ENVIRONMENTAL RISK ASSESSMENT OF ALKALINE ELECTROLYSER'S GLOBAL VALUE CHAIN ACTORS

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STATUTORY DECLARATION

I, Elissa Mitsuko Tokusato hereby declare,

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ACKNOWLEDGEMENTS / DEDICATIONS

As I write this thesis, the Southernmost state of my country, Brazil, was destroyed by the worst flooding ever registered. It is the equivalent of the territory of the UK under the water and the losses are still inestimable. I want to dedicate this humble study to all victims of this climate catastrophe and all living beings affected by the climate crisis. I would like to recognise the work of countless anonymous people who have been fighting to sustain life on this planet, be it through education, spiritual connection, policy building, innovative solutions, activism, or regenerative businesses. Together with them, I dedicate my life to tackling this ecological humanitarian crisis.

Thank you to my mother, father, sister, and friends, for your unconditional love and support.

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ABSTRACT

This study provides a global overview of the biodiversity and water-related risks associated with key actors in the Global Value Chain (**GVC**) of alkaline electrolysers (**ALK**), one of the most mature pieces of equipment for advancing green hydrogen production. While there is a concentration of raw material extraction (necessary for ALK green hydrogen production) in the Global South, the ALK green hydrogen sector is concentrated in the Global North. The inequitable access is plain and essential to enabling the just energy transition.

Using a GVC perspective, the study complements existing life cycle assessments (**LCA**) by identifying broader environmental risks such as increased water footprint and reputational concerns. It presents risks across the GVC stages—ranging from nickel and zircon mining to ALK projects and nickel recycling—including water quality, pollution, and historical conflicts over water resources. Specific environmental impacts like water scarcity, biodiversity loss and deforestation, vary by stage and could be tackled as such. Actors in the Global South, mostly nickel producers, who are the first tier of the GVC, are the most exposed to acute climate risks such as tropical cyclones, landslides, flooding, and drought, which urgently drive the need for climate adaptation measures.

Recommendations include improved transparency (especially in the first GVC stages), community engagement, and enhanced water management which is tailored to regional needs. These strategies can support businesses in meeting new sustainability reporting standards and adapting to evolving value chains. Despite data gaps and inconsistencies in risk assessment tools (particularly indigenous and local community lands and water scarcity indicators), this study calls for a broader and inclusive approach to the green hydrogen economy.

Keywords: Green hydrogen, Alkaline electrolyser, Global value chain, Nature-related risks.

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ABBREVIATIONS

ALK: Alkaline electrolyser

CSRD: Corporate Sustainability Reporting Directive

CSDDD: Corporate Sustainability Due Diligence Directive

DEMO: Demonstration projects

ESG: Environmental, Social and Governance

EITI: Extractive Industries Transparency Initiative

FID: Final Investment Decision

GICS: Global Industry Classification Standard

GHG: Greenhouse Gas

GVC: Global Value Chain

IEA: International Energy Agency

IRENA: International Renewable Energy Agency

ISIC: International Standard Industrial Classification of All Economic Activities

IP: Indigenous Peoples

ISSB: International Sustainability Standards Board

LCs: Local Communities

LCA: Lifecycle Assessment

NZE: Net Zero Emissions by 2050 scenario

PEM: Proton Exchange Membrane electrolyser

PV: Photovoltaic

SDGs: United Nations' Sustainable Development Goals

SEC: United States' Securities and Exchange Commission

SOEC: Solid Oxide Electrolyser

TCFD: Taskforce for Climate-related Financial Disclosures

TNFD: Taskforce for Nature-related Financial Disclosures

VC: Value chain

WWF: World Wildlife Fund

WWF-RF: WWF Risk Filter

WWF-BRF: WWF Biodiversity Risk Filter

WWF-WRF: WWF Water Risk Filter

1 INTRODUCTION

The world has transitioned into the Anthropocene era, where the pressures of the global economy on Earth's finite resources are considered as intense and extensive as a geological force. Natural capital—e.g. biodiversity, freshwater, atmosphere, coral reefs, oceans, forests, and ice sheets—plays a crucial role in maintaining the planet's stability and thus the economy. Historically, economic theories from Adam Smith to Keynes emerged when the environmental degradation seemed inconsequential but this perspective has shifted since the 1980s, marked by issues such as the ozone hole, fishery collapses, and climate change (WEF, 2017). The transition to a sustainable economy poses not only challenges to society and business, but also opportunities to address old social issues such as financial inequalities.

In the face of the climate crisis, green hydrogen is presented as a promising technical solution to substitute carbon-intensive practices and reduce Greenhouse Gas (**GHG**) emissions. Hydrogen is an energy carrier that can tackle 'Variable Renewable Energy' intermittence (from sources such as solar, tidal and wind) by acting as a battery and allowing for a 100% renewable supply. It can also substitute fossil fuels in carbon-intensive industries, such as cement, steel, fertilisers, transport, and gas and coal power plants (Oliveira et al., 2021). The International Renewable Energy Agency (**IRENA**) states that hydrogen could contribute 10% of the GHG mitigation and 12% of the final energy demand needed to achieve a 1.5°C Scenario (IRENA, 2022b), highlighting its importance for the energy transition.

Even though green hydrogen is not substituting business-as-usual practices at the pace that it should (Boehm et al., 2023), the recognition of its untapped potential for decarbonisation and market advantage from many business and nations (Won et al., 2017) is gaining political momentum, and the technologies associated with it are soon expected to be scaled (IEA, 2023a).

While this shift is encouraging, it is imperative to conduct a socially just energy transition. Current economic models disproportionately benefit the wealthy, exacerbating inequality and failing to incorporate long-term global risks. In parallel, the economic system remains trapped in the "tragedy of the commons", failing to internalize environmental costs, thus heightening catastrophe risks (WEF, 2017). Based on ideas from the sociotechnical studies, the scalability of green hydrogen technologies should not reproduce nor reinforce current social (e.g. the exploitation of the Global South's people and natural resources to benefit a minority in the Global North) and environmental challenges and must avoid creating new socio-environmental obstacles.

Additionally, the purpose of having more green hydrogen is to mitigate GHG through the substitution of fossil fuels, and not to increase energy consumption. To enable a just transition, it is important to understand the current and possible environmental impacts of the production of green hydrogen, which are still unclear (Weidner et al., 2023), and one reason for this could be the complexity of its Global Value Chain (**GVC**; i.e. the economic activities involved from a product's conception to end use and extended to post use), especially for highly complex green technologies (Surana et al., 2020). Valuing nature correctly will allow for the internalisation of environmental and social costs, while allowing firms to seek for opportunities in a green economy. Previous research related to this topic has investigated environmental, social and governance (**ESG**) aspects in supply chains using systematic literature reviews (Truant et al., 2024), environmental lifecycle assessments of large-scale electrolysers (Terlouw et al., 2022; Weidner et al., 2023), and public perceptions of a hydrogen economy (Gordon et al., 2023; van Wijk, 2022), but few adopted an approach of sustainability and GVC concomitantly.

To gain a comprehensive understanding of the environmental impacts of the electrolyser stack (the machine that produces green hydrogen), this author argues that it is essential to analyse its GVC as undertaken in this study. A systemic approach to this particular technology is important to avoid the trap of implementing short-term solutions which may do little in the long term(or exacerbate problems), also known as the "fixes that fail" system archetype (Kim, 1992).

This paper *identifies environmental challenges throughout the value chain of the alkaline electrolyser (**ALK**), using geospatial analysis at the global level and risk scores at the regional level*. This paper assesses the ALK stack, as it is most likely the electrolyser to be scaled up, one of the most mature Power-to-Hydrogen technology (Risco-Bravo et al., 2024), and currently the cheapest and most common form to produce green hydrogen (IEA, 2023a). It is also one of the most simple technologies, that does not require any precious or rare metals (Abu et al., 2023).

While ESG as a lens is broadly adopted in the private sector, this paper does not address governance. Instead, it focuses on the environmental dimension (via biodiversity and water environmental aspects), with some brief acknowledgment of social aspects. After identifying these impacts and dependencies *for firms across all stages of the GVC of* *the ALK stack*, it aims to *provide recommendations them to add just transition to their business strategies.*

This paper consists of four parts: literature review, GVC actors' mapping, environmental risk assessment, and managerial implications.

The literature review defines key concepts and investigates the current state of green hydrogen electrolyser technologies and their environmental impacts. The key concepts discussed are GVC, circularity, energy just transition to a low carbon economy, sustainability and green hydrogen. The literature review informed the decision to assess the ALK stack.

The methodology applied for this assessment combines a methodology from academia with practitioners' frameworks and methods. For the GVC mapping, this paper applies Frederick's methodology (2019), published in the Handbook of Global Value Chains (Ponte, 2019). To classify the stages of the value chain while embedding a circular economy approach, the 'Value Hill (Achterberg et al., 2016) framework is referenced. To identify hotspots of environmental risks (defined as business dependency and impact), the WWF Risk Filter (**WWF-RF**) tools are used to obtain risk scores across 33 biodiversity indicators (WWF Biodiversity Risk Filter, 2023) and 32 indicators for water (WWF Water Risk Filter, 2023), at the hydrographical basin level. These indicators are classified into physical risks such as water scarcity, deforestation and extreme weather events, and reputational risks such as media scrutiny, conflict and financial inequality.

Finally, the paper discusses the results, and offers recommendations and observations relating to managerial implications on how just transition approaches could be implemented by firms in the ALK GVC. It is hoped that the insights of this research will support the advancement of hydrogen electrolyser technologies through a sustainable and just path.

2 LITERATURE REVIEW

This section outlines key concepts in the study of GVC, environmental sustainability and the latest advancements in green hydrogen, leading to the justification of the methodology.

2.1 Theoretical background: Global value chains and just energy transition

The term "value chain" (**VC**) was introduced by Michael Porter in 1985 to describe the full range of activities that firms undertake to bring a product or service from its conception to its end use, highlighting how businesses aim to create financial value through a series of interconnected processes. Around a decade later, Gereffi & Korzeniewicz (1994) coined the term "global value chain" (**GVC**) to describe the international fragmentation of production, which became a powerful driver of increased efficiency and firm competitiveness. Since the 1960s, companies have been dividing their supply chains to find low-cost and capable suppliers offshore, a trend that has significantly reshaped global industries (Gereffi, 2014).

The GVC framework is defined by the series of stages taken to produce a product or service, each of which adds value. It focuses on the expansion of supply chains globally and how value is created and captured within them. By analysing the range of activities that firms and workers perform to bring a product from its conception to its end use and beyond, the GVC approach offers a holistic view of global industries. In contrast to bilateral transactions between a single exporting nation and a single importing nation, a GVC trade is distinguished by its iterative crossing of borders among multiple entities (World Bank, 2020). In the case of an electrolyser, for instance, the raw materials might come from Australia and Indonesia, the components manufactured and assembled in China, to be finally exported to the Netherlands.

One form of value that GVCs can bring is social upgrading, defined as “the improvement of rights and entitlements of workers as social actors within global value chains, as well as the improvement of the quality of their employment” (Erdoğdu et al., 2016). However, networks’ power asymmetry and uneven distribution of the suppliers and buyers, both geographically and organisationally, could cause the inverse, ‘social downgrading’ (J. Lee & Gereffi, 2015). Thus, governance is a key element of GVC analysis as it reveals how power within a VC can be exerted by lead firms or suppliers, distinguishing between 'producer-driven' chains (dominated by final-product manufacturers) and 'buyer-driven' chains, where retailers and marketers of final products hold the most power (Gereffi, 2014).

In the current globalised economy, countries tend to specialise in specific business functions. Still, it is important that actors understand their role in global production networks, as it is relevant for holistic policy and sector/industry standard areas including trade policy, national competitiveness, employment and economic growth. As highlighted by OECD, understanding these roles helps tackling issues related to upgrading and development, as well as managing global systemic risks (De Backer & Miroudot, 2013).

In parallel, decades before the VC term came into place, the underlying concept of *sustainability* was already created. It originated from concerns about environmental degradation as outlined in Rachel Carson's Silent Spring (1962) to the limitations of traditional economic growth models. The term "sustainability" itself gained prominence in the late 20th century with the publication of key reports such as "The Limits to Growth" in 1972 by the Club of Rome, which highlighted the potential consequences of economic and population growth in a world with finite natural resources. This was followed by the 1987 report "Our Common Future" (also known as the Brundtland Report), which provided a widely accepted definition of sustainable development as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs', referring to the needs of the poorest and the limitation posed not only by the environmental but also social organisations and technology (United Nations, 1987). In 1994, John Elkington coined the term "triple bottom line", which refers to financial, social and environmental performance measures, to integrate the concept into businesses. It is also known as the "three Ps": People, Planet, and Profit (HEC Paris, n.d.; Miller, 2020). Ten years later, the United Nations officialised the term ESG in its report, "Who Cares Wins" endorsed by large financial institutions (UNEP-FI, 2004) and popularised nowadays.

With the rise of civil society climate movements, the concept of a just energy transition was included in definitions of "sustainability". This is because fossil fuel for energy generation is the major source of climate change and air pollution (United Nations, n.d.-a), with around 7 million people dying prematurely every year due the latter only (World Health Organisation, n.d.). This approach recognizes the urgent need to shift from fossil fuels to renewable energy sources to tackle climate change while also addressing social and economic inequities. A just energy transition emphasizes the importance of ensuring that the benefits and costs of this transition are distributed equitably across society (World Bank, n.d.). It seeks to protect vulnerable communities, create sustainable jobs, and foster inclusive economic growth. Initiatives such as the EU Green New Deal, the Paris Agreement and the Agenda 2030 highlight the need for comprehensive strategies that combine environmental sustainability with social justice. This evolution reflects a growing recognition that achieving sustainability requires not only environmental stewardship but also the promotion of social equity and economic resilience.

In recognition of its importance, the central concept guiding this paper is the 'just energy transition towards a low carbon economy', a theory for socio-technical transition, defined by García-García et al. (2020) as follows:

"…a long-term technological and socio-economic process of structural shift that affects the generation, distribution, storage and use of energy and causes rearrangements at micro (innovation), meso (social networks, rules and technical elements) and macro (exogenous environment) levels, while also ensuring that the desired socioeconomic functions can be accomplished through decarbonised and renewable means of energy production and consumption ***safeguarding social justice, equity and welfare****."* (García-García et al., 2020, p. 5)

In practice, this term goes to proactively mitigating, adapting, and compensating for loss and damage, especially in the Global South, as well as ensuring a voice for vulnerable populations (Villagrasa, 2022) and minimizing negative social and economic impacts on workers and communities reliant on fossil fuels. Therefore, understanding GVCs as a dynamic network provides an approach to comprehending challenges at local, regional, and global levels (De Marchi & Gereffi, 2023), especially recognising its impacts and dependencies on nature and society.

Consolidating the concepts of GVC and sustainability, it is notable that the traditional definition of VC limits the chain at the final consumer (Porter, 1990), while a circular economy approach to GVC is more holistic and adequate to address current global issues, such as climate change and biodiversity collapse (Albaladejo & Mirazo, 2023). It is still in line with the traditional definition, considering that *value* is added through downstream and end-of-life stages via new forms of production, innovative materials, products, services, and business models (Hofstetter et al., 2021) aimed at decoupling from the logic of exploitation and consumerism. Nonetheless, the complexity of today's materials, especially electronics, makes it very challenging to map a product's value chain using the ‘circular economy’ approach. It is laborious to identify and separate elements, and maintain quality as guaranteeing purity (including non-toxicity) remains a challenge for manufacturers (Ellen MacArthur Foundation, 2014). Therefore, this paper combines both concepts, recognising their respective benefits and limitations, as explained in section 3 (Methodology).

GVCs can be studied at three main levels, similarly to the just energy transition definition: the macro-, or global; the meso-, which refers to industry or national level, using input-output or imports-exports data; and the micro level, which refers to firms and communities (Ponte, 2019). While a significant portion of GVC literature is produced by international organizations and used by policymakers (Gereffi, 2019), a gap remains between concepts of sustainable GVCs and practice (De Marchi & Gereffi, 2023; Ellen MacArthur Foundation, 2014). To address this gap, some practitioners and academics prefer a micro-level actor-centred approach (multinational companies), focusing on real-world solutions, data production, and access for research and analysis (Antràs, 2020). Indeed, lead GVC firms are the main players and shapers of GVCs. Likewise, sustainability efforts are spearheaded by practitioner organizations such as The World Business Council for Sustainable Development, We Mean Business Coalition, and The Ellen MacArthur Foundation, which contribute studies, publications, and tools with a firm-level action-oriented approach.

As for information sources, traditional GVC studies rely on customs data, the standard source for international trade flows, which informs where the good or service was produced, but not on how it was produced, nor how it will be used (Antràs, 2020). This is a major challenge when studying sustainability in GVCs too. As an attempt to address this lack of traceability and transparency, this paper overlays actors’ locations with nature-related risk and dependencies maps, specifically on biodiversity and water security. This approach aligns with the recommendations from the Taskforce for Nature-related Financial Disclosures (TNFD, 2023), a globally recognised framework with global endorsements from the G7 and the G20, for organisations to disclose their governance, strategy, risks and opportunities, and metrics and targets used to identify, assess and manage nature, both in their operations and their value chains.

The micro/actor level of GVC study seems to be the most adequate for sustainability studies, which is in line with De Marchi & Gereffi (2023), who suggest the following pillars on how to approach the study of global environmental crisis through a GVC lens:

i) A definition, or definitions of sustainability should be a result of a multi-actor perspective and distinctions between their motivations, actions, and outcomes regarding performance. For instance, a company's net zero public commitment does not imply that it is acting accordingly.
ii) Sustainability should be measured across diverse geographic scales, since a one-level approach could generate negative consequences to another, such as the so-called "spilling", "leakage" and rebound effects.
iii) Since GVCs and sustainability are dynamic, the analysis should indicate upgrading and downgrading performance indicators.
iv) GVC resilience should be viewed as a product of the interaction of environmental and economic influences, inserted in an even more complex and broader system. Hence, the importance of emphasising the context when examining industry, national, and geopolitical-related aspects.

These pillars should guide the analysis and discussion in this paper.

2.2 Defining green hydrogen

Hydrogen is the most abundant chemical element and can function as an energy carrier, serving as a fuel for storing, transporting, and delivering energy. When combusted, it produces only water as a by-product, making it pivotal for reducing emissions from GHG-emitting energy sources (Moreira & Laing, 2022). The hydrogen production routes require splitting molecules using either renewable or non-renewable energy, with different technologies varying the GHG emission at the point of production.

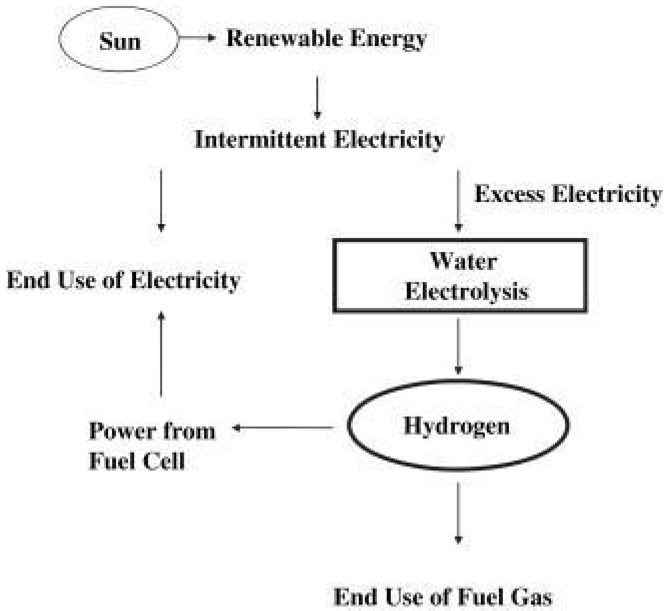
Although the most popular terminology for hydrogen is the colour classification ('Annex A'), these production route differences should be reflected in the hydrogen taxonomy, which is not yet globally regulated. Currently, most hydrogen (83%) is produced from fossil fuels such as black coal, brown coal, and natural gas (IEA, 2023a). These methods, categorized as black, brown, grey, or turquoise hydrogen depending on the specific technology, highlight that hydrogen is not a brand-new invention. It already has a significant industrial presence, but transitioning towards cleaner production methods is crucial. Thus, because green hydrogen is the only type that does not emit GHG or pollutants at its point of production, it is the ideal one for the net zero transition the chosen one for this paper's sustainability assessment. Despite its environmental benefits, water electrolysis represented only 0.1% of the current worldwide hydrogen production by the end of 2023 (IEA, 2023a).

Although the colour range is a widely-used classification (including by the International Renewable Energy Agency (IRENA)), it is not a consensual regulated taxonomy. In April 2023, the IEA and the International Partnership for Hydrogen and Fuel Cells in the Economy presented a report to G7 defending that a more comprehensive terminology would help increase transparency and, consequently, investments to deploy hydrogen projects. They also criticise the use of "sustainable", "low-carbon" or "clean" hydrogen, as being vague terms (IEA, 2023b). Adding to the wide variety of terminologies, we see references to "carbonised" versus "decarbonised" hydrogen; "low emission" hydrogen, which refers to both green and blue hydrogen; and "renewable" hydrogen as the ones generated using renewable electricity sources, which can include biomass and geothermal. Moreover, the taxonomy extends to the final use of energy (Power-to-X: Power-to-Gas, Power-to-Heat, etc). The term green hydrogen could be used interchangeably with renewable hydrogen, but it differentiates itself from the latter by referring only to sources with no GHG emissions at the point of generation, such as solar photovoltaic, wind, tidal and hydroelectric power (excluding biomass, for example). The debate around a common taxonomy that recognises the wide variety of hydrogen denominations is important and an ongoing conversation. Nevertheless, for simplicity matters, this paper will adopt this latter definition of green hydrogen in Power-to-Power applications.

Furthermore, the scalability of green hydrogen is also a subject of debate. A study from the World Bank states that new electrolysers probably emit more GHG compared to other types of low-carbon hydrogen (Moreira & Laing, 2022), because manufacturing them can have a substantial impact. They defend the preference for adaptation of current fossil-fuel-based systems, coupling them with carbon, capture and storage technologies (i.e. blue hydrogen). However, this is limited to the scope of material extraction and does not consider long-term GHG mitigation. Moreover, as seen in the proceeding sections, green hydrogen electrolysis has the lowest water consumption compared to others. In general terms, to enhance the security of supply and minimize material impacts, it is crucial to improve recycling and reuse, minimise material intensity, advocate for material substitution, and promote designed circularity.

Green hydrogen requires the incoming electricity to come from a renewable source. To be used as electricity (also known as power-to-power application), the hydrogen production and consumption system works as a battery. The surplus of renewable electricity (the amount that is not dispatched to the grid) powers the electrolyser, which produces the hydrogen gas. This hydrogen is then compressed and stored in tanks to be transported and consumed. If it is used back as an electricity source, a fuel cell consumes this hydrogen, generating electricity and water ('Figure 1', below). Since the electrolyser is the central piece responsible for generating the gas hydrogen, it is the chosen product to have its GVC sustainability analysed.

Figure 1: A diagram depicting a conceptual distributed energy system with water electrolysis.



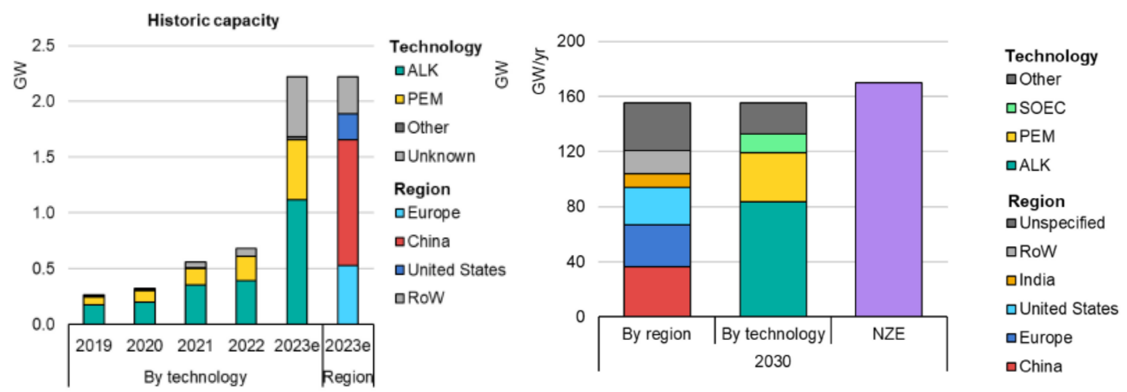
Source: Zeng & Zhang, 2010. "Recent progress in alkaline water electrolysis for hydrogen production and applications".

2.3 The state of water electrolysers

A technology's potential to scale will depend on matters such as production and operation costs, supply chain risks, market expectations, and policy interventions. To choose a specific type of water electrolyser for the GVC sustainability assessment and maintain the relevance and practical usefulness of this paper, the status of hydrogen worldwide needs to be outlined. This section asserts the selection of ALK based on its higher technology and market maturity, its lower costs of production (which encourages its adoption), and the exemption of use of critical and rare metals for its production compared to other types of electrolysers.

The urgency of green hydrogen scaling to meet global climate targets is supported by the latest International Energy Agency (IEA, 2023) Hydrogen report. Although the capacity of electrolysers worldwide has almost tripled from 2022 to 2023, it remains insufficient for the global manufacturing capacity needed per year for the next six years, until 2030, according to the Paris Agreement. By then, the electrolysis capacity now installed in the EU will need to rise by about 900 times (Ansari et al., 2022). In 2023, operational projects corresponded only to 0.3% of the total expected installed capacity needed to be in line with the IEA's Net Zero Emissions by 2050 (NZE) scenario. From these 2 GW of capacity worldwide, China and Europe held an equal share of one-third each. In terms of the type of electrolyser technology, ALKs comprised 60% of the total installed capacity, with proton exchange membrane (**PEM**) electrolysers following closely at approximately 30% (IEA, 2023a) ('Figure 2', below).

Figure 2: Electrolysers' capacity evolution from 2019 to 2023, and projected electrolyser yearly manufacturing capacity for 2030, based on currently announced projects.



Note: ALK = alkaline electrolysers; PEM = proton exchange membrane electrolysers; "Other" technology refers to solid oxide electrolysis, anion exchange membrane electrolysis or a combination of different technologies; RoW = rest of world; NZE: Net Zero Emissions scenario. 2023e = estimate for 2023 capacity, based on projects planned to start operations in 2023 and that have at least reached FID.
Source: IEA, 2023. "Hydrogen Projects Database".

There is still a high market uncertainty regarding the electrolyser's scalability. Based on announced projects, the capacity installed globally by 2030 could reach 175 to 420 GW, a very wide range in which the best-case scenario does not reach the ideal 600 GW needed for Net Zero. This range is wide because less than 4% of the capacity outlined in all announced projects has either reached the Final Investment Decision (**FID**) or is under construction. In practice, it means that there is still an expectation of material prices decline and a wait to harness benefits from future policies. (IEA, 2023a). Moreover, India and the United States are expected to increase their share of global production by 2030 and so. The results and methods used in this paper could be a reference for upcoming projects.

Most projects are using and will use ALK. Therefore, need to understand the environmental impacts of its scalability, which are usually hidden in complex supply chains. Additionally, information about the electrolyser projects announced is provided as an open-source Excel file from IEA and is used for the paper's GVC actors' mapping.

With respect to the just transition, the choice of ALK is guided not only as it is most likely to succeed in the market, but to support the most sustainable solution. From the point of view of product GVC, it would depend, primarily on the raw materials needed, especially for the electrodes (the main part of the electrolyser). 'Table 1' below provides a brief comparison between the three main types of electrolyser devices.

Table 1: Materials used for electrodes and supply chain bottlenecks, per electrolyser technology.

Electrolyser technology	Alkaline (ALK)	Proton Exchange Membrane (PEM)	Solid Oxide Electrolyser (SOEC)
Most common materials used for the electrodes	Nickel, cobalt, zirconium, molybdenum.	Iridium, platinum.	Lanthanum, nickel, strontium, yttrium.
Supply chain bottlenecks.	Possible competition of end use with battery production, regarding nickel and cobalt.	Worldwide iridium production is sufficient to produce only 8-20% of the expected demand. Possible competition of Platinum with the automotive industry.	Rare-earth material mines (lanthanum) are scarce and mostly controlled by one country, China.

Sources: IEA, 2022. "The Role of Critical Minerals in Clean Energy Transitions"; World Energy Outlook; Minke et al., 2021. "Is iridium demand a potential bottleneck in the realization of large-scale PEM water electrolysis?". International Journal of Hydrogen Energy; Shiva Kumar & Lim, 2022. "An overview of water electrolysis technologies for green hydrogen production". Energy Reports.

Although a higher quantity of material is needed for ALK, compared to PEM and SOEC, it is the only one of the three that does not employ critical or rare-earth metals. For the same reason, it has cheaper capital expenses (IEA, 2022). From this simplified comparison, ALK is shown to be the most sustainable device in terms of financial accessibility and environmental impact from key raw materials.

In summary, ALK is the most desirable technology to expand (and be the subject of this paper's GVC's mapping and environmental risk assessment) as it is:

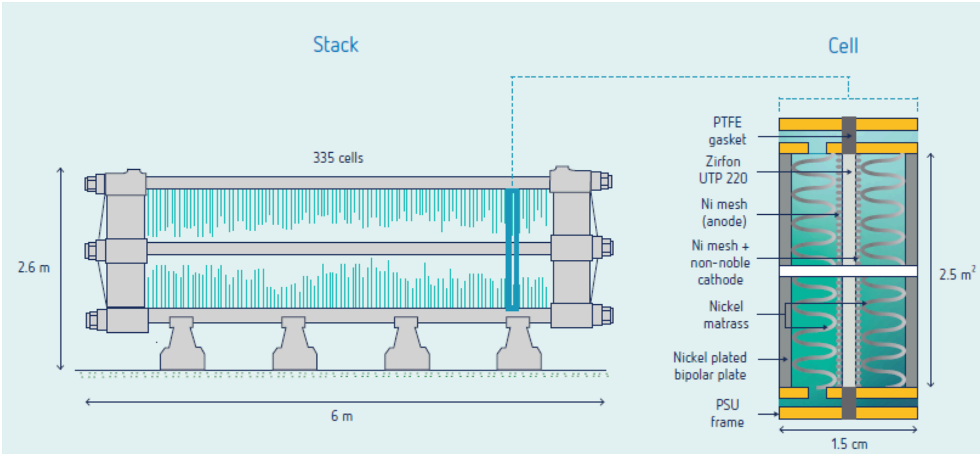
1. the most common type of electrolyser worldwide.
2. the most simple design (Ansari et al., 2022),
3. the cheapest and the most mature technology; and
4. not reliant on critical or rare metals for its manufacturing.

2.4 Alkaline electrolyser components, raw materials, and outsourcing locations

The increase in green hydrogen electrolyser demand will also increase its raw materials demand, creating pressure on natural environments and social systems. The criticality classification is region and context specific. It can be based on the balance of supply constraints and internal demand, or as a strategy to gain a competitive advantage in global supply, (e.g. Canada, China and Australia). The constraints can be geological, geopolitical, economic, social and environmental, while the demand is driven by economic development and digital and green transitions (Hendriwardani & Ramdoo, 2022).

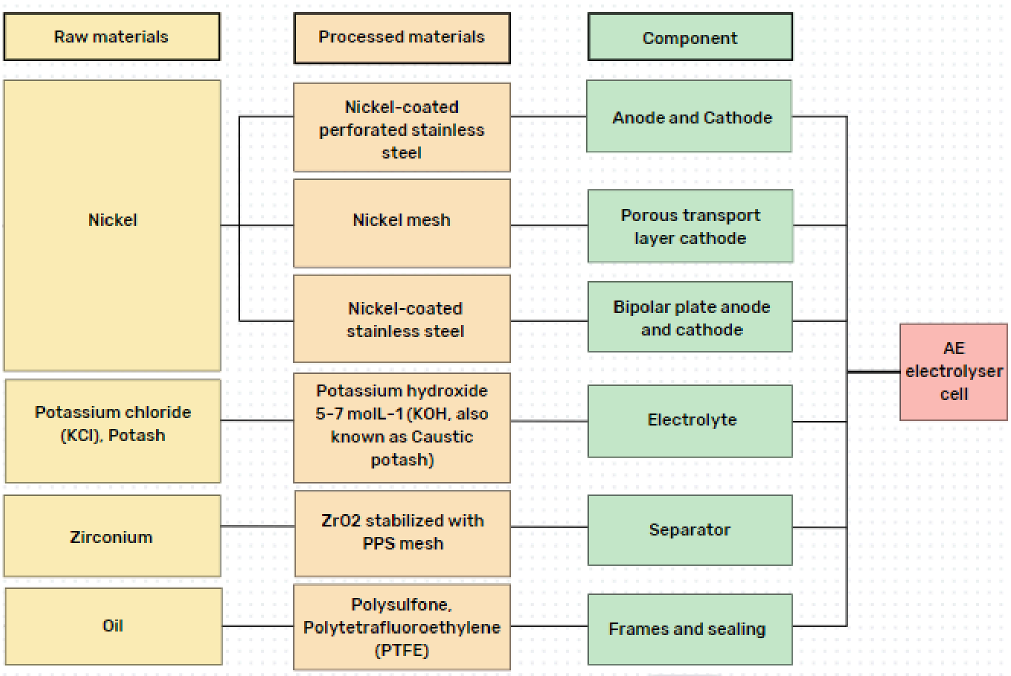
Electrolysers do not have a specific standard yet (Signoria & Barlettani, 2023) which makes it challenging to identify the materials and components with precision. However, a general representation of an ALK's component can be found below ('Figure 3', overleaf) while a few organisational and academic publications disclose some of the main materials to manufacture ALKs, which were summarised in 'Figure 4' (overleaf).

Figure 3: Schematic representation of an ALK from the Hydrohub GigaWatt Scale Electrolyser project.



Source: Ripson & van't Noordende, 2022. "A One-GigaWatt Green-Hydrogen Plant: Advanced Design and Total Installed-Capital Costs".

Figure 4: List of raw materials, manufactured materials, and subcomponents of an ALK cell.



Sources: Munjal et al., 2023. " Supporting the energy transition by addressing the technology gaps of electrolyzers"; Shiva Kumar & Lim, 2022. " An overview of water electrolysis technologies for green hydrogen production"; The Scottish Government, 2022. "Assessment of electrolysers: report". Figure created by the author.

Electrolysers require a large amount of material and energy to be produced. The IEA (2022) estimates that 1 MW of ALK could require around 100 kg of zirconium, half a tonne of aluminium and more than ten tonnes of steel, along with smaller amounts of cobalt and copper catalysts. A recent study shows that an ALK's closed-loop recycling system can cut the total demand for steel by 29–40% and nickel by 25–46% (Matz et al., 2024).

Indonesia is the leading producer of nickel, responsible for almost half of global output in 2022, followed by the Philippines and Russia. As for nickel processing, Indonesia also leads the global rankings, followed by China, Japan, Russia and Canada ('Table 2' below). From 2018 to 2022, there was a 160% increase in nickel production in Indonesia which corresponded to a 37% increase in global nickel production (Idoine et al., 2022). These two GVC stages, mining and metal processing, do not necessarily happen in the same country. Canada, Japan and Finland (developed countries) are on the leading list for metal processing but not for mining. On the other hand, Philippines and New Caledonia are leaders in nickel mining but they do not process the metal. That is, these developing countries export raw materials to developed countries. As an attempt to protect their markets, Indonesia forbade the export of raw nickel in 2020 in order to maintain domestic nickel processing and value-added to their products, and the Philippines is considering adopting a similar tactic (Ansari et al., 2022).

Table 2: Leading countries in production of nickel extraction from mines and processing through smelter and refinery.

Country	Nickel mine	Nickel smelter/refinery
Indonesia	49%	44%
Phillipines	11%	Insignificant
Russia	7%	5%
New Caledonia	6%	2%
Australia	5%	4%
China	3%	32%
Canada	3%	5%
Finland	1%	3%
Japan	Insignificant	6%

Data from British Geological Survey, 2022. "World Mineral Production 2018 to 2022". Table created by the author.

Although the EU has some advantages in the global hydrogen economy, it has shown signs of protectionism towards other markets: it is the location of 40% of the world's electrolysis capacity, 60% of the world's capacity for producing electrolysers and 40% of all pertinent patents. Yet they depend on the minerals and metals from the Global South and have started a formal dispute against Indonesia's nickel policy to the World Trade Organisation (WTO, 2022). Moreover, the competition with China can be challenging as they can produce similar electrolysers at 20% of the European cost. Up until now, China has concentrated on ALK electrolysers and produces half of the world's total. (Ansari et al., 2022). The geopolitics of the hydrogen economy is not a main subject of this paper but will continue to be referenced to contextualise the interactions amongst GVC actors.

2.5 Environmental and social concerns in the alkaline electrolyser's value chain

This subsection outlines the definition of nature-related risks and a preliminary identification of environmental impacts from industries involved in the ALK VC.

One of the foundational concepts to understanding nature-related risks for organisations is the so-called 'double materiality', meaning that economic activities depend on ecosystems while impacting them at the same time (Täger, 2021). For instance, one of the main components of an ALK is nickel, a metal that is mostly mined in Indonesia where water availability is an important environmental issue. Some of these nickel mines might be in water-stressed areas, presenting a risk of enhancing water scarcity while having their operations negatively affected by the same reason. Each stage of the GVC has very distinct environmental impacts, at first, due to their location of operations and their economic sector; therefore, the relevant indicators will vary according to the relevant conditions of each actor involved.

'Nature-related risks' are those associated with an organization's impact and dependence on nature, which can be classified as physical risks (transitional or systemic). 'Nature-related opportunities' are business activities that have positive outcomes for nature, such as to mitigating negative impacts and improving restoration through business strategy, products, services and investments (TNFD, 2023). The definition of the distinct risk types in WWF-RF are:

- *Physical risks* refer to the organisational losses that degrade the natural ecosystem. It can be sub-classified as 'acute', which can cause immediate disruption, such as wildfires and oil spills; or 'chronic', which is the gradual deterioration of nature that can threaten a company's medium or long-term activity, such as water shortage due to overconsumption and declining crop yields caused by soil erosion (TNFD, 2023).

- *Regulatory risk* is associated with the management or governance of water in a region or country. It is closely connected to the concept of good governance, as businesses flourish in a stable, effective, and well-implemented regulatory environment. This type of risk is analysed only for water, due to the capacity of the WRF tool.
- *Reputational risk* is associated with stakeholders' and local communities' perceptions of whether companies operate sustainably and responsibly concerning the use of natural resources. It depends on how responsibly the resources are used at the sites. Some characteristics within the basin, such as water-related conflicts, cultural importance of water and biodiversity richness can also increase the likelihood of reputational risks arising.

Current studies on the environmental aspects of ALK primarily focus on the operational impact of the electrolyser and LCA from cradle-to-gate (from production to operation). Regarding the first stages of the GVC, ALK LCA studies reveal significant impacts on water acidification and human toxicity due to nickel mining, smelting, and refining (Krishnan et al., 2024). A previous study on social LCA shows that poor working conditions from equipment outsourcing from developing countries is the major hotspot in an ALK green hydrogen supply chain (Akhtar et al., 2023). These traditional approaches are highly valuable to understanding the impacts centred on the environment but, differently from this paper, they do not take double-materiality into account. This means that the actors of the GVC would not understand how the threats to the natural environment are also impacting their businesses. The value of this information for businesses means that the ability to communicate it is significant to procuring buy in for the sustainable transition from the private sector.

There are various particularities in the environmental risks related to economic activities of the ALK. Major concerns in the nickel mining industry concern the treatment and safe disposal of smelter slags and leaching residues as they can contaminate soil and water. Depending on the process used, heavy metals, which are more harmful to human and environmental health, can be found in the waste (Bartzas et al., 2021).

In terms of the ALK operations (named "ALK projects" in this paper), *water consumption* is a major issue. The global regions with greater potential for renewable generation and green hydrogen production are the ones that present higher water stress. As the production of hydrogen demands substantial water resources, it is imperative for governments to understand how to prioritize its use, balancing it against other critical needs such as food production and direct consumption. By 2040, India is projected to allocate 99% of its hydrogen capacity in high water-stressed regions, and other countries will face the challenge in different ways, as climate change intensifies water stress (IRENA, 2022a). However, compared to other clean hydrogen technologies, green hydrogen production is still the most water efficient. An increase of one percentage point in electrolysis efficiency can lead to approximately a 2% reduction in water intensity, both in terms of withdrawal and consumption (IRENA & Bluerisk, 2023). This shows the critical role of technological advancements and efficiency improvements in mitigating the water footprint associated with hydrogen production.

Further, there are well-founded concerns as to the social implications of green hydrogen projects. The Neom green hydrogen project, is, a futuristic city project in Saudi Arabia, is a useful case study for this phenomenon, in addition to the environmental impacts. The project has raised human rights concerns with the displacement of thousands of people from traditional communities, alongside arrests and reported killings for those protesting against the project (Michaelson, 2020). The project uses Thyssenkrupp electrolysers subsidised by the German government (Eberhardt, 2023; Thyssenkrupp, 2021). In addition, the Middle East region has been suffering from droughts and the disappearance of entire lakes. Desalination of sea water is already a customary practice in the region, but the disposal of brine enhances water pollution. This example shows the intricacies of social and environmental issues in the energy transition context, which goes beyond national and continental borders.

Concerning the state of the post-use or end-of-life stages, according to the currently available literature, the reuse, remanufacture and repair of ALKs present a low technology readiness level (Krishnan et al., 2024). The most likely end-of-life route for electrolysers is recycling, as the processes for most metals are known and consolidated practices. A major challenge in replacing degraded components is a product design that does not allow for degradation (Matz et al., 2024), potentially due to profit maximisation aims. While little need for ALK's repair was reported, as some have been operating for 20 years without the need to do so (Smolinka et al., 2011), ongoing research is exploring economic and technical feasibility (H. Lee et al., 2023; R. Nakajima et al., 2023). At present, the main materials with recycling potential are polytetrafluoroethylene (**PTFE**), through plastic recovery, nickel, hydrometallurgical process and steel through re-melting (HyTechCycling, 2018).

Moreover, a study showed that nickel production has not become any more efficient or sustainable since 2010, as energy and water use grew at the same pace as nickel output (Golroudbary et al., 2023). In addition, it is estimated that 48% of the nickel mined globally is wasted throughout its lifecycle (Reck & Graedel, 2012). These outcomes indicate a need for improvement in the nickel recycling process, and the need to increase the material efficiency along the nickel GVC to address its environmental impacts.

Regarding socio-environmental indicators, the FC-Hy Guide (2011) provides instructions for conducting an LCA of hydrogen production. It suggests the consideration of the following impact categories: global warming potential, acidification potential and eutrophication potential, with optional factors including ozone depletion potential, human-toxicity potential, resource depletion and water footprint. Although the guide does not specifically focus on the electrolyser GVC, but rather on hydrogen projects in general, this paper uses a meso-level approach to risks (hydrographic basin). A deep-dive of these indicators is covered in this paper's analysis, except for the "Global Warming Potential", since the TNFD framework used here relates to nature, as an evolution of its climate change version, the Taskforce for Climate-related Financial Disclosures (**TCFD**).

In summary, ALK environmental and social impacts require careful consideration, as they can exacerbate existing environmental issues, particularly water scarcity in key green hydrogen production regions, as well as social impacts throughout its GVC. Technological advancements and improved design can play a key role in mitigating environmental footprints, especially to save water in operations and for the end-of-life of the ALK stack. The concept of "double materiality" and nature-related risk types highlight the interconnectedness between economic activities and the natural environment, and fostering this communication about interdependencies is critical to promote a just energy transition.

3 METHODOLOGY

For this paper the author analysed secondary data, organised into two main parts: (1) a GVC mapping and (2) an environmental risk assessment at the hydrographical basin level. The first part is based on manually gathered information, varying from 2000-2021 for mines, and 2022-2024 for the other GVC actors. The second part used the WWF-RF, a web tool that compiles 76 peer-reviewed databases on global biodiversity and water-related issues from the period of 2013-2022.

In the previous section, the literature review nominated ALK as the electrolyser technology for analysis. In the Section 4 (Electrolyser's Global Value Chain Mapping), the main manufacturers, processors and mines are identified, and their operation locations are mapped. In Section 5 (Environmental Risk Assessment Results), these locations are overlayed with maps of biodiversity and water issues, revealing water stress locations, biodiversity conservation areas and financial inequality.

With respect to the analysis conducted for Section 5, using the WWF Biodiversity (**WWF-BRF**) and Water Risk Filters (**WWF-WRF**), each site was scored across 64 nature-related indicators, leveraged by risks presented by industry, location and business importance. The tools were made for companies and investors to identify the hotspots of their operation facilities, other actors of the VC and/or investees (WWF Biodiversity Risk Filter, 2023; WWF Water Risk Filter, 2023). The methods are new, used once in academia, together with the authors from WWF, to screen existing and projected hydropower projects for climate and biodiversity risks (Opperman et al., 2022). This tool allows for a consistent coverage level between global and local datasets, despite variations in indicators. In the Section 6 (Managerial implications for companies in the GVC), the results are discussed and compared to existing literature, highlighting this paper's contribution for policy and businesses. The empirical methods are summarised in 'Figure 5' (overleaf) and detailed in the proceeding subsections.

Figure 5: Summary of empirical methods.

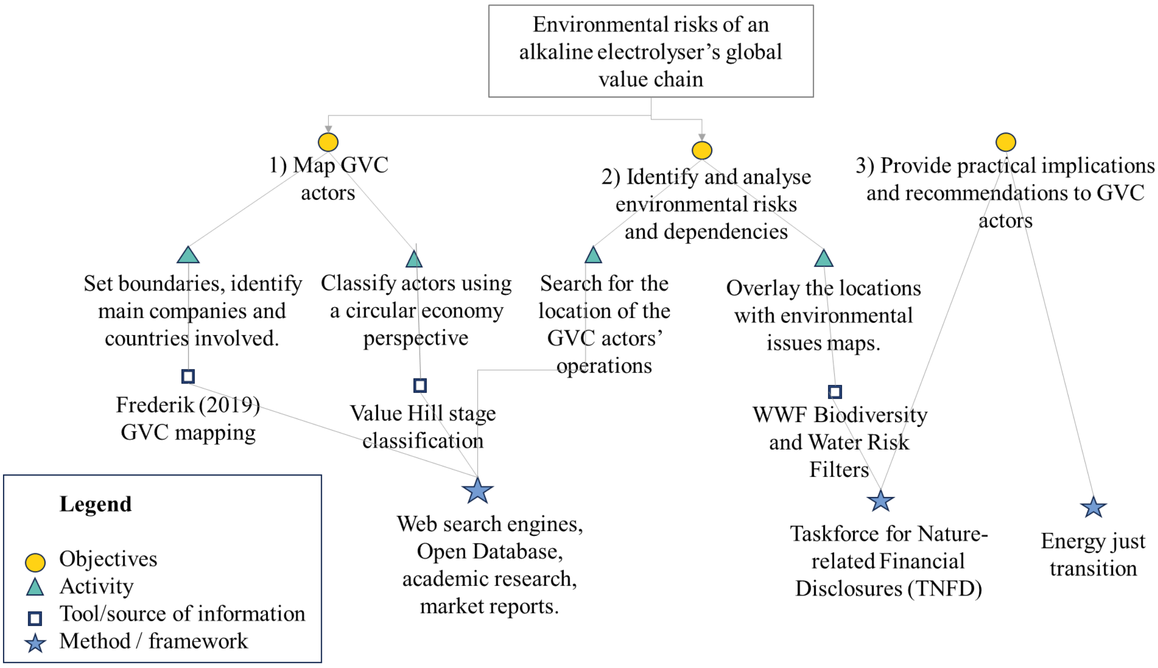
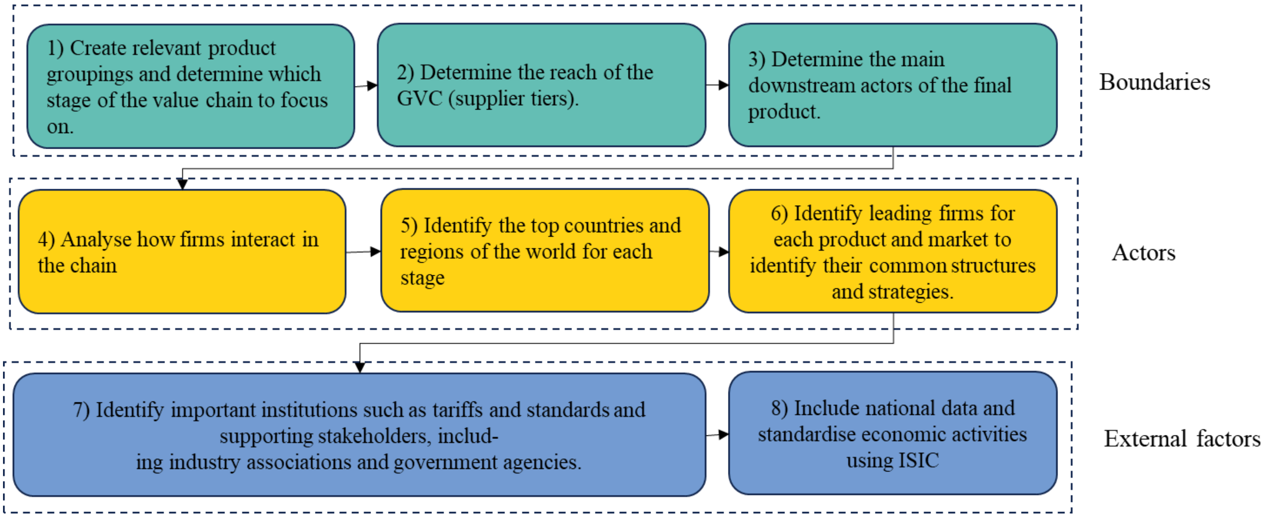


Figure created by the author.

3.1 Global value chain's boundaries and stages

Frederick's (2019) methodology approaches GVC mapping with qualitative steps, as summarised in 'Figure 6' (overleaf). The first three steps, in green, are related to the definition of boundaries, which should be connected to the formulated hypothesis and research question and defined in Section 2 (Literature Review). The steps in yellow start a high-level analysis of the actors and their relationships, presented in Section 4 (Electrolyser's Global Value Chain Mapping); and the last steps, in blue, add elements related to policies and important stakeholders that were not directly involved in the GVC. The last steps, 7 and 8, are adapted to aggregate environmental-relevant information done in conjunction with the WWF-RF tools, presented in Section 5 (Environmental Risk Assessment Results). Step 8, classifies economic activities using the Global Industry Classification Standard (**GICS**) instead of International Standard Industrial Classification of All Economic Activities (**ISIC**), also using WWF-RF.

Figure 6: Qualitative research steps for GVC mapping.



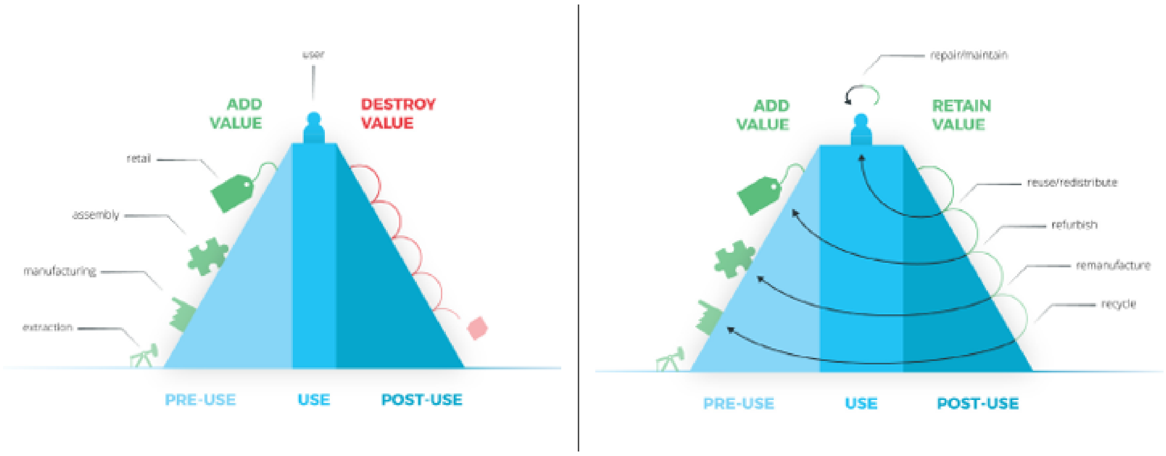
Source: Frederik, S. (2019). "Global value chain mapping", Handbook on Global Value Chains. Figure created by the author.

One limitation of GVC mapping is the lack of traceability and/or disclosure from electrolyser manufacturers, which prevents tracing direct links between actors. Instead of focusing on a specific existent commercial product, this paper intends to use secondary data and proxy information to produce generalised results.

The 'Value Hill framework' is adopted to define the GVC stages, as it was created for practitioners to visualise their transition from linear to circular business models ('Figure 7', overleaf). This framework was developed by the NGO Circle Economy, focused on firms and, here, it is applied from the point of view of an ALK manufacturer. Although originated from practitioners, Value Hill has already been cited in previous academic research (Rodrigo-González et al., 2021; Upadhayay & Alqassimi, 2020).

The linear approach of GVC, focused on the supply chain and production only, adds value in each of its stages (uphill), reaching its peak at the consumer (top hill), and completely losing its value in the post-use phase (downhill). The Value Hill proposes a recovery of these values downhill, through reuse, refurbishment, remanufacture and recycling, in addition to a sustainable design for the uphill, which consists of extraction, manufacturing, assembly and retail stages, and optimal use at the top hill (Achterberg et al., 2016). When applying this structure to value chains, each actor is positioned in a stage of the Value Hill, identifying existing commercial relationships as well as gaps and opportunities in terms of circular value, which matches steps 1, 4 and 6 of Frederik's methodology.

Figure 7: The Value Hill in a linear model, on the left, and in a circular economy on the right.



Source: Achterberg et al., 2016. "Master Circular Business with the Value Hill".

3.2 Global value chain actors' mapping

The GVC actors and facilities' location mapping is the first step for a geospatial analysis for the environmental risk assessment, and it is conducted manually using a wide variety of sources.

Nickel, zircon and potash (minerals containing potassium) mines, refineries and smelters are selected from an Open Database on Global and Coal and Metal Mine Production (Jasansky et al., 2023) (referred to as Open Database from now on). This Open Database contains data from 1,900 publicly and freely accessible mining company reports, from the period of 2000 to 2021, so the data's availability and veracity were not verified. Comparing this Open Database with GlobalData top 10 nickel mines in 2022 (Carmen, 2022), four locations were missing, and were added to the sample.

For components manufacturing mapping, a list of 10 major companies producing potassium hydroxide, for electrolyte production, from an American digital platform specialised in industrial products for engineers and researchers (Metoree, 2024) were used.

For ALK manufacturers, a list of 14 leading companies was published by the World Resources Institute (**WRI**) and is used as the starting reference for the actors of this stage. However, in this sample, again, there is only one company from China, the country that leads the imports and exports of electrolysers globally (WTO & IRENA, 2023). As an attempt to bridge this gap, this list was then complimented by another from BloombergNEF (Klevstrand, 2022), adding 11 more companies, mostly from China, India and the Republic of Korea. From the sample, three companies were subtracted due to the lack of information available online (Wasserelektrolyse Hydrotechnik, from Germany, Sagim S.A, from France and Guofu, from China). Next, a manual web search on each company's website and reports was conducted to list the number of industrial plants manufacturing ALK and their respective geographical coordinates.

Regarding ALK project mapping, this study utilises the IEA's Hydrogen Projects Database, a comprehensive and publicly available resource tracking global hydrogen production initiatives for clean energy and climate change mitigation since the year 2000. The analysis focuses on the 2023 version, which contains over 2,000 entries. As depicted in 'Figure 8' (below), the database was filtered to isolate projects intended for power generation, resulting in a sample representing approximately 10% of the total. Within this subset, roughly 20% utilize ALK, with half categorized as demonstration (**DEMO**) projects, with no direct objective of commercialising hydrogen. All DEMO projects were decommissioned, which makes them unsuitable for the forthcoming sustainability analysis. Additionally, a significant number of these experimental projects were university-led, probably lacking commercial viability. Two exceptionally small and outdated projects (< 1 MW capacity) were also excluded and a Colombian project was eliminated due to missing location and reference data. The final sample for analysis constitutes only 0.6% of the initial database, which shows that most of the hydrogen production technologies are still relying on non-renewable sources, and that electrolysers, especially of large capacity, are not yet mature in the market.

Figure 8: Sampling filtering process to define the ALK projects to be analysed.

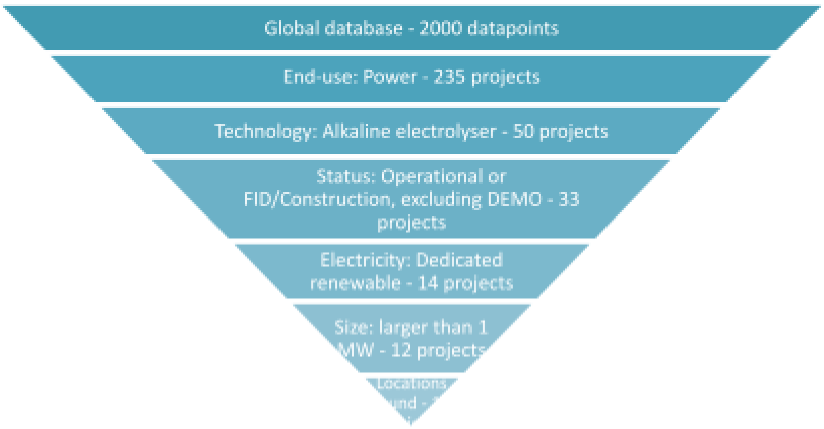


Figure created by the author. Data source: IEA, 2023. "Hydrogen Projects Database".

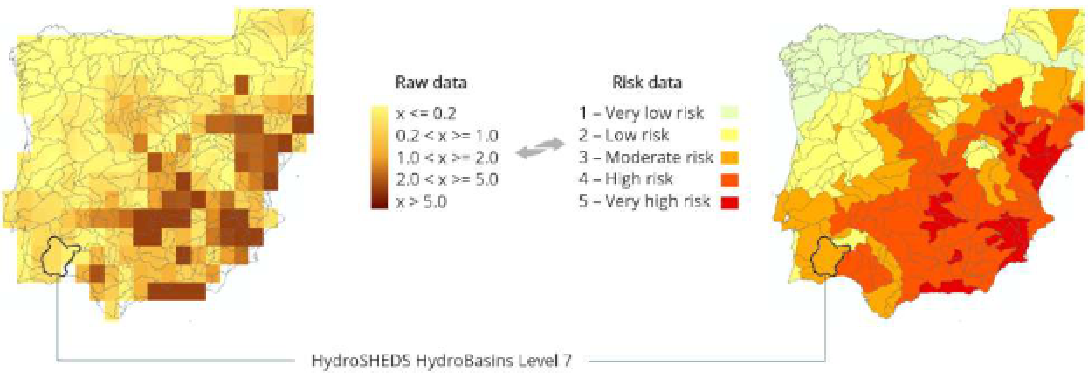
Finally, the end-of -life stage refers to the list of nickel recycling market leaders from Xenon Market Insights (2024).

Once the main actors in the electrolyser's value chain were identified and classified (steps 5 and 6 of Frederik's methodology), their locations were listed to then identify the environmental hotspot locations and key topics through maps overlaying and analysing the risk scores from WWF-RF tools.

3.3 Environmental risk assessment

The WWF-RF tool defines risk as a combination of impact and dependencies on the natural environment. To generate the indicators, WWF transformed raw datasets into risk scores. They are initially spatially aggregated or converted to a consistent scale based on river basins, and then classified into five risk score categories (ranging from 1 to 5) ('Figure 9', below). This standardization process allows the comparison between different indicators and enables their combination. The spatial units for aggregating basin risk data and visualising maps are typically either: 1) HydroSHEDS HydroBASINS Level 7; 2) World Meteorological Organisation (**WMO**) Basins, which consolidate HydroBASINS into larger hydrographic regions; or 3) Country boundaries. The level of aggregation or conversion is chosen based on the characteristics of the raw data. Most data are aggregated/transposed using the HydroBASINS Level 7 layer, but if the raw data are provided as country-specific values, they are represented using country boundaries (WWF Biodiversity Risk Filter, 2023; WWF Water Risk Filter, 2023).

Figure 9: Example of raster raw data conversion to risk indicator scores.



Source: WWF, 2023. Water Risk Filter Methodology Documentation & Biodiversity Risk Filter Methodology Documentation.

Aggregated risk scores are determined by applying weightings specific to different industries. The WWF-RFs provide default weightings tailored for 25 distinct industry categories (refer to ‘Appendix 1’ for detailed weightings for each category). These categories are derived from a harmonized list of various standard industry classifications, such as the GICS and CDP industry classification. Some broader GICS categories, like Food and Beverage, which face higher water risks, are further subdivided, while others with lower water risks, like Professional Services, Software, Real Estate, and Financial Institutions, are grouped together. The default weightings are established through extensive consultations and peer reviews with stakeholders including NGOs, academics, financial institutions, and businesses, and are also informed by sector trends from CDP Water Security data. It is important to note that the underlying approach of the risk assessment is to evaluate average, recent risk conditions and some level of anticipated future risk. It focuses on typical conditions with a bias towards recent data, rather than assessing real-time risk scenarios (WWF Water Risk Filter, 2023).

The outcomes of the risk assessment allow the identification of environmental risks and opportunities for each facility site across 65 indicators to each of them. The WWF Biodiversity Risk Filter (**WWF-BRF**) uses a four-level system to assess these biodiversity risks, composed by eight different risk categories (five physical risk categories and three reputational risk categories).

i. Level 1: Risk type – Physical or Reputational.
ii. Level 2: Risk category
    a. Provisioning Services, Regulating & Supporting Services – Enabling.
    b. Regulating Services – Mitigating, Cultural Services.
    c. Pressures on Biodiversity.
    d. Environmental Factors, Socioeconomic Factors.
    e. Additional Reputational Factors.
iii. Level 3: Risk indicators – The above risk categories have different number of indicators and indicators’ scores that consider the local importance of biodiversity and potential threats (‘Annex B’).
iv. Level 4: Risk scores - which come from raw data sets on various aspects of biodiversity in a specific location.

The "scape risk" scores to specific biodiversity refers to landscape and waterscape, considering industry and local factors. The industry dependence considers how reliant a specific industry (e.g., electrolyser manufacturer needing nickel) is on the biodiversity aspect in question (e.g., nickel availability). The local factors consider how severe is the threat to that biodiversity aspect at the specific location (e.g., very little nickel available). This score can vary depending on both the location and the industry a company operates. For instance, "limited nickel availability" might pose a bigger risk for an electrolyser manufacturer located in an area with scarce nickel compared to a paper mill company in the same location. The industry materiality matrix and the description of each of the 33 indicators can be found in the Appendix section of the WWF Biodiversity Risk Filter Methodology Documentation (2023).

Similarly, the WWF-WRF has 32 indicators divided into 12 Basin Risk Categories, which are aggregated into the 3 major risk types: physical, regulatory and reputational. The physical risks related to water are (i) Water scarcity; (ii) Flooding; (iii) Water quality; and (iv) Ecosystem services status. The regulatory risks comprise the aspects of (i) Enabling environment; (ii) Institutions & governance; (iii) Management instruments; and (iv) Infrastructure & finance. The reputational risks comprise 4 categories: cultural importance of water to local communities, freshwater biodiversity importance, media scrutiny/coverage of water-related issues, and risk of hydro-political conflicts in the river basins. Details on the indicators for each risk category can be found in 'Annex C' and the databases compiled by the tool in the "Global Basin Risk Indicators - Descriptions, Sources and Links" (WWF, 2021) file.

To analyse the filters' output, the paper pivots the type of risk, GVC stage and global region. For the analysis per risk type, an average score is calculated for each indicator of both filters allowing for a group-level analysis, comparing the average physical risk across all sites. The results per GVC stage, an average of the biodiversity and water results per risk type are estimated, revealing the hotspot sites. Finally, an analysis per global region is also presented.

4 ELECTROLYSER’S GLOBAL VALUE CHAIN MAPPING

The first step in mapping a GVC involves creating relevant product groupings and identifying the specific stages to focus on within the chain (Frederick's, 2019). Based on Value Hill, this paper identified eight GVC stages centred around electrolyser operation projects, where the green hydrogen is generated. The pre-use stages consist of the extraction of minerals, metal processing, manufacturing of components and assembly of the electrolyser cell and stacks. The post-use consists of the reuse and redistribution of electrolyser, which could refer back to the electrolyser assembly companies and to the subcomponent manufacturers, the remanufacturing, which could repurpose the electrolyser components, and, finally the recycling, which can reduce the overload of mining by fuelling the material processing industries (‘Figure 10’, below).

Figure 10: Alkaline electrolyser GVC stages.

Product phase	**Pre use**				**Use**	**Post use**		
GVC stage	Extraction of raw materials	Manufacturing / processing materials	Subcomponents	Product	Installation and operation	Reuse/redistribute of main component	Remanufacture processed materials	Recycle raw materials
Main actors	Mining companies	Materials processing industries	Subcomponents manufacturers	Electrolyser manufacturers	Companies responsible for producing the green hydrogen	Electrolyser manufacturers and sectoral initiatives	Materials and Subcomponents manufacturers, network organisations	All previous
Location of interest	Mines	Industrial plants	Industrial plants	Industrial plants	Projects	Metal waste logistic centres	Metal waste logistic centres	Nickel recycling plants

Figure created by the author.

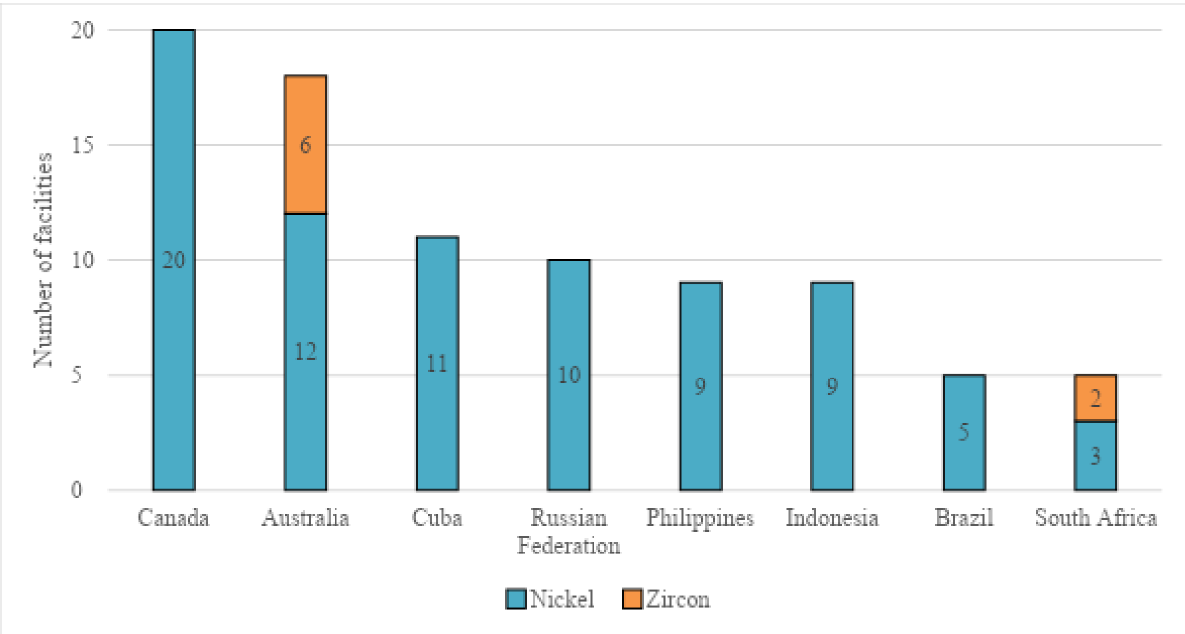
4.1 Pre-use stage actors: Supply Chain

This subsection presents the results and a brief discussion of the identification and mapping of GVC actors (companies) and their facilities.

Nickel and zircon mining

The actors of this stage were retrieved from Open Database and GlobalData top 10 nickel mines in 2022. Forty-four companies own the 102 facilities mapped (90 related to nickel production, 11 related to zircon, and 1 to potash), which are almost equally balanced between Global North (45%) and Global South (55%). Most of these facilities are in Canada and Australia ('Figure 11', below), which does not reflect the domination of the Indonesian nickel market, as outlined in 'subsection 2.3'. The top production countries identified match the latest report of "World Mining Data" (Reichl, 2024), although not in the same ranking order.

Figure 11: Top 8 countries by number of mines, smelters and refineries of nickel and zircon.

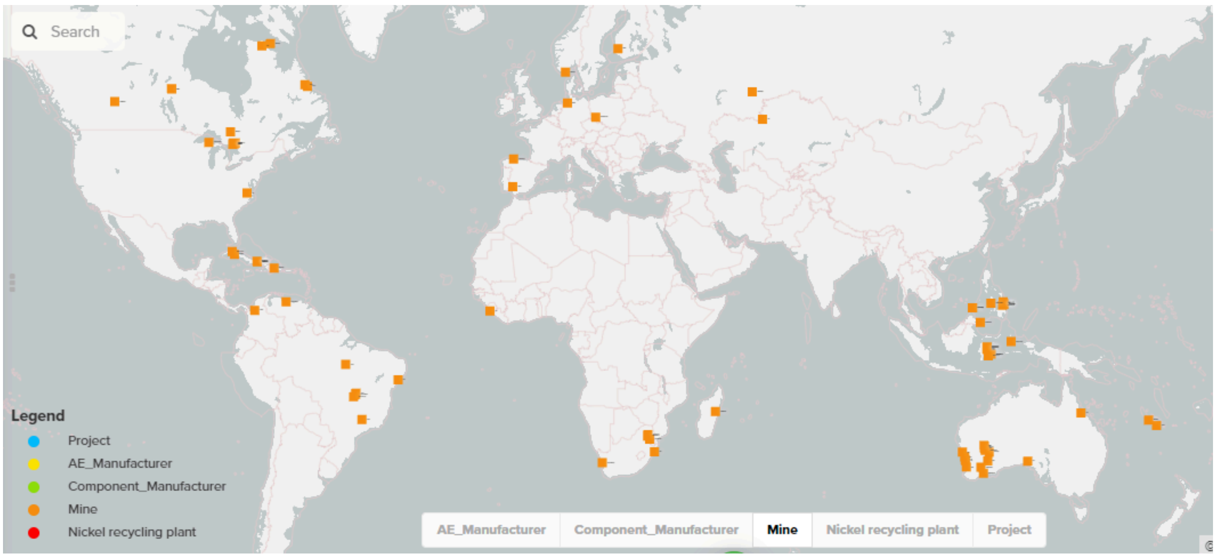


Data source: Jasansky et al., 2023."Open Database on Global and Coal and Metal Mine Production". Figure created by the author.

Limitations of this mapping consist of lack of facilities' production capacity and underrepresentation of facilities in the Global South, an issue intimately related to achieving a "just energy transition towards a low carbon economy". The facilities' production capacity is not being considered here, only the number of facility units, since the Open Database has little information on capacity. Moreover, its reliance on public, freely available information, implies that countries and companies with lower transparency will be underrepresented. For example, non-listed companies are not obliged to provide annual nor sustainability reports, and democratic countries or the ones with larger capital markets, might have stricter regulations regarding disclosures.

Meanwhile, the underrepresentation of facilities in the Global South is not only applicable to Indonesia. The authors of the Open Database recognise its underrepresentation of China (even though its classification as Global South is debatable), which had an overall low recorded facilities' location when compared to the UNEP IRP Global Material Flows Database. Indeed, when plotting the mine facilities on the world map, a lack of locations in East, South and Central Asia and the Middle East can be noticed ('Figure 12', below). This limitation reflects the unequal levels of data generation across the globe, associated with the availability infrastructure for data collection and storage, and also presents a challenge in tackling their environmental issues (Mehmood, 2021).

Figure 12: Global geographical distribution of extraction of nickel and zircon.

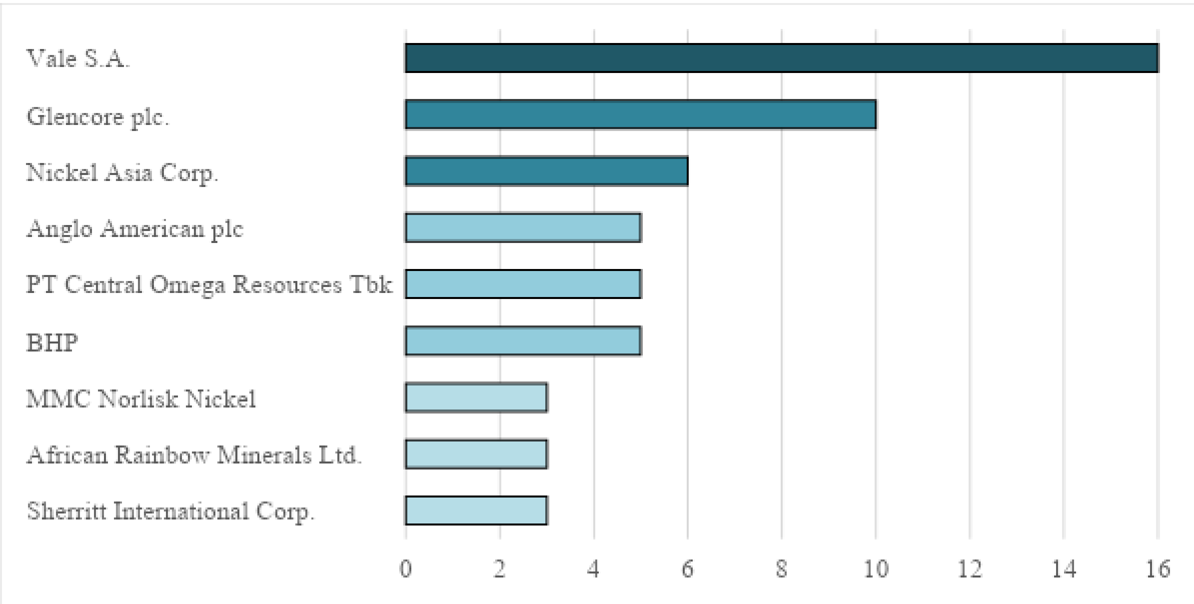


Source: Jasansky et al., 2023."Open Database on Global and Coal and Metal Mine Production". Figure created by the author using kumu.io.

The Open Database lacked 70% of the owner/operator firms of the nickel and zircon facilities. However, for this paper, this gap was reduced to 28% by using Large Neuro Language Model websites with the basic prompt “who owns/operates the following mines” Open AI (2024) and Gemini (2024). The purpose of the ownership information is to find connections between other GVC actors, potentially drawing analysis about the firm’s relationships.

On the firm level, large-scale mine companies are known for a series of social and environmental issues, from deforestation to land degradation and soil and water pollution, disrespect (or attacks) towards Indigenous and Traditional peoples, local communities, and labour concerns. It is also a highly centralised sector, despite the presence of over 4,000 medium-sized mining companies globally, the top 10 largest control a third of the world's mineral production (Dou et al., 2023). The leading companies in this GVC stage are Vale, Glencore and Asia Nickel Corporation (‘Figure 13’, below).

Figure 13: Major mine owners/operators, per number of facilities.



Source: Jasansky et al., 2023.”Open Database on Global and Coal and Metal Mine Production”. Open AI (2024) and Gemini (2024). Figure created by the author.

Vale, the largest nickel producer, faces criticism for its environmental impact, including pollution of waterways and deforestation. In Brumadinho, Brazil, for example, a dam failure disaster unleashed a wave of iron ore waste that devastated the surrounding area, killing 272 people and causing irreversible environmental damage (Sax, 2024). In

Vale's Canadian nickel mines, the company has also faced labour disputes on workers' rights and strikes that dropped the nickel production by 14.3% compared to the previous quarter (Kinch, 2021).

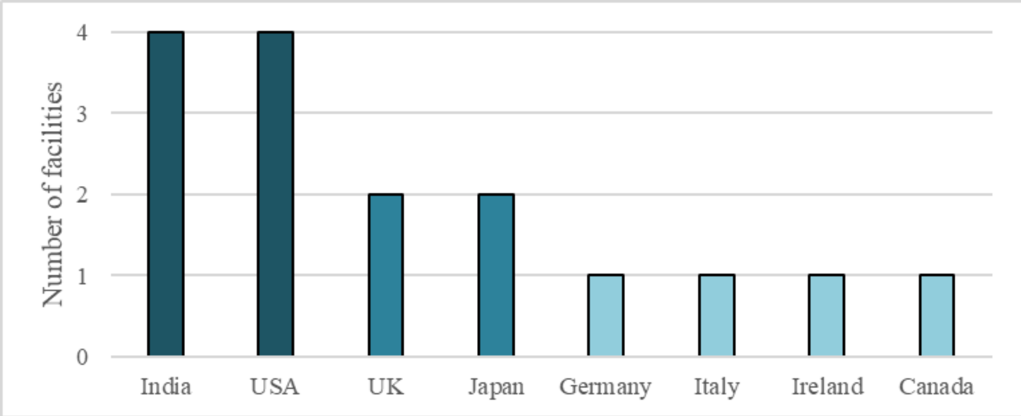
Similarly, Glencore has faced the court for allegedly expanding a mine into a sacred indigenous land in Australia (Nichols, 2021; Pelly & Ker, 2024). In addition, a subcontractor of Nickel Asia Corporation's was said to abuse workers' rights from a nickel mine in the Philippines (Amnesty Philippines, 2021). In response, Amnesty International, (2021) asked Chinese companies, who purchase the nickel from the referred mine, to require human rights due diligence in all companies of their nickel supply chain. All these examples show how significantly the mining industry still must improve from the perspective of environmental protection and human rights.

Electrolyser's component manufacturing

The actors of this stage were retrieved from a list of 10 major companies producing potassium hydroxide (for electrolyte production) and from the business units of ALK manufacturers that also produce their own components. This GVC stage has the least quantity of actors since manufacturing cathodes, anodes and electrolytes are specific activities, of which relevant references were not found.

The electrolyser manufacturer Thyssenkrupp nucera/DeNora stated that they produce their own components in different plants across the globe. In India, the company produces cathodic protection and brine chlorination, in Italy, separators for chlor-alkali diaphragm technologies, in Germany, gas diffusion electrodes and catalysts, and in the US, they produce anode and mixed metal oxide coating (Thyssenkrupp, 2021)., From the list of 10 major companies producing potassium hydroxide (Metoree, 2024), 14 locations were retrieved. Most facilities are in India and the US, followed by the UK and Japan ('Figure 14', overleaf).

Figure 14: Distribution of component manufacturer per country.

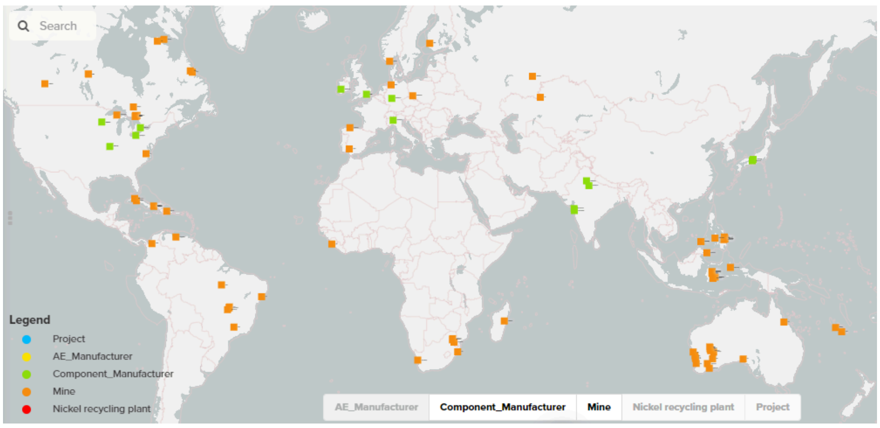


Source: Metoree (2024), De Nora Deutschland, n.d.; De Nora India, n.d.; De Nora Italy, n.d.; De Nora Tech - Concord & Mentor, n.d. Figure created by the author.

Like the previous stage, data from China is probably missing from the sources used, as its industrial productivity is very high. The main limitation of the mapping of the actors from this stage is the small sample size and difficulties in selecting relevant producers for specific industrial components. Due to this, analysis per firm was not conducted.

As expected, there is a considerable distance between these actors in relation to the mine locations in 'Figure 15' (below), except for some locations in the US and Europe. This geographical distance between mineral extraction and processing was outlined in the literature review (section 2.4) and indicates where the aggregated value of a product is being retained, and inequalities between countries can already be observed.

Figure 15: Geographical distribution of mines (in orange) and some ALK component manufacturers (in green).

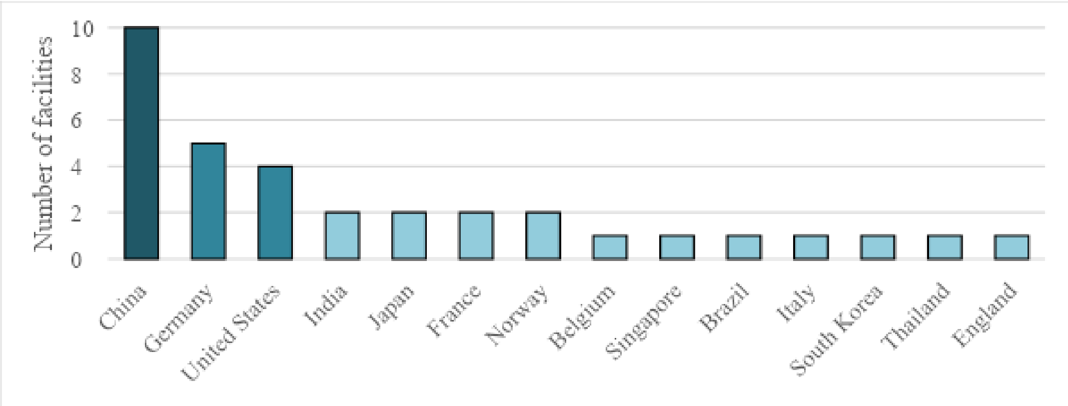


Data source: Jasansky et al., 2023."Open Database on Global and Coal and Metal Mine Production"; Metoree (2024), De Nora Deutschland, n.d.; De Nora India, n.d.; De Nora Italy, n.d.; De Nora Tech - Concord & Mentor, n.d. Figure created by the author.

Electrolyser manufacturing

In this stage, the Chinese market leadership is observed. Twenty-two companies were identified and 34 of their facilities were mapped, of which more than half are concentrated in China, Germany and the US, with one third being only in China (‘Figure 16’, below).

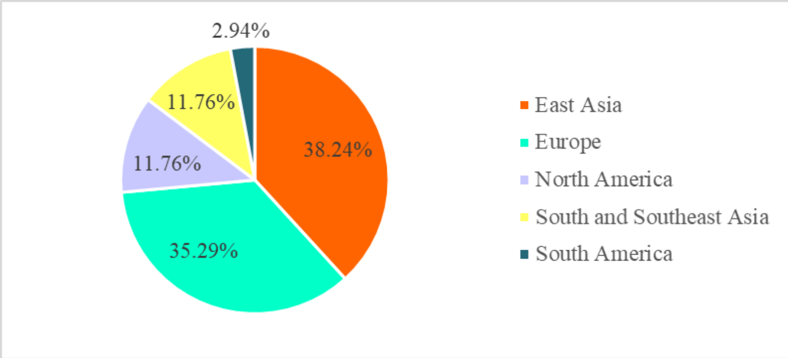
Figure 16: Distribution of mapped ALK manufacturing plants per country.



Source: Munjal et al., 2023.” Supporting the energy transition by addressing the technology gaps of electrolyzers” World Resources Institute; Klevstrand, 2022. “Chinese companies take top three slots in BNEF's list of worlds 20 largest hydrogen electrolyser makers” HydrogenInsight & BloombergNEF. Figure created by the author.

Aggregating per global region, 85% of the facilities are in the Global North and China. Most of the ALK facility plants are in East Asia (China, Japan, and South Korea) and Europe (mainly in Germany and France), as represented in ‘Figure 17’ (overleaf). This is convergent with the top electrolyser exporter countries reported by the World Trade Organization and the IRENA from 2020 to 2022 (WTO & IRENA, 2023).

Figure 17: Distribution of mapped ALK manufacturing plants per subcontinent.

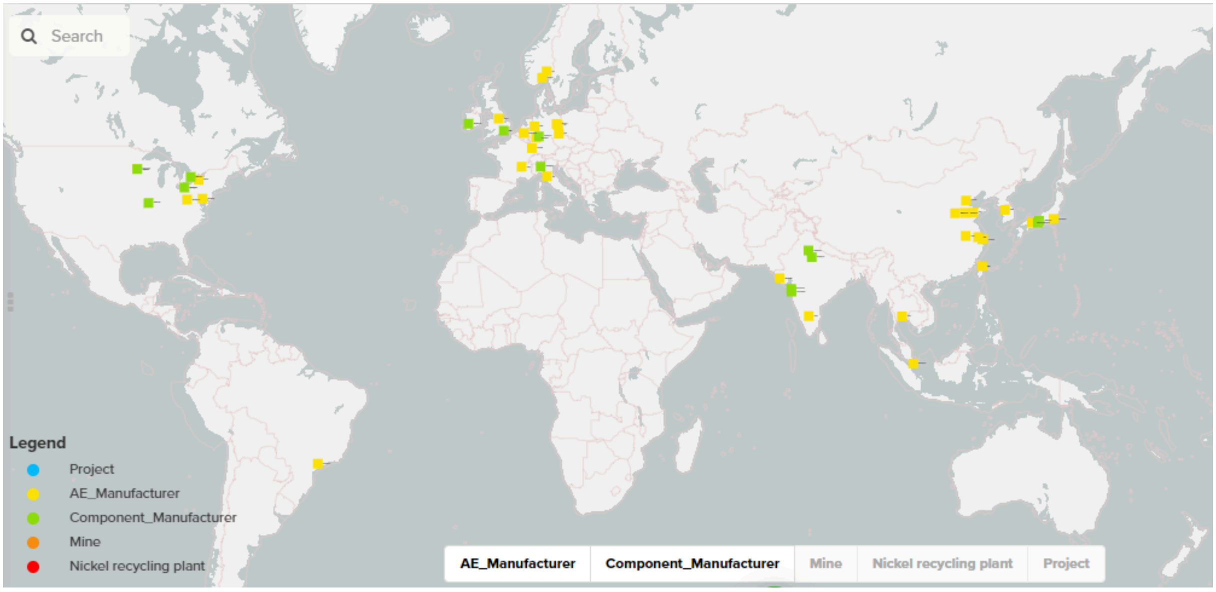


Source: Munjal et al., 2023." Supporting the energy transition by addressing the technology gaps of electrolyzers" World Resources Institute; Klevstrand, 2022. "Chinese companies take top three slots in BNEF's list of worlds 20 largest hydrogen electrolyser makers" HydrogenInsight & BloombergNEF. Figure created by the author.

The companies with a larger number of facilities are Thyssenkrupp nucera/DeNora (7), Cummins-Hydrogenics / Accelerazero (6), SunGrow (3) and McPhy (2). The two leading companies are subsidiaries of large industrial conglomerates who have recently joined forces with electrolyser manufacturing companies. Thyssenkrupp nucera and De Nora, Italian multinational, firmed a joint venture that plans to list Thyssenkrupp's shares in the Frankfurt Stock Exchange to boost the AKL business (De Nora, 2023). In parallel, the American multinational company Cummins acquired Hydrogenics, a Canadian electrolyser manufacturer, recently put up are branding effort change using the name Accelerazero (Collins, 2023). This gives them the advantage of controlling more stages of their ALK supply chain.

Different from the actors of the two previous GVC stages, electrolyser manufacturers are geographically closer to component suppliers, as seen in 'Figure 18' (overleaf), which might indicate a closer relationship between these GVC actors and/or be related to countries' level of industrialisation.

Figure 18: Geographical distribution of some ALK component manufacturers (in green) and leading ALK manufacturing plants (in yellow).



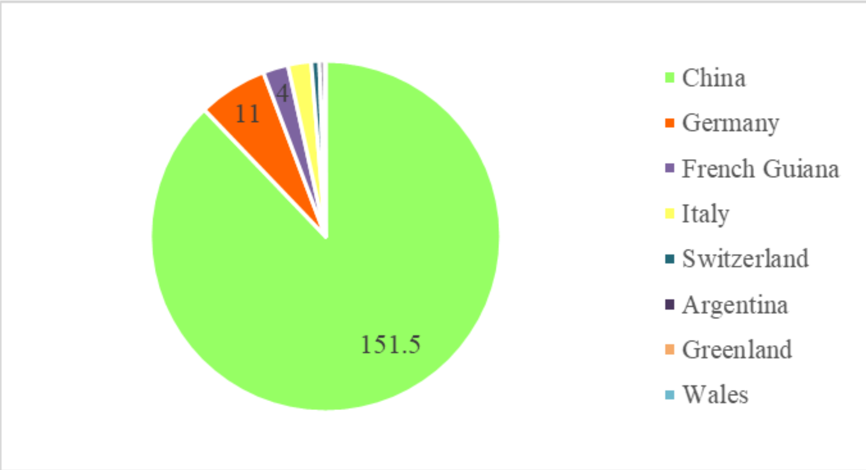
Source: Munjal et al., 2023." Supporting the energy transition by addressing the technology gaps of electrolyzers" World Resources Institute; Klevstrand, 2022. "Chinese companies take top three slots in BNEF's list of world's 20 largest hydrogen electrolyser makers" HydrogenInsight & BloombergNEF; Metoree (2024), De Nora Deutschland, n.d.; De Nora India, n.d.; De Nora Italy, n.d.; De Nora Tech - Concord & Mentor, n.d. Figure created by the author.

4.2 Use stage: Alkaline electrolyser projects

According to the IEA's Hydrogen Projects Database, eleven ALK projects are relevant for this paper – the ones that are renewable-powered, currently in operation or in the Final Investment Decision phase. As outlined in the literature review, many companies announced that their green hydrogen projects are in the initial stages of development and their type of technology are still to be determined. More than double of the ALK project sample is in the feasibility study phase, with unknown electrolysis type nor consumption, reflecting a possible uptake of the projects and their value chains. Therefore, a few of the leading ALK manufacturer companies were not connected to the current projects, for example, the Chinese company SunGrow (Dokso, 2023).

These 12 commercial ALK projects (64%) are located mostly in Europe, with only two in South America and two in China. Although it might suggest Europe's pioneering in the technology and a growing market demand, they are small scale applications. Meanwhile, the Chinese projects are the largest ones in terms of production capacity ('Figure 19', overleaf).

Figure 19: ALK projects' country location per capacity, in MW.



Source: IEA, 2023." Hydrogen Projects Database." Figure created by the author.

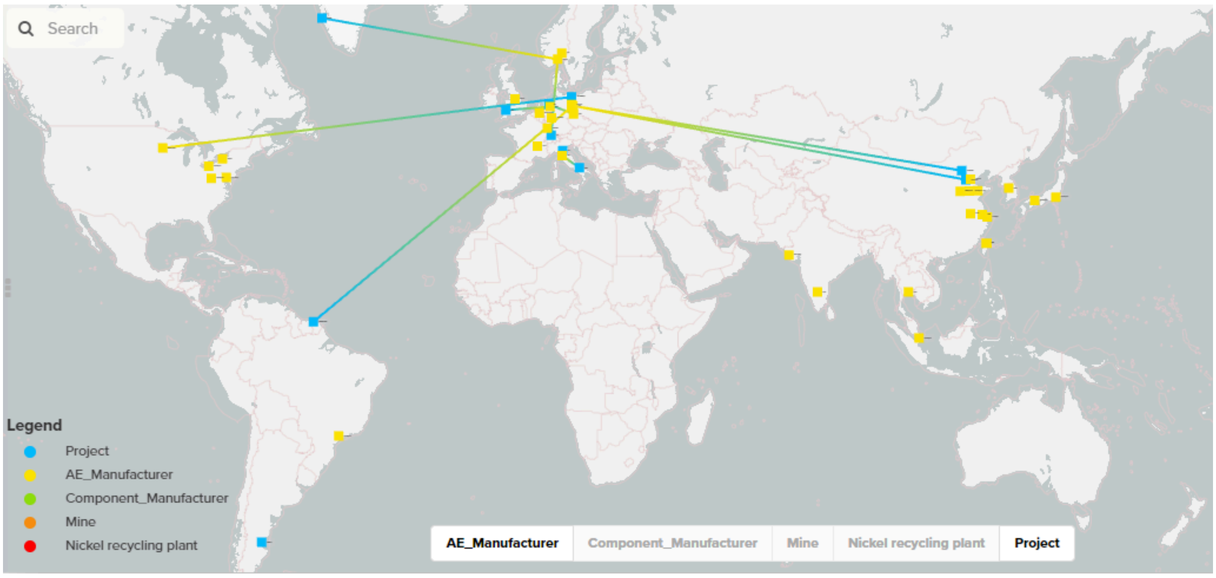
The main firm responsible for the projects in China is Hebei Construction and Investment Group Co., Ltd., which will be powered by wind sources. Most projects have stated receiving some type of public financial support. Direct electrolyser suppliers were identified for all projects, except for the one in Argentina ('Table 3', below, and 'Figure 20' overleaf).

Table 3: ALK projects and respective electrolyser suppliers, in order of capacity size.

Project name	Electrolyser provider
Hebei Jiantou Guyuan wind project, phase 1	McPhy
H2 Pilotanlage Lingen, phase 1	Sunfire
Centrale Electrique de l'Ouest Guyanais (CEOG)	McPhy
Hyper Hydrogen Energy Zhangjiakou Wind Power Hebei, phase 2	McPhy
IdrogeMO	De Nora
Hydrospider	Nel Hydrogen
INGRID	McPhy
RH2 Grapzow, Mecklenburg Vorpommern	Cummins-Hydrogenic
Hychico	Unkown -
H2KT	Nel Hydrogen
Baglan Energy Park Wales	Enapter

Source: own elaboration.

Figure 20: Geographical distribution of the leading ALK manufacturing plants (in yellow) and its place of operation (in blue).



Source: IEA's Hydrogen Projects Database, 2023; Munjal et al., 2023." Supporting the energy transition by addressing the technology gaps of electrolyzers" World Resources Institute; Klevstrand, 2022. "Chinese companies take top three slots in BNEF's list of world's 20 largest hydrogen electrolyser makers" HydrogenInsight & BloombergNEF;Actusnews wire, 2021; Green Car Congress, 2009; H2-View, 2023; McPhy, n.d., 2020; RWE, n.d.; S&P Global Commodity Insights, 2020. Figure created by the author.

Six out of the ten connections between ALK manufacturing plants and projects (where stacks operate) occur inside Europe, with only Germany and Italy having domestic ALK suppliers, and China and the US increasing the competitivity of their domestic market. Outside Europe, long geographical distances are observed between ALK manufacturers and the places where ALK stacks operate, meaning that the environmental footprint for transport will also be higher.

4.3 Post-use actors: Nickel recycling

As outlined in section 2.5, the ALK's reuse and repair, which are highest in the Value Hill hierarchy, are not currently viable technically and economically, as some references state that the current designs do not allow for reuse or remanufacturing. Therefore, this section focuses on the recycling of the main raw material of the ALK, nickel. The sample for this paper comprised 131 nickel recycling facilities, owned by 13 companies. Two dominant companies within the dataset possess hundreds of plants collectively.

A major limitation of this mapping is that the data lacks clarity regarding the specific number of facilities engaged in nickel recycling or the implementation of proper procedures for ALK disassembly across their entire holdings. To address this, a statistically derived sample (n=92) was drawn from these two companies, representing approximately 70% of the total sample pool. This skewed distribution results in a situation where over half of the analysed facilities are within the US (‘Figure 21’, below). Although the substantial number of plants aligns with the maturity of the metal recycling industry, it does not imply a positive scenario, since the analysis does not take the production and processing capacity of the facilities. Furthermore, processing several types of materials that involve nickel, such as stainless steel and batteries has a considerable difference. Therefore, it is important to note that this is a rough analysis that does not consider the technical specificities of each facility, but a very generalised estimation. To refine this work, more variables should be considered, but more transparency on the companies’ side is also important to make the facilities’ technical specificities clearer. Many of the firms in this stage are also involved in the nickel and zircon mining stage. Similarly to them, there were few companies that owned many facilities, concentrated in the US.

Figure 21: Geographical distribution of the leading nickel recycling plants.

Source: Xenon Market Insights (2024). Figure created by the author.

A key player found in nickel recycling, stage Glencore, was also mapped in section **4.1**. as one of the world’s largest nickel mining companies (Glencore, n.d.). Several other companies of this GVC stage primarily focus on activities within the nickel mining, refining, and/or trading sectors. They are Umicore, Sims Metal, Schnitzer (Radius Recycling), Hanwa, GEM, Aurubis, Stena Nickelhütte Aue GmbH. No evidence of nickel recycling was identified amongst the remaining leading nickel mining companies. In summary, eight companies out of 13 seem to have the potential to operate circularly within their vertical chain, even if not on a close loop yet.

Although the firms of these two stages are similar, the spatial distribution of the facilities is not. While most of the recycling is in the geographical north, similarly to the previous manufacturing-related stages, the raw material extraction still relies on the global south.

4.4 Summary of the analysis

A GVC actors mapping was manually conducted based on a variety of data sources, and main companies and countries involved in each stage were identified. In total, 46 countries, 101 companies and 297 facilities participate in the GVC.

The primary countries involved in mining and raw material production are Canada, Australia, and Indonesia. The distribution of number of facilities across global regions is relatively balanced, and the only stage of which African countries participate. Most of the component manufacturers and ALK manufacturers are in Asia, followed by Europe. Germany, France, and Italy are the current suppliers ALK technology, with China emerging as a significant future supplier. In the project stage, although Europe has more quantity of ALK plants, China holds a dominant position in terms of capacity size. Finally, the United States leads in the end-use stage, being the location of most of the nickel recycling plants of the sample (‘Figure 22’, overleaf).

Figure 22: GVC actors' distribution across global regions.

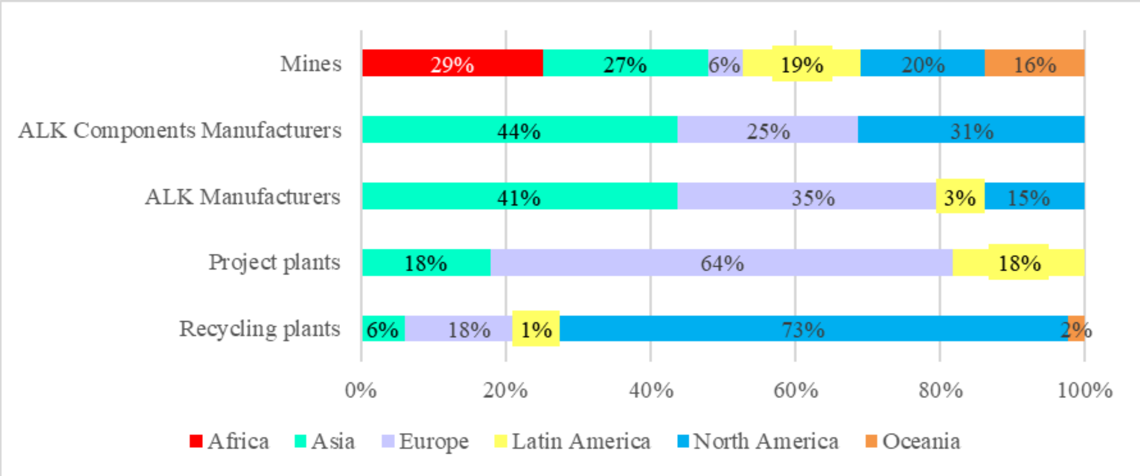


Figure created by the author.

The findings suggest a tighter relationship between ALK projects and manufacturer electrolysers stages, while the others play an indirect role, being also geographically farther from the ALK projects and manufacturers' concentration in western Europe. The first is based on evidence of direct traceability that could be found from the electrolyser manufacturer to the project but, for all the other stages, it was not possible to do so, since companies might not track all the tens of thousands of suppliers it has not disclose them due to commercial reasons.

The identified leading firms of the GVC are Vale, Glencore, Nickel Asia Corporation, Thyssenkrupp Nucera/DeNora, Cummins-Hydrogenics/Accelerazero, McPhy and Hebei Construction and Investment Group Co., Ltd. From the compound names of some ALK manufacturers, it was found that a common business strategy in the sector is merging and/or acquisitions of other private or startup companies. Moreover, it was found that many of the current ALK projects are partially funded by the public sector, such as in France and in China. These findings demonstrate the importance of partnerships for the energy transition, be it public-private or between firms.

In line with the circular economy approach, linkages between the first and the last GVC stages (raw material production and recycling) were found to be closer than expected, as the few companies that extract nickel also recycle it, even though their rate of extraction and recycling were not compared and could be questioned. However, considering that the Value Hill framework is a hierarchy, recycling is at the bottom, being the process that would require more energy and natural resources for the material to be recovered.

The above-mentioned concentration of ALK projects and manufacturers in western Europe tends to shift due to Chinese green hydrogen demand, which currently has the largest ALK project in the world. As geographical proximity reduces suppliers' risk taking (Huang & Fan, 2022), we could infer that the mining stage is the one that presents higher risk, since the actors are located farther from the rest of the GVC and the risk of information asymmetry is higher.

Furthermore, a visual inspection of the geographical distribution of the GVC actors per stage indicates that nickel production is far from the places of its consumption, reinforcing the findings of Nakajima et al. (2017) on global land use for nickel supply and demand. Adding the environmental risk approach to this aspect, it is further discussed through the lenses of just transition in the next section.

5 ENVIRONMENTAL RISK ASSESSMENT RESULTS AND DISCUSSION

This section presents the outputs of the WWF-RFs for the GVC actors mapped in the previous section. To identify the main environmental challenges throughout the ALK's GVC, a range of 64 biodiversity (scape) and water-related (basin) indicators, are divided into physical and reputational risks. were scored from 1 to 5 (from very low to very high). The risk score threshold of which this section will focus the analysis is "high" and "very high" indicators, or scores greater and equal to 3.4.

However, not all indicators were considered relevant to the industries included in the GVC stages. For biodiversity, 13 out of the 20 indicators were considered relevant, and the result scores are presented in ' All water-related indicators were considered relevant according to the WWF-WRF, for basin physical risk ('Table 5') and basin reputational risk ('Table 7') types.

To support the recommendations for firms to implement a just transition approach across all stages of the GVC and De Marchi & Gereffi (2023) pillars for the study of GVC's sustainability, this section separates the results per GVC stage and, additionally, per global region.

Table 4' (overleaf), for scape physical risks, and in 'Table 6', for scape reputational risks. All water-related indicators were considered relevant according to the WWF-WRF, for basin physical risk ('Table 5') and basin reputational risk ('Table 7') types.

To support the recommendations for firms to implement a just transition approach across all stages of the GVC and De Marchi & Gereffi (2023) pillars for the study of GVC's sustainability, this section separates the results per GVC stage and, additionally, per global region.

Table 4: Average scores of GVC actors on the Biodiversity Scape Physical Risk indicators.

A score from 1.0 to 1.8 represents very low risk (light green), from 1.9 to 2.5, low risk (light yellow), from 2.6 to 3.3, moderate risk (orange), from 3.4 to 4.2, high risk (dark orange), above 4.2, very high risk (red), and NA when there is no significant impact or dependency.

Risk category		1. Provisioning Services			2. Regulating & Supporting Services - Enabling		3. Regulating Services - Mitigating				5. Pressures on Biodiversity			
GVC stage	**Sector**	**Water Scarcity**	**Forest Productivity**	**Limited Wild Flora & Fauna Availability**	**Water Condition**	**Air Condition**	**Landslides**	**Fire Hazard**	**Extreme Heat**	**Tropical Cyclones**	**Land, Freshwater and Sea Use Change**	**Tree Cover Loss**	**Invasives**	**Pollution**
Mines (nickel and zircon)	Metals & Mining	3.6	3.4	NA	2.4	2.2	3.3	3.0	3.1	3.4	3.4	3.9	2.7	3.4
ALK Components	Chemicals & Other Materials Production	3.1	NA	2.6	3.6	2.6	3.2	3.2	3.2	3.2	2.0	1.4	NA	4.1
ALK Manufacturers	Electronics & Semiconductor Manufacturing	3.2	NA	NA	3.0	2.5	3.2	3.2	3.0	3.4	2.0	1.8	NA	4.1
ALK Projects	Electric Energy Production - Solar, Wind	2.7	NA	NA	3.1	2.5	3.4	3.2	2.5	2.7	2.6	1.7	NA	3.5

Recycling plants (nickel)	Metals & Mining	3.6	3.2	NA	2.7	2.4	3.2	3.1	3.4	3.4	3.9	4.0	3.1	3.7

Table created by the author using WWF Biodiversity Risk Filter.

Table 5: Average scores of GVC actors on the Basin Physical Risk indicators.

A score from 1.0 to 1.8 represents very low risk (light green), from 1.9 to 2.5, low risk (light yellow), from 2.6 to 3.3, moderate risk (orange), from 3.4 to 4.2, high risk (dark orange), above 4.2, very high risk (red), and NA when there is no significant impact or dependency.

Risk category		1. Water Scarcity							2. Flooding		3.Water Quality	4. Ecosystem Services Status		
GVC stage	Sector	Aridity Index	Water Depletion	Baseline Water Stress	Blue Water Scarcity	Available Water Remaining	Drought Frequency Probability	Projected Change in Drought Occurrence	Estimated Flood Occurrence	Projected Change in Flood Occurrence	Surface Water Quality Index	Fragmentation Status of Rivers	Catchment Ecosystem Services Degradation Level	Projected Impacts on Freshwater Biodiversity
Mines (Nickel and Zircon)	Metals & Mining	1.6	1.6	1.9	2.3	2.5	2.6	2.6	2.6	2.5	2.7	2.2	2.9	2.5
ALK Components	Chemicals & Other Materials Production	1.4	2.0	1.9	2.5	2.4	1.9	NA	3.5	2.3	4.2	4.2	1.4	2.1
ALK Manufacturers	Electronics & Semiconductor Manufacturing	1.4	2.0	2.6	2.1	2.7	2.1	2.8	3.3	2.2	4.2	3.7	2.1	2.1
ALK Projects	Electric Energy Production - Solar, Wind	1.9	1.9	2.5	2.0	3.2	2.1	3.5	2.4	2.0	4.3	2.8	1.9	2.9
Recycling plants (Nickel)	Metals & Mining	1.4	1.7	2.3	2.0	2.4	2.2	2.9	3.4	2.3	3.3	4.0	2.9	2.3

Table created by the author using WWF Water Risk Filter.

Table 6: Average scores of GVC actors on the Biodiversity Scape Reputational Risk indicators.

A score from 1.0 to 1.8 represents very low risk (light green), from 1.9 to 2.5, low risk (light yellow), from 2.6 to 3.3, moderate risk (orange), from 3.4 to 4.2, high risk (dark orange), above 4.2, very high risk (red), and NA when there is no significant impact or dependency.

Risk category		6. Environmental Factors					7. Socioeconomic Factors			8. Additional Reputational Factors			
GVC stage	Sector	Protected / Conserved Areas	Key Biodiversity Areas	Other Important Delineated Areas	Ecosystem Condition	Range Rarity	Resource Scarcity: Food, Water, Air	Labor/ Human Rights	Financial Inequality	Media Scrutiny	Political Situation	Sites of International Interest	Risk Preparation
Mines (nickel and zircon)	Metals & Mining	4.0	3.3	3.5	3.6	3.0	2.3	3.6	2.4	4.6	2.8	2.6	2.2
ALK Components	Chemicals & Other Materials Production	2.7	2.1	1.8	2.0	1.6	1.9	2.8	2.1	4.3	2.0	1.9	2.0
ALK Manufacturers	Electronics & Semiconductor Manufacturing	2.8	2.2	1.9	2.2	1.7	1.9	2.8	2.2	2.8	2.2	1.9	1.8
ALK Projects	Electric Energy Production - Solar, Wind	3.2	2.7	2.1	2.4	2.3	NA	2.4	2.4	3.2	2.2	2.4	1.9

Recycling plants (nickel)	Metals & Mining	3.8	3.1	3.1	3.1	2.8	2.2	3.9	2.3	4.9	2.5	2.3	1.6

Table created by the author using WWF Biodiversity Risk Filter.

Table 7: Average scores of GVC actors on the Water Basin Reputational Risk indicators.

A score from 1.0 to 1.8 represents very low risk (light green), from 1.9 to 2.5, low risk (light yellow), from 2.6 to 3.3, moderate risk (orange), from 3.4 to 4.2, high risk (dark orange), above 4.2, very high risk (red), and NA when there is no significant impact or dependency.

Risk category		**9. Cultural Importance**	**10. Biodiversity Importance**		**11. Media Scrutiny**		**12. Conflict**	
GVC stage	Sector	Cultural Diversity	Freshwater Endemism	Freshwater Biodiversity Richness	National Media Coverage	Global Media Coverage	Conflict News Events	Hydro-political Likelihood
Mines (nickel and zircon)	Metals & Mining	3.7	3.2	3.0	4.0	3.0	3.8	2.0
ALK Components	Chemicals & Other Materials Production	4.2	2.8	4.6	4.2	3.4	4.6	3.6
ALK Manufacturers	Electronics & Semiconductor	3.9	3.5	4.1	3.9	3.2	4.3	2.4

	Manufacturing							
ALK Projects	Electric Energy Production - Solar, Wind	2.6	4.4	3.5	3.7	2.9	4.0	1.8
Recycling plants (nickel)	Metals & Mining	4.5	3.0	3.8	3.9	3.0	4.6	2.5

Table created by the author using WWF Water Risk Filter.

5.1 Nickel and zircon mining

In the previous sections, the nickel and zircon mining stage showed that facilities across the world are highly concentrated in the hands of a few large companies, who were previously accused of damage to the environment and social rights. Using the available location and ownership data of mines, considering the lack of information from Global South countries, this subsection outlines the overall main environmental issues, based on risk scores.

The nickel and zircon mining stage presented the highest biodiversity risk across the GVC, for both physical and reputational types. The mining facilities with the overall highest physical risk scores, for both water and biodiversity, are mostly in the geographical global south. The major biodiversity physical risk category driving this result is "Provisioning Services", meaning that the facilities in this GVC stage significantly rely on and impact the ecosystem services. For water, the reputational risk was higher than the physical, driven by “Cultural importance”, “Media scrutiny” and “Conflict”, briefly explained below. Based on these key findings, the focus of the subsection is the output of the WWF-BRF.

“Water scarcity” and “Forest productivity and distance to markets” are the main biodiversity-related indicators with high risk, related to the “Provisioning services” category. Water is an important natural resource consumed by mining production operations, especially for temperature control, dust suppression in industrial processes, and treatment of metal ores that have high impurity levels (Ikeuchi, n.d.; Klaren, 2024). If the water management is not done sustainably, it generates water scarcity and could be a threatening factor, not only for the businesses but for the entire VC, if the scale is large or large/key firms and facilities. In parallel, the “Forest productivity and distance to markets” aspect refers to the impact on timber availability and was not foreseen in the literature review. The high score result of these indicators is explained by the reliance of the mining pits on infrastructure made out of timber, such as underground supports, temporary bridges and facilities, and fencing (Reid et al., 1952; Staley, 1962), a consolidated practice in the industry. Moreover, its impact on timber availability is not only from its consumption, but also from impact on the fauna and flora of its surrounding environment (International Energy Forum, 2024; Lamb & Wade, 2022), including pollinators which are key for forest productivity, for example.

This topic is interrelated to another high-score risk indicator from the “Pressures on Biodiversity” category, driven by “Tree Cover Loss” and “Invasive Species.” Cases of mines in Indonesia (Jong, 2024) reported indiscriminate deforestation driven by nickel exploitation, while in Canada, it poses pressure on ecosystem sensible areas (Struzik, 2023). Deforestation is directly related to the occurrence of invasive species, from the disturbance of the ecosystemic chains to more frequent occurrences of infectious diseases (Guégan et al., 2020; Wertz-Kanounnikoff, n.d.; Zimmer, 2019). A recent study in Brazil, for example, found that bat species presented DNA damage due to long exposure to metals in nickel mining area (Sotero et al., 2023). Mining is also correlated to the widespread of invasive plant species, as demonstrated by (Calinger et al., 2015).

Mining's chronic impact on land degradation is an important aspect that was not captured by one indicator or database but, instead, a set of indicators that, compared to previous research, could be improved at a local level of analysis. From the results tables, the “Tree cover loss” indicator represents the association of mining activities with deforestation and soil erosion, while the “Soil Condition” focuses on soil organic matter composition (WWF Biodiversity Risk Filter, 2023), which actually becomes lower in mining sites and post-nickel mining sites (Kumar, 2013). Moreover, the “Landslide Hazard” considers acute soil movement events. Comparing them to the literature, regional indicators of land stability – as developed in Indonesia (Barus et al., 2022), could help decision-makers manage and mitigate land issues, for example. Also, although the soil conditions after nickel mining are found to be poor with very difficult capacity for reforestation (Prematuri et al., 2020), it could be used for growing non-timber crops, as shown in a study from (Neswati et al., 2020).

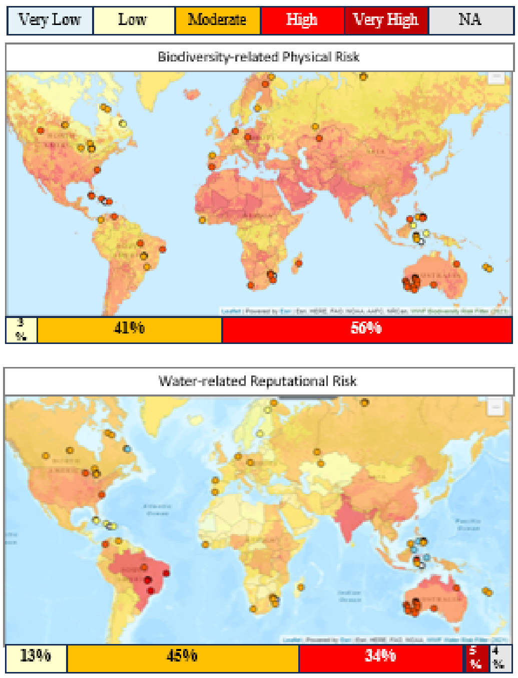
Water pollution due to nickel mining, smelting and refining was identified in the literature review as one of the main hotspots of the ALK LCA (Krishnan et al., 2024). However, it was not reflected in the risk score, possibly because of the scale of analysis. An LCA study is more detailed to a specific product, while this paper shows a regional level analysis of the GVC actors at a global scale.

The most vulnerable mining facilities with the overall highest physical risk scores are in the tropics, more specifically in the geographical south, which is more susceptible to climate change effects (Corlett, 2014), enhancing current environmental challenges. More than half of the mining facilities (56%) presented a high biodiversity physical risk (‘Figure 23’, overleaf). The hotspot facilities of the GVC are in the Limpopo region of South

Africa, owned by African Rainbow Minerals, and in Western Australia, owned mostly by BHP. Their vulnerabilities are driven by the same key indicators explained above, in addition to a reputational risk of “Cultural Importance.”

Regarding reputational risks, 39% presented a high or very high reputational risk on water (‘Figure 23’, below). In line with the literature review and mapping sections of this paper, the sites of Vale in Brazil are the only ones that present very high-risk scores on water-related reputational risks. The company BHP in Australia, and Asia Nickel Corp in the Philippines present high risk, which is in line with the discussion in the mapping section. In this GVC stage, 30% of the facilities present a very high level of cultural importance, especially in Australia, Indonesia and Brazil, showing a need for greater care for local communities in these sites. Moreover, **“**Labour/Human rights”, already flagged as a hotspot in the green hydrogen supply chain by Akhtar et al. (2023), were highly scored, driven by the sites in Indonesia, Cuba, Russia, Brazil and Philippines, in this order. Finally, areas of conservation and protection and ecosystem conditions, which vary from moderate to high, is also a key reputational aspect for GVC actors to take into consideration in their business strategies.

Figure 23: Risk score classification mappings for biodiversity physical risk and water reputational risk; for nickel and zircon production facilities.



Note: the blue elements in the water reputational risk map are facilities in which the tool had no available data. Figure created by the author using WWF Risk Filter.

5.2 Electrolyser's component manufacturers

The actors involved in manufacturing components for an ALK were located mostly in India and in the US, the same countries expected to increase their share of global production of green hydrogen via ALK by 2030 (IEA, 2023a), and where most of the risks were concentrated.

The ALK component manufacturers stage presented the highest risk score on "Freshwater Biodiversity Richness" across all the GVC – which refers to a higher risk of reputation exposure of companies operating in basins with higher freshwater biodiversity (WWF Water Risk Filter, 2023). This stage presented, overall, higher risks related to water compared to biodiversity. For water, the reputational risks were higher than the physical risks, while for biodiversity it was the opposite. The main water reputational risk categories were related to "Biodiversity importance" "Media Scrutiny" and "Conflict". In parallel, the main aspects of physical biodiversity risks were in "Water condition" and "Pollution", which are complementary to each other.

The biodiversity and water physical risks of this GVC are concentrated in the category "Ecosystem Services Status", in indicators of "Water Quality" and "Fragmentation Status of Rivers", meaning that the GVC actors of this stage are in locations already with some vulnerability and/or have the potential to exacerbate it. This result is in line with the wastewater impact of the "Chemicals & Other Materials Production" industry, especially concerning electrolyte handling (Heider et al., 1999) as well as its dependency on good quality water for their operations. In parallel, "Fragmentation Status of Rivers" or river modifications (such as channelization and dams) and soil sealing from human activities disrupt natural flow patterns and increase flood risk in settled areas (Rentschler et al., 2023; WWF Water Risk Filter, 2023) (Rentschler et al., 2023; WWF, 2021). This explains the high "Estimated Flood Occurrence" for this GVC stage, as it is linked to the specific river basin actors operate in.

In this stage, 31% of the ALK component manufacturers present high or very high risk for water-related issues and 25%, have a high risk for biodiversity physical risks ('Figure 24', overleaf). Almost 50% of the sample presented a very high risk of "Water quality", an aspect related to the basins.

Figure 24: Physical risk mapping and classification for ALK Component manufacturers' facilities.

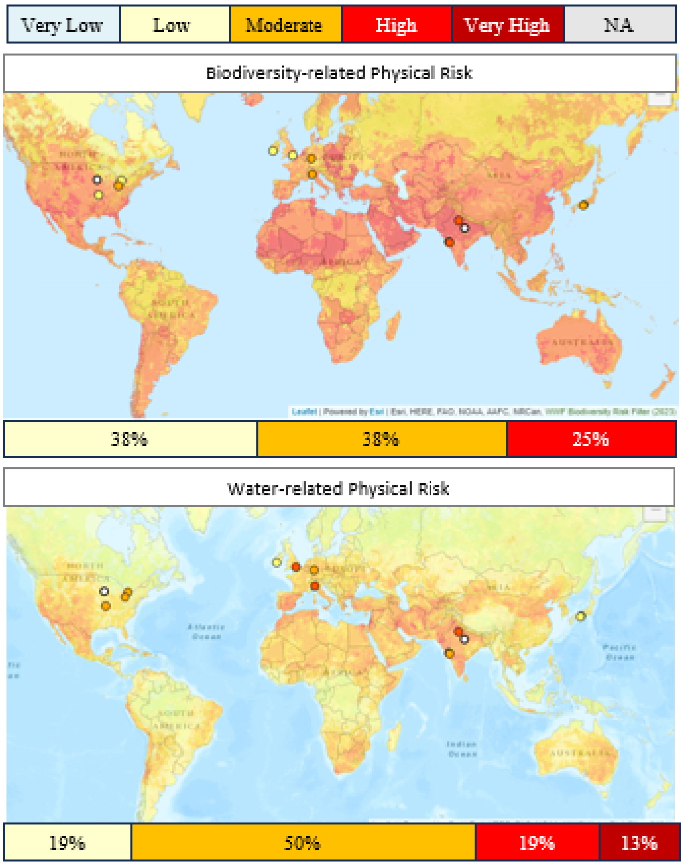


Figure created by the author using WWF Risk Filter.

The facilities with highest physical and reputational risks combined are in India, in the provinces of Delhi and Uttar Pradesh, in Yamuna and Arabian Sea landscapes. The second highest risk region is in the United States, in the Mississippi Basin ('Figure 24'). Both basins include perennial rivers that are becoming seasonal due to continuous pollution (Mushtaq & Chaudhry, 2023) and global warming. Furthermore, they are also the ones with higher "Cultural Importance", meaning that their conservation has a very important social layer to be taken into account.

In the previous subsection, the energy just transition was approached from an international point of view. Here, as the sample is smaller, a focus on the two hotspot countries is favourable to guide a discussion towards social inequalities within them. India and the US are very large countries with many social contrasts. While some regions might benefit from a cleaner environment and social wellbeing, the regions in which the actors of this GVC stage are located are far from benefiting from clean sources of energy for which they are building the infrastructure. Although Mississippi, Delhi and Uttar Pradesh have extensive potential for solar power generation, these regions still heavily rely on fossil fuels (Kuebler, 2021; US EIA, n.d.). Because of this, the air pollution situation in India has been aggravating so much that a study from the University of Chicago estimated that it has been prematurely shortening the lives of people by 10 years (BBC, 2022) and an estimated 2.5 million people die each year in the country due to air pollution (Vohra et al., 2021). It is known that the firms of this GVC stage are not necessarily in the green industry, but it is still important for them to raise awareness of their workers and surrounding communities towards energy transition and water availability as well as re-skilling personnel to create more "green jobs". In the meantime, national policies to substitute fossil fuels for renewables are slowly taking place in these regions (Economic Times, 2022; Mills, 2022) and, little by little, investors are becoming more aware of the nature-related financial risks of their portfolios (TNFD, 2023), also recognising the climate just transition with water accessibility in Mississippi (EHI Cleantech Ventures, n.d.), for example.

The recommendation for this stage's actors is related to water management practices, from wastewater treatment and reuse, improvement of water use efficiency, and sustainable source of raw materials. The actors of this stage can exert the client's power of procurement to select suppliers with best practices on sustainability, while working collaboratively with other stakeholders upstream, including their own clients.

5.3 Electrolyser manufacturers

The majority of the ALK manufacturing plants are in China, Germany and the US. This concentration of ALK production in Global North countries could reinforce global inequalities, as this industry, of more aggregated value, will benefit socioeconomic advantageous regions. However, as discussed in the previous subsection, the benefits of the energy transition do not imply that they are equally distributed within developed countries either.

The ALK manufacturers, in general, presented fewer physical risks and more reputational risks. These risks were more significant in water rather than biodiversity and the results were similar to the component manufacturers. This stage has the highest share of actors (76%) with high-risk water scores, as opposed to only 15% for biodiversity. Most of these high-risk actors are in China, India, and Germany ('Figure 25', overleaf).

Figure 25: Biodiversity physical risk and water reputational risk mapping and classification for ALK manufacturers' facilities.

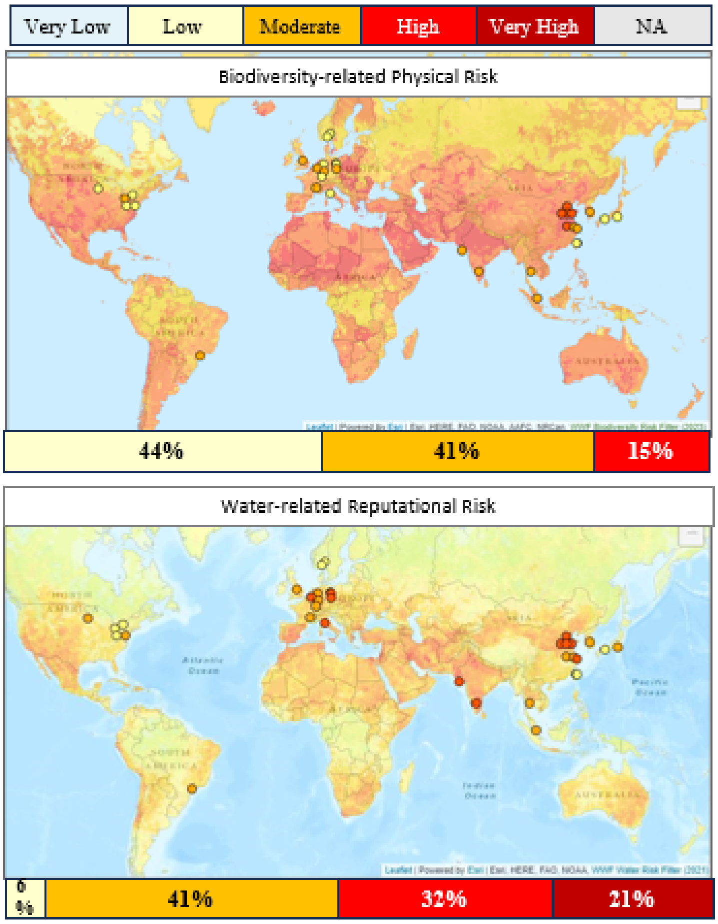


Figure created by the author using WWF Risk Filter.

Similarly to the previous GVC stage, ALK Manufacturers present high risk in "Water Quality", "Fragmentation Status of Rivers", and "Estimated Flood Occurrence", "Pollution" emerged as the highest biodiversity physical risk indicator for this stage, which refers to air pollution and freshwater nutrient pollution. To mitigate these impacts, material selection and less resource-intensive production processes can be important. For example, some electrolyser systems can achieve a lower environmental footprint by using steel manufactured through low-carbon methods (Krishnan et al., 2024).

The actors with the highest risks are in China and India, driven by high "Cultural Importance" and "Water Quality" risks. Of these, five are in the Yellow Sea & East China Sea and Cháng Jiāng (translated as Yangtze) Basins, and two are in India, at the Bay of Bengal and Arabian Sea regions. The Yellow Sea & East China Sea carry great importance on birds and marine life reproduction, that has been threatened by the rapid industrialization of East China in the last decades (Choi et al., 2020; WWF China, n.d.). In parallel, the Arabian Sea region has also been rapidly industrialised, and its bodies of water face enhanced impacts from the global temperature rise and discharge of brine from salinity (Le Quesne et al., 2021). This leads to a discussion on the priority of water use, which should be given to food production and direct consumption to the local people, instead of the manufacturing of ALK, which is also important to mitigate the highest reputational risk of the stage, “Conflict News Events”. This indicator, determined using RepRisk's country-weighted score of negative news, reflects historical political conflicts over scarce water resources (WWF Water Risk Filter, 2021).

5.4 Alkaline electrolyser projects

China and Germany lead the current ALK projects regarding capacity. In terms of quantity of projects, Europe is the leading region, with a few pilot projects in place. No projects are in Southeast Asia, the main global nickel producer, nor in India, where many of the ALK manufacturers and component manufacturers are located. This distribution, again, gives a sense of regions of extractions and regions that are benefited by the energy transition.

This GVC stage, the use stage, where green hydrogen is produced, presented the lowest risk score overall. Similar to the ALK manufacturers, the ALK projects presented a low risk for biodiversity and a slightly higher for water. More than half of the projects are in areas of moderate water basin physical risk, 36% are in low or very low risk areas and data Greenland is missing in the WWF-RF. The sites with higher physical risks are in China and Italy, especially due to “Water scarcity” and “Water quality” (‘Figure 26’, overleaf).

Figure 26: Physical risk mapping and classification for current ALK projects.

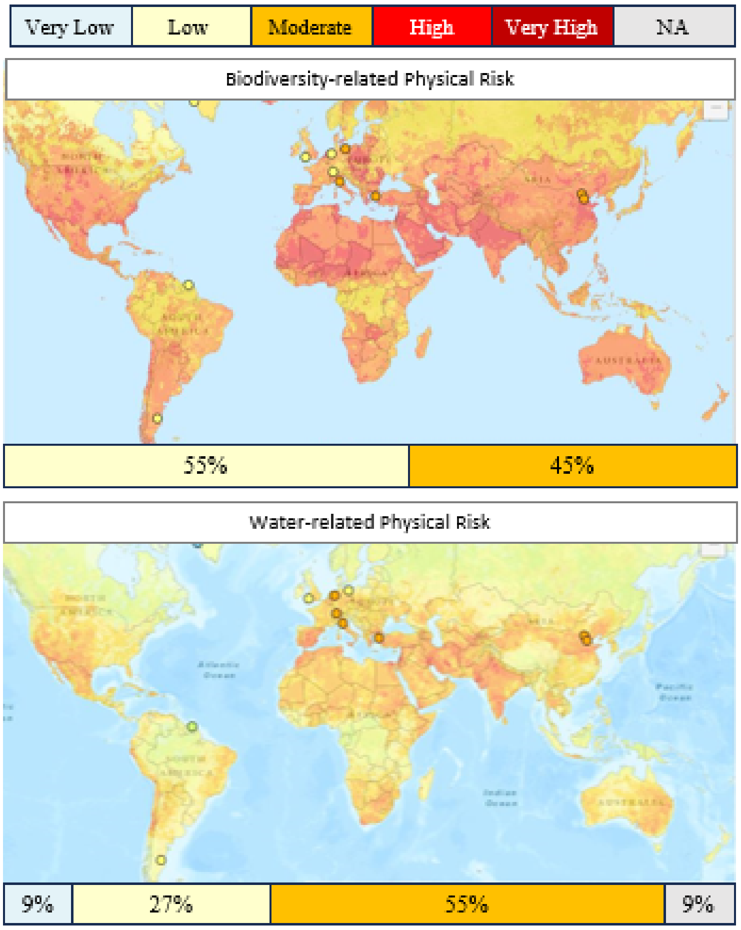


Figure created by the author using WWF Risk Filter.

"Water Quality" emerged as the highest biodiversity physical risk indicator for this stage, followed by "Pollution" and "Projected Change in Drought Occurrence". The latter is the highest for this stage, and moderate for the rest of the GVC. Because the ALK project has a lifespan of approximately 10 years (Davies et al., 2021), the overall consumption of water will be very large and the projected change in drought could be reinforced by the intense water consumption for green hydrogen production. The projects also depend on good quality water for the electrolysation and its coupling with desalinisation is a topic discussed by some organisations (IRENA & Bluerisk, 2023; Villagrasa, 2022) who defend the implementation of desalination plants only if they also benefit the local community, by alleviating water stress and increasing overall water availability. Although the technical solutions to enable it are not explored here, pivoting on just transition means to promote strong water management, taking into consideration needs and priorities of local residents, throughout the upcoming decades of operation of the projects.

In terms of reputational risks, “Freshwater Endemism” was highest for this stage across the entire GVC. It refers to areas with more unique fish species and a greater risk of damaging their public image. This is driven by 60% of the actors, located in Europe and Argentina, who had the highest risk score for this indicator. Similarly to previous stages, it also presents high scores for “Freshwater Biodiversity Richness”, “Media Scrutiny” and “Conflict News Events”. Current ALK Projects reputational hotspots are China and North of Germany, also due to their proximity to preservation/conservation areas.

5.5 Nickel recycling

The literature review of ALK end-of-life stage outlined the need for resource efficiency improvement (especially water and energy) in nickel recycling processes and the need for advancement of research and design that allows for repair and refurbishment. In parallel, the mapping phase showed that more than half of the actors of the sample are concentrated in the US and Central and Eastern Europe.

The actors in the nickel recycling stage are most vulnerable to biodiversity physical risks and water reputational risks. The highest risk category was "Pressures on Biodiversity", which includes land change, pollution, tree cover loss and invasive species. The vulnerability was particularly higher for the “Land, Freshwater and Sea Use Change” indicator. For reputation, this stage is the second highest after the mining stage with a highlight on “Labor/Human rights” and “Cultural diversity”.

While land use change refers to changes in spatial configurations, the WWF-BRF refers to cropland expansion, marine shipping and fishing, and river fragmentation (WWF Biodiversity Risk Filter, 2023), which do not directly relate to the activity of this GVC stage. Although, on a facility level, metal facility industries could compete with other activities for the use of natural resources and be impacted by the externalities of other activities.

“Labour and human rights” and “Cultural diversity” risks are the highest for facilities in China and in the south of the US. In addition to these reputational risks, all indicators under the “Environmental Factors” category, which includes areas of conservation, protection and ecosystem conditions, were moderate or high.

As the last stage to be analysed, it shows some similarities to the previous ones. Because the industry is classified as the same as nickel and zircon mining stage (metals and mining), their results were similar. One example is the very high risk on “Pollution”, “Tree cover loss” and “Water scarcity”. In addition, it presented similarities to ALK components probably due to the location as most of the actors of both stages are in the US, presenting high basin physical risk on "Fragmentation Status of Rivers" and “Estimated Flood Occurrence”.

Reflecting the mapping stage, China and US are the countries that presented the highest risks in this stage (‘Figure 27’, overleaf). The first includes the basins of South China Sea, Yellow Sea & East China Sea, and the latter, the North Pacific, Colorado and Rio Grande regions. The physical risk is driven especially by “Pressures on Biodiversity”. In addition, this stage presents the worst risks on “Extreme Heat” across the entire GVC, driven by these locations, showing its vulnerability to acute climate change events and potentially a need for the facilities to adapt their operations accordingly. In an environment of furnaces, extreme heat enhances the workers’ exposure threatening their safety and wellbeing. Therefore, adapting the working environment is a simple measure that could be foreseen, nevertheless it is a measure of climate adaptation.

Figure 27: Physical risk mapping and classification for current recycling facilities.

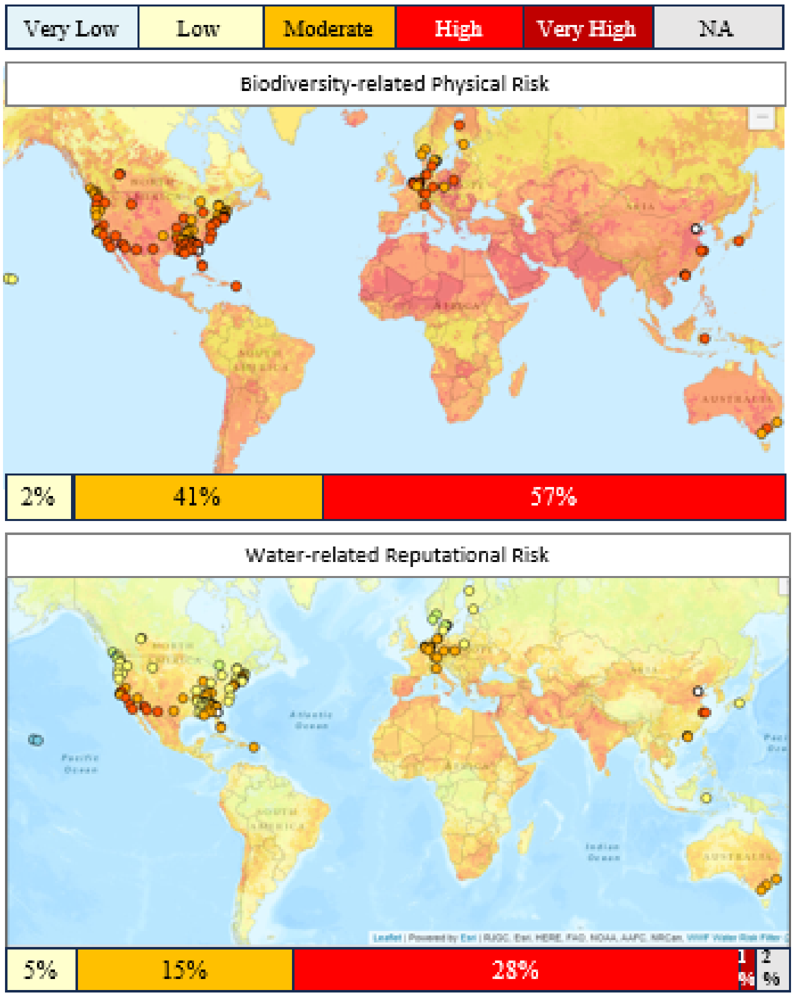


Figure created by the author using WWF Risk Filter.

This stage is key for a just energy transition because it enables the circularity of the key material of the ALK, aiming at reducing the extraction of raw materials while enabling for more renewables. Complementing the insights from the mapping stage, the environmental risk assessment results of this stage showed similarities to other GVC actors from the aspect of the industry type and basin location. These shared challenges indicate possibilities of collaboration between actors of distinct stages. One example is Research and Development. Invest in R&D to explore the technical viability of manufacturing ALK components with recycled nickel and advancing the reuse and repair of ALK stacks.

5.6 Results per global region

This subsection summarises the main nature-related vulnerabilities per continent, and the main results of the Basin Regulatory risk type to provide a more macro vision of the results. As identified in previous subsections, some concerns are common throughout the GVC, regarding water quality, pollution, media scrutiny, and protected areas. In addition, sustainability in GVCs should be measured across different geographic scale and as a product of the interaction of environmental and economic influences, as outlined in the literature review (De Marchi & Gereffi, 2023; Frederick, 2019). This subsection aims to identify regions and countries' specificities in terms of regulatory risk ('Table 8', overleaf), an outcome from the WWF-WRF, and environmental risk types.

The "Enabling Environment" category assesses how well countries implement Integrated Water Resource Management (**IWRM**) frameworks, which are crucial for ensuring sustainable water use and availability. Complementing the results from previous subsections, ALK GVC actors in India were identified as a hotspot in this category due to challenges in fully implementing water management plans, posing risks related to water availability and regulatory compliance for businesses operating there (Biswas & Tortajada, 2011; Vaidyanathan, 2006)

The "Institutions and Governance" category relates to how corruption and lack of political freedom can create a precarious business environment, increasing operational risks and reducing the predictability of the business landscape. In this category, ALK GVC actors in Venezuela and Russia are highlighted due to their perceived elevated levels of corruption and challenges in governance, which can undermine business stability and long-term planning.

The "Infrastructure and Finance" looks at how access to safe drinking water and sanitation, along with inadequate financial investment in water infrastructure, can severely affect operations, especially in water-intensive industries, for example for ALK projects. However, the hotspot for this category is mines in Sierra Leone due to significant gaps in water infrastructure and financing, posing challenges for maintaining reliable water supply and sanitation standards (Jimmy et al., 2012), essential for workers' health.

By understanding these risk categories and the associated indicators, companies can better navigate the complex landscape of operating in different regions, particularly those with identified hotspots, and develop strategies to mitigate these risks effectively.

Table 8: Main outcomes of the Basin Regulatory risk type.

Risk category	Key indicators	Brief description	Hotspot countries
Enabling Environment.	• "Freshwater Law Status" • "Implementation Status of Water Management Plan".	Degree of implementation of Integrated Water Resource Management (IWRM).	India.
Institutions and Governance.	• "Corruption Perceptions Index" • "Freedom in the World Index".	Unstable and ineffective institutions and governance can jeopardize business viability.	Venezuela and Russia.
Infrastructure and Finance.	• "Access to Safe Drinking Water" • "Access to Sanitation" • "Financing for Water Resource Development and Management".	Development and management of water infrastructures can pose a GVC risk factor.	Sierra Leone.

Table created by the author using WWF-RF.

The African continent only has actors in the mining GVC stage. Some of its main risks are "Tree cover loss", and closeness to important conservation/preservation areas. A particularity of this continent are high risks on "Access to Sanitation", "Financial Inequality" and "Sites of International Interest". Similar to other regions, "Water quality" and "Media scrutiny" are some of the main concerns.

In Asia, "Labor/Human Rights" and "Pollution" are the main concerns. For the first, 87% of actors present high or very-high risks. Half of the actors present high or very high risks for landslides and tropical cyclones. High or very high risks of "Cultural Diversity" and "Media scrutiny" englobe almost all actors in Asia. More than half of the actors are high or very high in Freshwater Endemism and Biodiversity Richness, as well as "Corruption Perceptions Index", driven by Indonesia, the Philippines and Russia.

In Oceania (Australia and New Caledonia), “Media Scrutiny" stands out with the highest risk (100% of the actors), followed closely by "Protected/Conserved Areas", of which 95% of actors presented a high and very high risk. Invasive species pose a significant threat (90% with high risk), a topic that is specifically sensitive for island nations as invasive species can threaten the entire ecosystem context (Kingsford et al., 2009). In parallel, water scarcity and fire hazards are moderate concerns (85% with high or very high risk for each) although very important for the Australian context (Australian Government, 2021).

In Latin America, “Protected/Conserved Areas” was presented as a main topic, with a significant portion of the facilities in the region (54%) facing very high risk. “Range Rarity” sits at a moderate level, with 71% of the facilities facing high or very high risk. “Important Delineated Areas" and "Media Scrutiny" (both 88% high or very high risk) were also very relevant. All these indicators reflect the biodiversity importance of the region as well as the vulnerability in the face of deforestation driven by illegal mining and agribusiness (Acselrad, 2022).

In North America, Canada and USA, "Media Scrutiny" and "Protected/Conserved Areas" stand out as the top two most threatened categories, with more than 90% of actors with high or very high risk. “Land, Freshwater and Sea Use Change” pose a moderate risk to a substantial portion of the areas (around 80%). "Labor/Human Rights" violations are also a significant concern for nearly 70% of the facilities, while threats such “Invasive Species” and “Tree cover loss” have about 65% of actors in high or very high risks.

In Europe, “Pollution” stands out as the most concerning threat, with 92% of the actors with high or very-high risks. Water quality is also a major concern, with 67% of facilities facing high risk. Land use changes, deforestation, and threats to protected areas also pose significant risks to more than half of the facilities.

The businesses involved in the GVC need to combine social responsibility and environmental stewardship as they manage regional challenges. This entails improving community engagement, assuring fair labour standards, and minimising direct operating impacts on biodiversity and water resources. For instance, tackling labour and human rights issues, especially in high-risk areas like Indonesia and the Philippines. In Oceania, the threat from invasive species and the need to protect conserved areas require tailored conservation efforts. Similarly, in North America and Latin America, preserving biodiversity is essential for maintaining public trust, and mitigating reputational risks.

In the Global South, countries face vulnerabilities related to infrastructure, water management challenges, and governance issues. These regions often struggle with high levels of corruption, limited access to safe water and sanitation, and significant environmental pressures like deforestation and biodiversity loss. On the other hand, the Global North, encompassing regions like Europe, North America, and Oceania, experiences more pronounced risks related to media scrutiny, pollution control, and the protection of conserved areas. While the Global South's challenges are rooted in infrastructure and governance deficits, the Global North's issues tend to revolve around managing industrial impacts. This macro discussion on the Global North and South and continental levels, shows the need for tailored strategies that address the unique circumstances of each region to ensure a balanced and just transition towards sustainable ALK operations globally.

5.7 Summary of the analysis

The environmental risk assessment results and discussion identified environmental challenges throughout the ALK's GVC, using geospatial analysis at the global level and risk scores at the basin level. It provided a comprehensive overview of the challenges and vulnerabilities across various stages. The major common risks for all firms within the GVC are water quality, pollution and previous conflicts related to water. Each stage, from nickel and zircon mining to ALK projects and nickel recycling, revealed distinct environmental risks and impacts, ranging from water scarcity to biodiversity loss and deforestation. The analysis explored regional differences, highlighting specific hotspots and risk factors across different continents. From the GVC perspective, the analysis suggests that the water footprint and reputational risks associated with ALK are greater than those identified in studies concentrating solely on green hydrogen production. These findings reinforce the importance of integrating sustainability into GVC operations. According to the principles of sustainable development, as articulated in the United Nations' Sustainable Development Goals (**SDGs**), especially Goal 6 (Clean Water and Sanitation) and Goal 15 (Life on Land), addressing environmental risks such as water scarcity and biodiversity loss is crucial for promoting sustainable industrial(United Nations, n.d.-b). The research's focus on these risks reflects an alignment with the academic literature on the need for corporate responsibility in managing natural resources and environmental impacts (Elkington, 1998).

For each GVC stage, general recommendations to address the major nature-related risks were provided, based on the concept of just energy transition towards a low carbon economy. Finally, isolation of Southern countries in the ALK GVC was observed, as they participate predominantly in the peripheries of the VC with metal extraction. his reflects the ongoing challenge of global inequality in the distribution of economic benefits and environmental burdens. Sustainable development scholarship emphasizes the importance of equity in global economic systems, advocating for more inclusive practices that provide fair opportunities and mitigate negative impacts on disadvantaged regions (Sachs, 2015). This subsection presents some overall analysis of the GVC, summarising the previous key findings per stage and global region, stating its contributions and acknowledging limitations and future directions.

The outcomes of the environmental risk assessment show that actors at the periphery of the GVC (mining and metals) tend to have higher exposure to biodiversity physical risks, while the middle stages, related to manufacturing, presented higher physical risks associated with water, especially in the ALK project stage (‘Figure 28’, below). In general, all of them presented high reputational risk related to water. Across all the evaluated actors, ALK projects exhibited, overall, the lowest risk scores, while mining and nickel recycling plants emerged with the highest risks, reflecting the risk profiles associated with each industry.

Figure 28: Results of nature-related risks, positioned in the Value Hill.

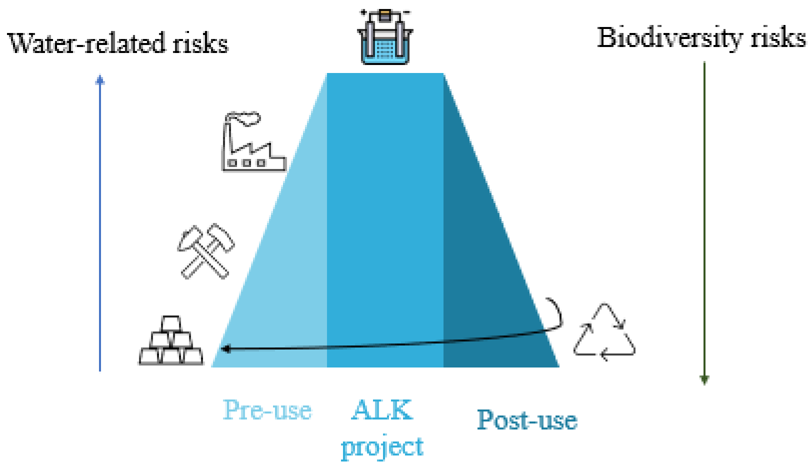


Figure created by the author.

In the nickel and zircon mining stage, the concentration of facilities in certain regions, particularly in the Global South, may drive deforestation and water scarcity. Reputational risks, including media scrutiny, closeness to protected areas and risk of disrupting ecosystem conditions demonstrate the need for transparent and accountable practices within the industry, which is in accordance with the news and the literature. Transitioning to ALK component manufacturing, ALK manufacturing and ALK project stages, the risks shift towards more water-related issues. Although the high-risk scores are balanced out between reputational and physical, when looking at the category level, their reputational concerns outweighing physical risks. Actors in China and India face significant challenges related to water quality and scarcity, needing rigorous water management strategies. The nickel recycling stage highlight the importance of community engagement, particularly in mitigating reputational risks and addressing local environmental concerns, alongside concrete actions on water and energy efficiency. Overall, the highest risk for all stages was reputational. To facilitate actionable insights to practitioners, these results were summarised and ranked in ‘Table 9, below.

Table 9: Indicators in order of priority, per GVC stage, according to risk scores.

Product phase	**Pre use**			**Use**	**Post-use**
GVC stage	**Nickel and zircon extraction and processing**	**Components manufacturing**	**ALK electrolyser manufacturing**	**ALK electrolyser projects**	**Nickel recycling**
Industry classification	Metals and mining	Chemicals & Other Materials Production	Electronics & Semiconductor Manufacturing	Electric Energy Production - Solar, Wind	Metals and mining
Indicator 1	Media scrutiny (4.6)	Freshwater Biodiversity Richness (4.6)	Conflict News Events (4.3)	Freshwater Endemism (4.4)	Media scrutiny (4.9)
Indicator 2	Closeness to protected/conserved areas (4.0)	Conflict News Events (4.6)	Surface Water Quality Index (4.2)	Surface Water Quality Index (4.3)	Conflict News Events (4.6)
Indicator 3	Tree cover loss (3.9)	Fragmentation Status of Rivers (4.2)	Pollution (4.1)	Conflict News Events (4.0)	Cultural Diversity (4.5)
Indicator 4	Water scarcity (3.6)	Surface Water Quality Index (4.2)	Cultural Diversity (3.9)	Pollution (3.5)	Tree cover loss (4.0)
Indicator 5	Ecosystem Condition (3.6)	Pollution (4.1)			Labor/Human Rights (3.9)

The green boxes represent biodiversity-related aspects and the blue, water-related ones. The speaker icon represents reputational risk while the leaf, physical risk. Only very high- and high-risk scores were considered in this table, the reason ALK electrolyser manufacturer and projects had no fifth indicator. Table created by the author.

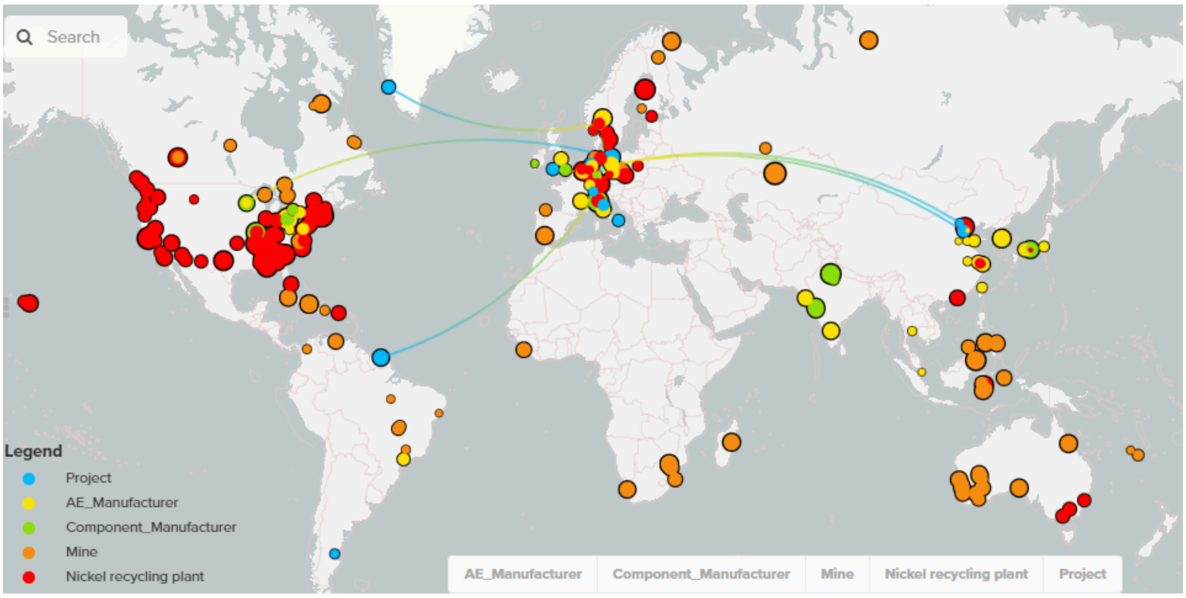
This analysis highlights the need for proactive risk management strategies that align with the principles of corporate sustainability. The integration of ESG criteria into business operations is increasingly seen as critical for long-term resilience and success (KPMG, 2022). By examining results per global region, the analysis provided insights into continent-specific vulnerabilities and regulatory risks. Using the Value Hill hierarchy, it was possible to observe the hierarchy between countries, depending on their socioeconomical profiles. The concentration of actors in the north, especially for manufacturing-related stages, together with a predominance of metal extraction in countries in the south reflect the global inequality of economy, pointing to the perpetuation of the same pattern towards who will produce and have access to green hydrogen.

Regions in the Global South face infrastructure and governance deficits, while the Global North faces challenges related to media scrutiny and pollution control. Thus, tailored strategies, focusing on community engagement, fair labour standards, and biodiversity conservation, are essential for ensuring a just and sustainable transition across continents. At the same time, actors in the same region/basin could collaborate in initiatives to promote regional sustainability, according to shared local needs. In summary, a fair global economy would involve a more equitable distribution of manufacturing capabilities that add value, as well as the balanced consumption of final products resulting from green technological advancements.

In the general analysis of the ALK GVC, physical and reputational risks shared among GVC stages were identified as significant for business operations. A major hotspot in terms of physical risk category was "Regulating Services – Mitigating" of which all GVC stages presented a moderate risk in all indicators of this category, which includes the occurrence of natural hazards such as landslides, fires, and storms. This category was little discussed in the subsections, since it was not a hotspot for any specific GVC stage, in particular. However, these extreme and more frequent weather events across all GVC stages can significantly impact the delivery of new ALK projects, leading to damage or even loss of assets. Therefore, maintaining healthy ecosystems can play a mitigating role, reducing the impact of certain natural hazards. This aligns with the academic perspective on ecosystem-based adaptation, which emphasizes the role of biodiversity and ecosystem services in enhancing resilience to climate change impacts (Munang et al., 2013)

Meanwhile, adaptation to extreme weather events is equally relevant to operations and workers' safety and wellbeing. Complementing the biodiversity output, the major basin risk hotspot in the GVC, across all water-related indicators was "Surface Water Quality Index", showing a shared concern across the GVC. The water and biodiversity physical risks were incorporated into the GVC mapping in 'Figure 29' (below), where it is also observable the isolation of Southern countries in the current state of ALK green hydrogen economy.

Figure 29: GVC actors' map.



The size of the circles is proportional to the water and biodiversity physical risks, compiling the mapping and the WWF-RF results. The connections represent commercial ties between actors. Figure created by the author using the kumu.io.

Regarding reputational risks within the ALK GVC, the most critical indicator was "Conflict News Events" related to water, which was rated very high for three GVC stages and high for two others. It means that most of the actors are in places and industries with historical of nature-related conflicts, from which they should derive lessons. "Cultural Diversity" is another significant factor for all stages, as regions with diverse cultures place a high value on water affect business reputation if not respected. Other notable factors include "Media Scrutiny", which ranges from moderate to high across all GVC stages; "Protected/Conserved Areas"; and "Labour/Human Rights", which are particularly relevant for the mining and metal-related stages. This reflects the growing recognition in sustainability studies of the importance of social license to operate (SLO) and the need for companies to gain and maintain the consent of local communities (Gunningham et al., 2004)

In summary, the environmental risk assessment of the GVC highlights that the mining and metals sectors (first and last stages), face the highest biodiversity risks, while the middle stages such as manufacturing are more vulnerable to water-related risks, particularly in ALK projects. Reputational risks, predominantly related to water, are pervasive across all stages, with significant media scrutiny and conflicts over resource use in regions with diverse cultures. The GVC perspective showed that the water footprint of the ALK and reputational risks seems to be much higher compared to most studies that focused only on green hydrogen production.

The results contribute to targeted strategies addressing both physical and reputational risks, especially in regions with infrastructure and governance challenges, to ensure a sustainable and equitable transition. It covered the aspect of measurement of environmental sustainability across diverse geographic scales, one of the pillars for the study of sustainability in GVCs (section 2.1) (De Marchi & Gereffi, 2023). This was suggested in the results through the identification of actors located in the same basin. Water quality, for example, was one of the priority indicators identified for ALK manufacturers, and their impact on water quality in the basin could affect the operations of ALK projects that depend on the same resource, negatively or positively. If the ALK projects' impact on water consumption is so high that makes impedes its viability of operating, the existence of the component and ALK stack manufacturers could also be jeopardised. At a larger scale, it would not generate the benefits on supporting the scalability of renewable energy sources needed for tackling the climate crisis. This reflects the interconnectedness of GVC stages and the need for comprehensive sustainability assessments to inform strategic planning (Sodhi & Tang, 2017) \. Another example is the labour rights violation at the mining stage that could be connected to ALK manufacturing, as it has been happening for EV batteries demand. This threatens the reputation, the just transition and the sustainability of the entire chain.

In terms of limitations, the WWF-RF presented some lack of data for five out of 297 locations, which are mines and recycling plants in Hawaii, Greenland, Canada, and the Philippines. Moreover, the WWF-BRF had no available data for "Indigenous Peoples (**IPs**); Local Communities (**LCs**) Lands and Territories" but, according to the developers, it will be incorporated in the next updates of the tool. Thus, assessments such as this paper are necessary to be frequently revised and updated. Another limitation identified were inconsistencies between the outputs of WWF-BRF and WWF-WRF regarding "Water

Scarcity". The Filter's methodology states that this indicator is the same as the "Water Scarcity" risk category from WWF-WRF, which considers seven indicators: aridity index, water depletion, baseline water stress, blue water scarcity, available water remaining, drought frequency probability and projected change in drought occurrence (WWF Biodiversity Risk Filter, 2023). However, the scores from the water filter are slightly lower than the one on biodiversity, revealing some inconsistency from the tools or its outdating.

It is also important to point out that there were seven biodiversity physical scape risk indicators that were excluded by the tool due to their lack of direct impact or dependence on the ecosystem services relevant to the actors' activities. They are marine fish, soil condition, ecosystem condition, pollination, aquatic pests, herbicides, and tourism attractiveness.

The ALK electrolyser is a technology that has not yet reached market maturity (IEA, 2023a), making it a relatively simpler to map its main GVC actors, due to a lower quantity of operational projects and major player firms, specifically for ALK manufacturing. Even though, the aggregate analysis of the environmental impacts and dependencies of the actors, to generate actionable insights from data, was challenging due to the variety of indicators that can become hidden.

For the future, it is important to attempt to bridge some data gaps found in this paper, such as the mining locations and ownerships, and more precise locations of nickel recycling plants. These are not only related to technicities but reflect some global social factors too. The databases used in this paper show an underrepresentation of actors from the Global South, especially for the nickel production facilities, where a comparison with countries' imports and exports was possible.

In conclusion, the environmental risk assessment of ALK's GVC provided a detailed evaluation of the significant risks across various stages, from mining to recycling. The analysis showed challenges on water quality, pollution, and historical water conflicts throughout most actors. While mining and metal sectors face acute biodiversity risks, the manufacturing and project stages are vulnerable to water-related issues, particularly in regions like China and India. Reputational risks remain high across all stages, driven by factors such as media scrutiny, proximity to protected areas, and cultural sensitivities. These results show a need for robust water management, transparent practices, and community engagement to address these risks effectively. It also emphasizes the importance of equitable value distribution and sustainable practices across regions to ensure a just transition to a low-carbon economy. Despite some data limitations, the insights gained provide a foundational basis for developing tailored strategies to mitigate both physical and reputational risks and promote regional sustainability. Future research should focus on bridging data gaps and enhancing the specificity of risk assessments to better support GVC actors in managing environmental sustainability.

6 MANAGERIAL IMPLICATIONS FOR COMPANIES IN THE GVC

The previous section identified water quality, pollution, and historical water conflicts as risk factors common across the GVC, with observed isolation of actors in Southern countries of the ALK global green hydrogen economy. It demonstrated the need for strong water management strategies, transparency in business practices, active community involvement to mitigate these risks, and fair distribution of value and the adoption of sustainable methods across different regions to facilitate a fair transition to a low-carbon economy. This section aims to translate these general ideas into practice, summarising the risk management general recommendations for companies in the GVC, per stage, although it will always depend on the local and specific context.

Nickel and zircon mining

For nickel and zircon mining companies, the most impactful sector on biodiversity, the analysis identified water scarcity and forest conservation as the key elements for the actors of this GVC stage, as they are also key for other important elements such as the preservation of the soil and the fauna, for mitigation of landslides, and respect for local communities. Mining operators themselves are primarily responsible for minimising its negative impacts and promoting regenerative practices on biodiversity. However, the aim of this paper is to understand the energy just transition considering the complex network in which these firms are inserted.

The first recommendation for nickel mining actors is to improve the transparency of facility-level data. General information such as mine locations, ownership, and production capacity, and social and environmental reports are key for accountability across the GVC. The firms might view this as a burden, but the operational and reputational risks from these aspects are deemed relevant, as shown both through examples of previous companies and for presenting the highest risk scores of the GVC for many indicators. A global initiative named Extractive Industries Transparency Initiative (**EITI**), for instance, has been developing standards for the mining industry, especially considering the energy transition. Community involvement, raising awareness and building skills for sustainable practices to employees are some of the recommendations of their reports. Clear communication on these topics will allow the next GVC actors and policy makers to understand the impacts that they drive through the demand for minerals and show opportunities for collaboration towards common sustainability goals.

The reputational risks related to workers of this GVC are high. This is a very important aspect of the energy just transition that has to be taken into account: to bring actual value to the local communities and workers of this GVC stage, as they rarely benefit from the products of the materials they are extracting to benefit a person of a higher social class, probably in another continent (Riofrancos, 2022). On a national level, however, the Indonesian attempt to retain value in their country by stating a mandatory onshoring of the nickel processing, was seen as an affront by many countries, particularly from Europe. In this case, these countries can also use media scrutiny to point out environmental and social problems in the Indonesian mines, in favour of their commercial interests. This dynamic highlight the complex task of navigating reputational risks in a GVC, with distinct interest, where promoting local prosperity can be badly received by external actors prioritizing short-term commercial interests.

This leads to the second suggestion on collaborative initiatives across the GVC. A previous study has already suggested partnerships between nickel supplier and consumer, specifically Japan, which is a large consumer, to promote a sustainable resource management in biodiversity supplier hotspots in Indonesia and the Philippines (K. Nakajima et al., 2017). This paper did not aim to trace nickel and zircon producers to its major primary consumers at a firm-level. However, it identified the hotspot mining facilities, their owners, and their respective key aspects for biodiversity and water impacts and dependencies. For future research, identifying these commercial relationships could help to be more precise towards socio-technical solutions to water scarcity, deforestation, and relationships with local communities. It will also allow to have a better look at the rate of metal extraction, which was not covered in this paper.

Electrolyser component manufacturers

For electrolyser component manufacturers, enhancing water management practices through wastewater treatment, reuse, and improved water efficiency is recommended. These manufacturers can already leverage their procurement power to select suppliers with strong sustainability practices, while working collaboratively with other stakeholders upstream, including their own clients.

Electrolyser manufacturers

Electrolyser manufacturers should similarly prioritize suppliers with robust ESG practices and minimize nature-related financial risks. Visualising the facilities using satellite imagery, the industrial plants are usually located in industrial parks close to urban areas, which shows a certain level of geospatial planning. They occupy an area much smaller than mines, so the overall environmental impacts tend to be smaller. However, in the GVC interaction, the actors in this stage can make a difference by using their power of procurement – now, for component manufacturers and origin of metals as a second tier – to choose suppliers with better ESG practices and lower nature-related financial risks. Furthermore, the local community should be aware of the impacts of the facilities and benefit from the skilled jobs created at this stage.

Alkaline electrolyser projects

Recommendations for the actors in this GVC stage include a careful medium and long-term water management plan, including consultations and involvement with communities that also depend on the same basin of operation. The nature-related reputational risks can be mitigated through investment in capacity-building for staff and local stakeholders, raising awareness of the importance of preservation and contingency plans for the major water-related risks. Furthermore, these skills training and research initiatives can empower local communities with the skills needed to fill new hydrogen production jobs in their region, increasing the “green jobs”.

For companies responsible for ALK project installation and operation, long-term water management plans and community consultations are crucial to mitigate reputational risks and foster local skills.

Nickel recycling plants

The higher biodiversity physical risk reinforces the need for the nickel recycling processes to be more energy and water efficient, as found in the literature. Therefore, the first recommendation for the actors involved in this GVC stage is to improve resource efficiency consumption. Secondly, reforestation to compensate for any biodiversity loss and as a measure of climate adaptation, to mitigate flooding risks and as an attempt to prevent extreme heat. Moreover, structures to protect workers against extreme heat should also be considered in the next years. Finally, it is important for the GVC actors to engage with local communities to understand and respect cultural diversity and mitigate potential negative impacts on local cultural sites or practices.

Across all stages, it is recommended for firms to foster community involvement, raising awareness about sustainable practices to benefit local workers and residents, especially in the Global South. This includes building local capacities to fulfil green jobs and advancing sustainable practices tailored to each sector's specialty. Additionally, ensuring that the local workforce and communities benefit from the energy resources they help produce is fundamental for a just transition.

The analysis in paper study can be particularly important for some of the main firms identified in the mapping stage. Large companies, in the short-term, due to new sustainability reporting regulations that require disclosing information about their value chains. Some of these main regulations in place are the Corporate Sustainability Reporting Directive (**CSRD**) and the Corporate Sustainability Due Diligence Directive (**CSDDD**) in Europe, the Securities and Exchange Commission (**SEC**) in the US is currently considering proposals for mandatory climate-related disclosures by publicly traded companies and, globally, the International Sustainability Standards Board (**ISSB**) for financial institutions (EU Commission, n.d., 2023; ISSB, 2023; M. Lee, 2024). The CSRD, specifically, has standards for “Pollution”, “Water and marine resources”, “Resource use and circular economy” and “Workers in the value chain”, in line with the topics of this paper.

One way to turn the findings into corporate action, as recommended by the TNFD (2023), would be to build a strategy prioritising different risk categories along different time horizons (short, medium and long-term), and identify material GVC actors according to the environmental impact and/or financial dependence (EU Commission, 2023). When looking at its GVC, a firm can start by focusing on the most material environmental risk category, such as “Pressures on Biodiversity” in the indicator of “Pollution” as found in the case of this paper and explore ways to mitigate it or implement regenerative practices. One improvement could have a positive trickle-down effect in the chain. However, it does not come without obstacles, especially when the tier of the VC is farther, and the information misalignment could be higher.

Although it was not the focus of this paper, to improve the quality of the results for firms' applicability on their value chain risk management, specific information about each facility should be taken into consideration. To do this, the WWF-WRF has an additional input section named "Operations risk assessment" in which the user should input a questionnaire response consisting of 22 questions related to specific sites such as "Total water withdrawn", "Toxic chemicals used or stored on-site" and "Involvement in water disputes with others". This would allow for more specific information and actionable insights. Furthermore, it will allow the indication of upgrading and downgrading of indicators of performance, and its comparison with peers of the same industry and region.

Future works could also take into consideration other important parts of the VC, such as transportation. This paper attempted to identify some connections and geographical distances between actors, but without success due to a lack of data availability. In this case, more suitable tools to evaluate the environmental impacts of connections, instead of nodes, should be adopted.

Beyond the involved actors, parts of the results could be used to evaluate the GVC of other important products for the energy transition. Due to the general approach of this paper, the nickel mining and recycling stages can be re-used to map and assess GVC of lithium-ion batteries, wind turbines and photovoltaic (**PV**) inverters (IEA, 2023c; Nickel Institute, 2021), for instance.

In summary, the implementation of strategies on transparency, and community engagement aligned with strong actions on water management, with a focus on water quality improvement, across the ALK GVC, will not only support a just energy transition but also prepare businesses to meet new sustainability reporting requirements and adapt to the evolving landscape of VCs. Looking forward, continuous evaluation and adaptation of these recommendations will be essential to navigate the complexities of environmental sustainability and ensure long-term resilience and success in the transition to a low-carbon future.

7 CONCLUSION

In the broader picture of sustainability, ensuring that GVCs and technological advancements align with environmental and social goals is essential for fostering long-term resilience and equitable development. This paper aimed to provide a global overview of the biodiversity and water-related risks of some of the main actors participating in the GVC of an ALK stack, considering their industry sector and location, being useful for policy makers, sectoral organisations, and companies. Despite the urgency of the scalability of the electrolysers for green hydrogen production driven by the climate crisis, and the optimistic projections of market scale up, it must be pivoted in just energy transition towards a low carbon economy.

The mapping of actors showed a concentration of the premature ALK green hydrogen economy in the Global North, pointing out for the need for countries in the periphery of the GVC to also benefit from clean, accessible, and reliable energy sources. In parallel, the environmental risk assessment compliments previous studies focused on the LCA of the ALK electrolyser and green hydrogen's VC, by using the GVC perspective. From the broader view of the ALK's GVC, the analysis suggested that the water footprint and reputational risks associated with ALK are greater than those identified in studies concentrating solely on green hydrogen production. The analysis indicated that the major common risks for all GVC stages are water quality, pollution, and reputational risk due to previous conflicts related to water.

Each stage, from nickel and zircon mining to ALK projects and nickel recycling, revealed distinct environmental risks and impacts, ranging from water scarcity to biodiversity loss and deforestation. For each GVC stage, the paper offered general recommendations to address the major nature-related risks, considering regional differences. Overall, they consisted of improved transparency, education, and capacity building for local residents to fulfill jobs that implement sustainable practices, and community engagement aligned to direct actions on the maintenance and improvement of water quality.

Implementing strategies that emphasize transparency and community engagement, alongside robust actions in water management focused on enhancing water quality across the GVC, can facilitate a just energy transition, allow businesses to comply with new sustainability reporting standards, and adapt to the changing dynamics of VCs. More specific actions should be prioritised according to local needs.

The WWF-RF faced data limitations for five of the 297 locations, particularly mines and recycling plants in Hawaii, Greenland, Canada, and the Philippines, and lacked information on IPs and LCs' lands, which was key for a work pivoting on just transition. However, the tool is expected to be updated with the data and it can be addressed in future updates. Additionally, inconsistencies were found in the "Water Scarcity" risk assessment between the WWF-BRF and WWF-WRF tools, with slightly lower scores in the biodiversity filter than in the water risk filter, highlighting potential discrepancies or outdated information. Some future efforts could aim to bridge data gaps, such as precise locations of mining and nickel recycling plants and address the underrepresentation of actors from the Global South in the databases used, particularly for nickel production facilities.

In conclusion, this paper highlights the environmental and social challenges within the ALK’s GVC, particularly concerning water and biodiversity, providing a global overview at the same time. As the green hydrogen industry grows, it is important to ensure that this expansion supports a just transition to a low-carbon economy, benefiting all regions, especially those currently underrepresented. Addressing these challenges requires enhanced transparency, community engagement, and targeted water management strategies. Despite data limitations and inconsistencies, the results from this paper calls for the companies involved in the green hydrogen economy to adopt a broader view of their GVC, considering tangible environmental aspects to promote a green hydrogen sector more aligned with global sustainability.

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ANNEXES

Annex A: Hydrogen production per energy source, technology and GHG emissions.

	Terminology	Technology	Feedstock/ Electricity source	GHG footprint*
PRODUCTION VIA ELECTRICITY	Green Hydrogen	Electrolysis	Wind | Solar | Hydro Geothermal | Tidal	Minimal
	Purple/Pink Hydrogen		Nuclear	
	Yellow Hydrogen		Mixed-origin grid energy	Medium
PRODUCTION VIA FOSSIL FUELS	Blue Hydrogen	Natural gas reforming + CCUS Gasification + CCUS	Natural gas | coal	Low
	Turquoise Hydrogen	Pyrolysis	Natural gas	Solid carbon (by-product)
	Grey Hydrogen	Natural gas reforming		Medium
	Brown Hydrogen	Gasification	Brown coal (lignite)	High
	Black Hydrogen		Black coal	

*GHG footprint given as a general guide but it is accepted that each category can be higher in some cases.

Source: Global Energy Infrastructure, 2021.

Annex B: Biodiversity-related risk types, categories and indicators assessed by the WWF Biodiversity Risk Filter.

Risk type (Level 1)	Risk category (Level 2)	Indicator (Level 3)	Code
Scape Physical Risk	1. Provisioning Services	1.1 Water Scarcity	S1_1
		1.2 Forest Productivity and Distance to Markets	S1_2
		1.3 Limited Wild Flora & Fauna Availability	S1_3
		1.4 Limited Marine Fish Availability	S1_4
	2. Regulating & Supporting Services - Enabling	2.1 Soil Condition	S2_1
		2.2 Water Condition	S2_2
		2.3 Air Condition	S2_3
		2.4 Ecosystem Condition	S2_4
		2.5 Pollination	S2_5

	3. Regulating Services - Mitigating	3.1 Landslides	S3_1
		3.2 Fire Hazard	S3_2
		3.3 Plant/Forest/Aquatic Pests and Diseases	S3_3
		3.4 Herbicide Resistance	S3_4
		3.5 Extreme Heat	S3_5
		3.6 Tropical Cyclones	S3_6
	4. Cultural Services	4.1 Tourism Attractiveness	S4_1
	5. Pressures on Biodiversity	5.1 Land, Freshwater and Sea Use Change	S5_1
		5.2 Tree Cover Loss	S5_2
		5.3 Invasives	S5_3
		5.4 Pollution	S5_4
Scape Reputational Risk	6. Environmental Factors	6.1 Protected/Conserved Areas	S6_1
		6.2 Key Biodiversity Areas	S6_2
		6.3 Other Important Delineated Areas	S6_3
		6.4 Ecosystem Condition	S6_4
		6.5 Range Rarity	S6_5
	7. Socioeconomic Factors	7.1 Indigenous Peoples (IPs); Local Communities (LCs) Lands and Territories	S7_1
		7.2 Resource Scarcity: Food - Water - Air	S7_2
		7.3 Labor/Human Rights	S7_3
		7.4 Financial Inequality	S7_4
	8. Additional Reputational Factors	8.1 Media Scrutiny	S8_1
		8.2 Political Situation	S8_2
		8.3 Sites of International Interest	S8_3
		8.4 Risk Preparation	S8_4

Source: WWF Biodiversity Risk Filter, 2023. "Biodiversity Risk Filter Methodology Documentation".

Annex C: Water-related risk types, categories and indicators assessed by the WWF Water Risk Filter.

Risk type	Risk category	Indicator *
BPH - PHYSICAL	BRC1 - Water Scarcity	B1_0 - Aridity Index
		B1_1 - Water Depletion
		B1_2 - Baseline Water Stress
		B1_3 - Blue Water Scarcity
		B1_4 - Available Water Remaining (AWARE)
		B1_5 - Drought Frequency Probability
		B1_6 - Projected Change in Drought Occurrence
	BRC2 - Flooding	B2_1 - Estimated Flood Occurrence
		B2_2 - Projected Change in Flood Occurrence
	BRC3 - Water Quality	B3_1 - Surface Water Quality Index
		B3_1_1 - *Biological Oxygen Demand (BOD)*
		B3_1_2 - *Electrical Conductivity (EC)*
		B3_1_3 - *Nitrogen (N)*
	BRC4 - Ecosystem Services Status	B4_1 - Fragmentation Status of Rivers
		B4_2 - Catchment Ecosystem Services Degradation Level
		B4_3 - Projected Impacts on Freshwater Biodiversity
BRG - REGULATORY	BRC5 - Enabling Environment	B5_1 - Freshwater Policy Status (SDG 6.5.1)
		B5_2 - Freshwater Law Status (SDG 6.5.1)
		B5_3 - Implementation Status of Water Management Plans (SDG 6.5.1)
	BRC6 - Institutions & Governance	B6_1 - Corruption Perceptions Index
		B6_2 - Freedom in the World Index
		B6_3 - Private Sector Participation in Water Management (SDG 6.5.1)
	BRC7 - Management Instruments	B7_1 - Management Instruments for Water Management (SDG 6.5.1)
		B7_2 - Groundwater Monitoring Data Availability and Management
		B7_3 - Density of Runoff Monitoring Stations
	BRC8 - Infrastructure & Finance	B8_1 - Access to Safe Drinking Water
		B8_2 - Access to Sanitation
		B8_3 - Financing for Water Resource Development and Management (SDG 6.5.1)
BRP - REPUTATIONAL	BRC9 - Cultural Importance	B9_1 - Cultural Diversity
	BRC10 - Biodiversity Importance	B10_1 - Freshwater Endemism
		B10_2 – Freshwater Biodiversity Richness
	BRC11 - Media Scrutiny	B11_1 – National Media Coverage
		B11_2 – Global Media Coverage
	BRC12 - Conflict	B12_1 - Conflict News Events
		B12_2 - Hydro-political Likelihood

* Indicator names in the Global dataset - For names in Local datasets, go to https://riskfilter.org/water/explore/data-and-methods

Source: WWF Water Risk Filter, 2021. "WWF Water Risk Filter Methodology Documentation".