes Consumption** – n/a, however Rio Tinto provides figures for the emissions directly attributable to the use of carbon anodes in its aluminium smelters (which, according to them, accounts for a 25% of the total[393]): in 2024, emissions from aluminium anodes amounted to 6.9 Mt CO2e (7.1 in 2023)[394]. Plus, the company mentions its commitment in the development of the ELYSIS™, a joint venture with Alcoa, supported by Apple, the Government of Canada, and the Government of Quebec aimed to develop a breakthrough inert anode technology that eliminates all direct greenhouse gases from the aluminium smelting process, replacing carbon anodes[395].

9 **Dross** – n/a

10 **Energy**

10.1 Total Energy – n/a

10.2 Renewable Energy Share – In 2024, Rio Tinto’s percentage of electricity from renewable sources was 78%[396]: an improvement from 2023’s 71%, for a company that with the explicit aim to reach 90% by 2030[397]. Most of this energy comes from operations in the Atlantic area (Canada, New Zealand, Iceland)[398], which are largely powered by hydropower; specifically, the New Zealand Aluminium Smelters (NZAS), signed long-term PPAs for a total of 572 MW of hydroelectricity[399].

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[391] Rio Tinto (2024), page 43, 176
[392] Rio Tinto (2024), page 11, 43
[393] Rio Tinto (2024), page 47
[394] Rio Tinto (2024), page 54
[395] Rio Tinto (2024), page 24
[396] Rio Tinto (2024), page 41
[397] Rio Tinto (2024), page 47
[398] Rio Tinto (2024), page 275
[399] Rio Tinto (2024), pages 51

In contrast, Pacific operations, particularly the Australian Boyne and Tomago smelters, rely on a coal-based power grid[400]. Despite difficulties, Rio Tinto is actively working to repower its Gladstone assets with renewable energy[401], including PPAs for a combined 2.2 GW of renewable energy to repower its Boyne smelter[402].

10.3 Energy consumed in Electrolysis – n/a

RUSAL (Russia), part of EN+ Group: KPIs Performance

RUSAL (United Company RUSAL) is one of the world's largest companies in primary aluminium and alumina production, based in Russia. Founded in 2000, its operations cover the entire aluminium supply chain: from bauxite mining to alumina refining and primary aluminium smelting. The company has production sites in Russia, Guinea, Jamaica and other countries. RUSAL is known for focusing on decarbonization, promoting the use of hydropower in its plants[403].

SUSTAINABILITY KPIs

1. **Aluminium Physical Emission Intensity (Scope 1 + 2) –** ≤ 2.2 tons of CO2e / ton of aluminium produced[404]. The Group launched its low-carbon aluminium brand globally in 2017 under the ALLOW trademark.
2. **Scope 1 + 2 Alignment** – not calculated

CIRCULARITY KPIs

3. **Share of Secondary Aluminium –** While RUSAL's focus is clearly on primary aluminium, the report explicitly mentions and provides data on "secondary alloys" production, which in 2024 was of 10.9 thousand tons, 58% more than the previous year[405].
4. **Recycled Input Rate (RIR) –** While RUSAL does produce secondary alloys, it does not provide data for their contribution to the overall metal output in relation to recycled input. However, it mentions that "IRKAZ [(the Irkutsk Aluminium Smelter – annual capacity of

[400] Rio Tinto (2024), page 48
[401] Rio Tinto (2024), page 53
[402] Rio Tinto (2024), page 51
[403] *RUSAL*. (n.d.). https://rusal.ru/en/.
[404] RUSAL (2024), page 50
[405] RUSAL (2024), page 87

425 thousand tons)] started production of the products with recycling content"[406]. Plus, RUSAL shares its successful testing of a new optimized PEFA alloy with 50% recycled content from post-consumer scrap,[407] demonstrating potential for increases recycled contents in future years.

5 **Pre- vs Post-Consumer Scrap –** As already mentioned, while RUSAL is primarily a producer of primary aluminium and recycles internal process waste (pre-consumer scrap)[408], RUSAL has successfully tested alloys incorporating post-consumer scrap.

RESOURCE EFFICIENCY KPIs

6 **Bauxite Residue –** While the sources do not provide a specific quantity or intensity figure for bauxite residue produced, RUSAL refers to efforts in "red mud basin disposal sites" restoration[409] and management of "waste mud"[410].

7 **Water Consumption –** Although specific data is not provided, RUSAL 2024 report shows that water management and consumption are aspects of their operations as (1) "the group's production facilities continued to improve closed-loop water circulation systems"[411] and (2) "implementation of schemes of waste heat removal from condensate, which is used for water turnover make-up" in the Ural Alumina Refiner[412].

8 **Carbon Anodes Consumption –** Again, RUSAL does not specify consumption intensity, though underlines the effort of development and testing of "electrolysers with inert anodes with zero carbon footprints"[413]

9 **Dross –** While RUSAL does not mention "dross", the report explicitly mentions that "the Bratsk, Krasnoyarsk, and Sayanogorsk aluminium smelters designed, built, and commissioned aluminium recovery facilities to process the Company's entire volume of aluminium-containing slag" (which in the context of aluminium casting is essentially dross), which "has made it possible to switch to zero-waste technology in the cathouses"[414].

10 **Energy**

10.1 Total Energy – n/a

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[406] RUSAL (2024), page 78
[407] RUSAL (2024), page 65
[408] RUSAL (2024), page 87, 6
[409] RUSAL (2024), page 256, 257
[410] RUSAL (2024), page 60
[411] RUSAL (2024), page 21
[412] RUSAL (2024), page 81
[413] RUSAL (2024), page 9, 64
[414] RUSAL (2024), page 70

10.2 Renewable Energy Share – RUSAL explicitly states that it "obtains over 99% of its electricity for metal production from renewable sources"[415]. For what concerns the smelting operations, they "are favorably located close to the Siberian hydropower plants sourcing approximately 94% of the Group's total electricity needs"[416].

10.3 Energy Consumed in Electrolysis – RUSAL does not give aggregate data, but provide specific data on energy consumed per ton of aluminium in the electrolysis process, particularly in the context of energy efficiency initiatives and new technologies:

- Testing and implementation of new high energy efficiency Heavy-duty pots (the RA-550 of the Sayanogorsk Aluminium Smelter), with a power consumption of less than 12,800 kW/h per ton[417].
- Conversion of existing pots that allowed for a reduction in power consumption of 500-900 kWh per ton of aluminium[418].
- 2024 energy-saving measures, which decreased direct current energy consumption by "493 kWh per ton" compared to 2013[419].

VEDANTA (India): KPIs Performance

Vedanta Aluminium, a business of Vedanta Limited, is India's largest producer of the metal and one of the top global aluminium manufacturers. With most operations located in India, particularly in Odisha and Chhattisgarh, the company operates in the upstream section of the aluminium supply chain: this includes alumina refining, aluminium smelting, and power generation, along with captive coal and bauxite mines. Furthermore, Vedanta Aluminium has committed to achieving NetZero Carbon by 2050 and has introduced low-carbon aluminium product lines, Restora and Restora Ultra, leveraging renewable energy and recycled content to reach said goal[420].

[415] RUSAL (2024), page 45
[416] RUSAL (2024), page 9
[417] RUSAL (2024), page 62
[418] RUSAL (2024), page 62, 63
[419] RUSAL (2024), page 78
[420] Vedanta Limited. (n.d.). *India's leading natural resources and technology conglomerate | Vedanta Group Company*. https://www.vedantalimited.com/eng/.

SUSTAINABILITY KPIs

1 **Aluminium Physical Emission Intensity (Scope 1 + 2) –** 16.8 tons of CO2e / ton of metal, which represents a 10,16% decrease compared to the FY2021, and a 29% one compared to the baseline of FY2012[421].

2 **Scope 1 + 2 Alignment –** not calculated

CIRCULARITY KPIs

3 **Share of Secondary Aluminium –** n/a (although Vedanta underlines its effort in general circularity, waste management and recycling[422])

4 **Recycled Input Rate (RIR) –** While Vedanta does not specify the exact amount of recycled content of its products, the most ambitious one seems to be the Restora Ultra, with a near-zero carbon footprint (less than 0.3 tCO2e/ton of Al)[423], which is manufactured from recycled aluminium dross.

5 **Pre- vs Post-Consumer Scrap –** The Vedanta 2024 focuses on the recycling of internal waste streams, particularly aluminium dross (which is pre-consumer scrap), not mentioning the use of any post-consumer scrap in their operations.

RESOURCE EFFICIENCY KPIs

6 **Bauxite Residue** – Vedanta discusses practices for managing bauxite residue or red mud (such as alkalinity and toxicity) and reusing it[424]. In FY 2023-24 it produced 2,42 million MT Bauxite residue, whose 0.11 million MT got utilized. Furthermore, Vedanta claims that it has achieved a 133% ash utilization rate[425], which however is another by-product aside from red mud.

7 **Water Consumption** – The Vedanta report discusses freshwater withdrawal (the amount of fresh water taken from external sources by Vedanta for its operations), which happens to amount to 99.11 million cubic meters[426] (in respect of a production of 2.36 MT of aluminium[427]). The resulting freshwater withdrawal per ton of aluminium is approximately

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[421] Vedanta (2024), page 72
[422] Vedanta (2024), page 108
[423] Vedanta (2024), page 15
[424] Vedanta (2024), page 103
[425] Vedanta (2024), page 3
[426] Vedanta (2024), page 86
[427] Vedanta (2024), page 3

41.99 cubic meters of water per million MT. Furthermore, Vedanta claims to have successfully recycled over 15 billion liters of water in FY 2023-2024[428], which, recalling the previous aluminium production data, means an approximate 6.36 cubic meters of water recycled per ton of aluminium produced.

8 **Carbon Anodes Consumption –** n/a (a specific quantitative figure for carbon anodes consumption, such as tons consumed or m³ per ton of aluminium produced, is not explicitly provided).

9 **Dross –** Vedanta Aluminium claims to actively manage and reuse/recycle dross and other hazardous waste streams. Of the over 2 MT of aluminium Vedanta produces, 1.5% of it is lost as a dross. Thanks to partnering with Ruyana Refining, Vedanta "ha[s] increased aluminium recovery to nearly 90%", ("and the non-metallic residues are repurposed into briquettes used in the steel industry")[429].

10 **Energy**

10.1 Total Energy – Vedanta's total energy consumption for the Aluminium sector in FY 2024 was 95.7 million MWH (410'225'334 GJ)[430], with an energy intensity in GJ/Production Output of 52.62 GJ/Production Output for BALCO, 51.47 for Jharsuguda, 7.28 for Lanjigarh (three operational sites and business of Vedanta), which they claim to be decreasing respect to the past[431], saving 1.3 Mn GJ[432].

10.2 Renewable Energy Share – according to the report, of the Vedanta's total energy usage in all business sectors (95'726190 MWH[433]), just the 3.7% was renewable energy[434] (1'294'659 MWH). Vedanta set the goals to reach 7% renewable energy by 2025 and 30% by 2030, through PPAs to secure 400 MW of RE power by 2025 and 1500 MW by 2030[435]. The long-term aspiration is to become 100% renewable energy by 2050[436].

10.3 Energy Consumed in Electrolysis – n/a. Nonetheless, Vedanta highlights energy-saving measures related to the smelting pots, such as implementing the patented Vedanta Lining Design, which reduces energy consumption by 200-250.

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[428] Vedanta (2024), page 87
[429] Vedanta (2024), page 107
[430] Vedanta (2024), page 80
[431] Vedanta (2024), page 80
[432] Vedanta (2024), page 81
[433] Vedanta (2024), page 80
[434] Vedanta (2024), page 3
[435] Vedanta (2024), page 8,9
[436] Vedanta (2024), page 79

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