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Finding tipping points in the global steel sector: A comparison of companies in Australia, Austria, South Korea and the USA

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ABSTRACT

The global steel sector is responsible for 7% of global greenhouse gas emissions, highlighting the need for significant changes in production practices and the adoption of low-carbon breakthrough technologies to achieve net-zero emissions. This study was conducted to explore positive tipping points at the company level, taking into account socio-political, economic and industry pressures that initiate the tipping process. The study operationalizes tipping points using the Triple Embededdness Framework, which incorporates indicators from the socio-political and economic environment, as well as the industry regime of companies. An analysis is performed of secondary data from four steel companies: BlueScope (Australia), POSCO (South Korea), voestalpine (Austria), and U.S. Steel (USA). The findings indicate that voestalpine is on the verge of reaching a positive tipping point, and POSCO is also on a promising track. In contrast, both BlueScope and U.S. Steel are lagging behind. In the tipping process, national policies play a critical role in expediting the transition to low-carbon steel production for frontrunners, while global climate policy has a greater leverage by influencing producers who operate in a less stringent national policy context. Additionally, the customer demand for low-carbon steel serves as a driving force for innovation and can incentivize steelmakers to produce low-carbon products.

1. Introduction

As the time window for reaching the targets of the Paris Agreement narrows, policymakers, industry stakeholders and society are focusing on how to achieve net-zero emissions in hard-to-abate industries (IPCC, 2022). The global steel sector is one of these industries, accounting for 15 % of the global coal demand (IEA, 2022a). As such, it is one of the largest industry emitters, contributing to 7 % of the global greenhouse gas (GHG) emissions (IEA, 2020a). Blast furnaces constitute a key problem, because they are used in 72 % of steel production plants and are almost seven times more intensive in terms of carbon dioxide (CO_2) emissions than steel recycling plants (IEA, 2020a).

Today, the global steel sector is still at the beginning of the transition. Thus far, steel companies have made only a little progress towards the goal of achieving net-zero emissions by 2050 and taken only incremental steps in terms of efficiency gains (Arens et al., 2021). However, escaping the existing carbon-intensive technology regime requires radical changes. The concept of positive tipping points (PTP), which are understood as nonlinear state change processes, has received an increasing amount of attention (Lenton et al., 2023; Lenton et al., 2022; Meldrum et al., 2023). For example, in socio-economic systems, a PTP refers to the non-linear uptake of a new technology that is associated with economies of scale and could lead to substantial reductions in GHG emissions (Geels and Ayoub, 2023; van Ginkel et al., 2019). In that regard, Meldrum et al. (2023) suggested that 6.25 % of the production fleet in the steel industry would need to shift to a net-zero solution to trigger a sector-wide PTP.

So far, the potential for the net-zero trajectory of the steel sector has been mapped using economic models and scenario analyses (Garvey et al., 2022; Mayer et al., 2019; Schneider, 2022), while national roadmaps and industry strategies outline the transition process (BMWI, 2020; Deloitte, 2023; European Steel Technology Platform, 2020). Still, the interventions for and triggers of a net-zero transition at the company level are not well understood. In recent years, companies have exhibited increasing activity, and particularly European steel companies, in the search for innovative solutions that they can apply to change their

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production processes (Vogl et al., 2021b). For example, the Swedish steel company SSAB seems to be on a promising track towards a PTP by redirecting their entire production capacity towards net-zero steel in 2022 (Kushnir et al., 2020; Öhman et al., 2022; SSAB, 2022). However, what constitutes a PTP in steel companies still remains unknown. For this reason, it is necessary to explore factors that drive decision-making in steel companies, supporting their transition to net-zero emissions, as well as the role institutional, political and economic pressures play and how steel companies respond to these pressures (Kim et al., 2022; Scott, 2014).

By leveraging empirical data and theory, our article aims at strengthening the evidence on PTPs (Lenton et al., 2023). We compare transition processes being applied to ensure low-carbon futures in four companies: BlueScope (Australia), POSCO (South Korea), voestalpine (Austria) and U.S. Steel (USA). In our study, we investigate whether any of these companies has reached a PTP, bringing them closer toward the goal of net-zero emissions, and identify socio-political, economic and industry pressures that may have enabled the company to reach this point. The process of changing industry practices to achieve net-zero production has just begun. Therefore, examining individual company transitions can offer crucial insights for potential sector and industry-wide changes. In this paper, we investigate the developments in four companies, referring to secondary empirical data while applying the Triple Embeddedness Framework (Geels, 2014) and the Positive Tipping Point concept (Lenton et al., 2023) as heuristic lenses and conceptual frameworks. As a result, we shed light on how these two theories can synergistically complement each other to understand the complexity of the steel sector transition.

2. Background and theory

2.1. Carbon lock-in

Steel companies are facing the challenge of carbon lock-in, which hampers their efforts to transition to a state of net-zero emissions (Unruh, 2000; Berkhout, 2002). The carbon lock-in concept was initially introduced by Unruh (2000), who defined it as the complex interplay among technological, institutional and social factors that creates resistance to climate change mitigation. In the context of the steel sector, two forms of carbon lock-in are particularly relevant. The first form, technological carbon lock-in, refers to a specific mechanism where the existing fossil fuel-based infrastructures and technologies exclude low-carbon alternatives due to their substantial initial investments and subsequent increasing returns (Janipour et al., 2020; Jin, 2021; Seto et al., 2016). More specifically, the steel industry has been operating in a situation where “one particular choice or action pattern has become the predominant mode, and flexibility has been lost” (Sydow et al., 2009, p. 692). This is recognized in the technology choice with a restricted scope for primary steel production relying on coal-dominant technology options only. The co-evolution with the energy carrier coal has amplified switching costs (Gerres, 2023), and fostered a monopolistic environment that hampered the development of alternative technologies. In fact, alternative technologies are still expensive to the point that unless incentivized or mandated, conventional production process are replicated perpetuating the existing regime.

The second form, institutional carbon lock-in, refers to the inertia stemming from formal institutions, such as policies, rules and commitments, and informal institutions, such as cognitive norms, narratives and expectations, as well as knowledge, competencies and micro-economic factors (Seto et al., 2016; Trencher et al., 2020). In contrast to technology and infrastructure lock-in, the institutional feedback loop builds on the conscious efforts by powerful economic, social, and political actors to continue the status quo (Mahoney and Thelen, 2009). This occurs when beneficiaries of the current technological system advocate for institutional rules that advance their interests, enhance their resources, consolidate their political and economic power, which ultimately enables them to wield more influence over institutional frameworks. Geels (2014, p. 267, drawing on neo-institutional theory typology by Scott, 2001) differentitates between four social lock-in mechanisms for firms in industries: 1) Technical knowledge and competencies serve as ’cognitive capital’ that actors are hesitant to disrupt or erode, 2) shared mindsets and cognitive frameworks may contribute to cognitive inertia, limiting actors’ awareness of developments beyond their immediate focus, 3) regulatory institutions can create incentives that steer actions toward specific directions rather than others 4) industry mission and identity prove active resistance to change due to their embeddedness in actors’ ingrained beliefs about themselves and their societal role. These mechanisms are specifically exemplified by activities to influence government decision-making through lobbying and political positioning drawing on arguments of labor market implications and on litigation measures (Geels and Gregory, 2023). This has been specifically observed in the favourable allocation of emission permits for steel makers in phase 2 and phase 3 of the European Emission Trading System (ETS) (Okereke and Mcdaniels, 2012).

Achieving a low-carbon steel sector necessitates overcoming technological, institutional and social lock-in within the steel industry. The PTP theory and the TEF provide valuable frameworks for understanding how company activities, practices and responses are influenced by their environment, shedding light on factors contributing to lock-in and helping to identify strategies to disrupt existing lock-ins.

2.2. Understanding positive tipping points

In the climate sciences, the concept of tipping points was originally

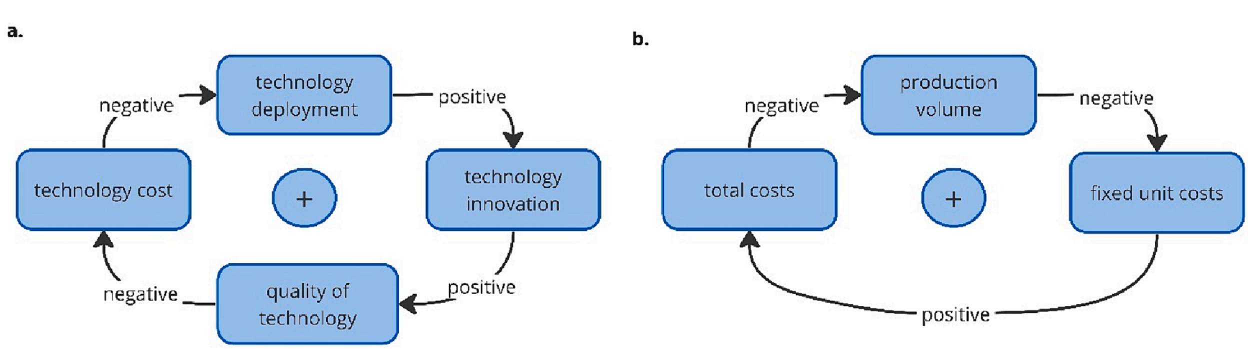

Fig. 1. Reinforcing feedback mechanisms that can lead to a PTP based on Meldrum et al. (2023). a. Learning-by-doing where a higher technology deployment leads to more innovation that optimizes the technology and therefore lowers the costs which then lead to an increase in technology deployment. b. Economies of scale where a higher production volume lead to lower fixed costs as they spread among a greater share of production units, lowering overall costs which amplifies the production volume. Positive link: if system element A changes in one direction, system element B changes in the same direction. Negative link: if system element A changes in one direction, system element B changes in the opposite direction.

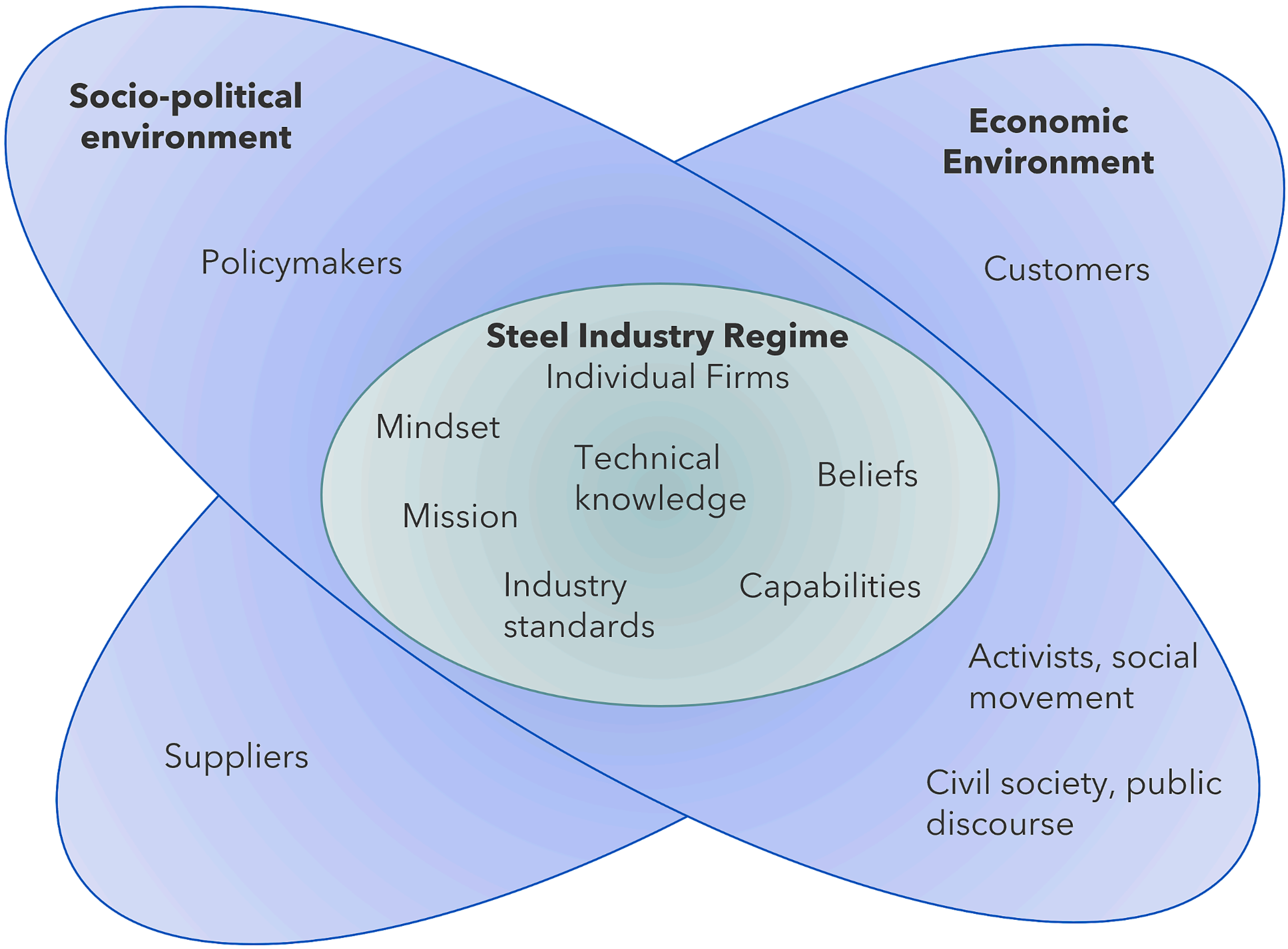

Fig. 2. Triple Embeddedness Framework adjusted to fit the steel sector based on Geels (2014).

used to describe radical shifts in the Earth system that are triggered by small qualitative changes, for example, the melting of the Greenland ice sheet as a result of global warming (Lenton et al., 2019; Scheffer et al., 2001; Schellnhuber, 2009). Recently, sustainability transitions researchers have focused an increasing amount of attention on this subject, discussing and exploring the existence of and evidence for positive tipping points (PTP), primarily as a response to dampen Earth system tipping points (Lenton et al., 2023; Milkoreit et al., 2018; Winkelmann et al., 2022).

In general, tipping points are defined by self-amplifying feedbacks that lead to abrupt and non-linear changes in a system which are irreversible and often have multiple stable states (McKay et al., 2022; Milkoreit et al., 2018). For PTP, desirability and intention are additional characteristics while their irreversibility is still unclear and therefore often is described as limited in reversibility (Lenton et al., 2023). The occurrence of a PTP is desired as they represent a proactive response to avoid potential Earth system tipping points, aimig for a safe and just societal state aligned with UN Sustainable Development Goals (SDGs) (Gupta et al., 2023; Rockström et al., 2023; United Nations, 2023). Unlike Earth system tipping points, which have negative impacts on society (Lenton et al., 2019), PTPs could lead to positive outcomes in accordance with the SDGs, making intentional change a crucial characteristic to deliberately promote such tipping points (Lenton et al., 2022; Mealy et al., 2023; Tàbara et al., 2018). Intentional interventions can occur in three ways: i) by creating the enabling conditions that destabilize the existing system structures, ii) enhancing amplifying feedbacks or neutralizing dampening feedbacks, and iii) providing a decisive trigger that eventually kicks off a non-linear system trajectory (Lenton et al., 2023). In that regard, cost parity between the conventional technology and the new technology is often described as a crucial enabling condition for a PTP in socio-economic systems and once achieved to trigger a PTP. For example, Lam and Mercure (2022) suggest that electric vehicles have already passed a PTP in the EU and China by achieving ownership cost parity with conventional cars. Similarly, Meldrum et al. (2023) argues that a PTP in the global steel sector can be reached when low-carbon alternatives become cost competitive through reinforcing feedbacks enabled by mechanisms such as learning-by-doing and economies of scale. See Fig. 1 for a representation of these two mechanisms.

However, while cost parity often is a necessary condition for PTP, in socio-economic systems there are other factors at play that can compensate potential reinforcing feedbacks (Lamberson and Page, 2012). For example, when incumbent companies resist to the introduction of alternative options, leading to weaker policies (Meldrum et al., 2023). Ultimately, a PTP can only occur when the reinforcing feedback effect becomes stronger than the balancing effect (Meadows, 1999).

In addition, scales and boundaries are an important consideration for PTPs (Milkoreit, 2022). In the steel production, three scales can be distinguished: the macro-scale describing the global steel sector, the meso-scale constituting steel companies with their network of production facilities and plants, and the micro-scale representing an individual company plant (Moglianesi et al., 2023). Once a PTP in the global steel sector has been crossed, the steel sector is in a new, qualitatively

Table 1
Overview of indicators, their descriptions, and how they interrelate within the TEF.

TEF	Pressures	Type of pressure/ response	Indicator	Indicator description	Pressure-indicator link
Socio-political environment	**Policy (makers)**	exogenous	Global climate agreements	Goals and year of implementation	Growing international consensus on the need for environmental sustainability and carbon emissions reduction. Compliance with or opposition to these agreements can signal how steel companies are responding to external pressures to adopt cleaner technologies, reduce emissions, and adapt to changing regulatory environments.
		exogenous	Global/International climate targets	Emission reduction targets and year of announcement	Broader international commitment to mitigating climate change and reducing greenhouse gas emissions. Compliance with global climate targets requires significant adjustments in steel companies, as such adherence to or deviation from these targets can demonstrate the level of influence that socio-political factors exert on steel companies' operations, strategies, and long-term viability.
		exogenous	National climate targets	Emission reduction targets and year of announcement	Indicators for exogenous socio-political pressures on steel companies because they reflect the specific regulatory and policy frameworks established by governments to address climate change within their jurisdictions. The alignment of steel companies with national climate targets indicates their responsiveness to external pressures, as well as their ability to effectively manage socio-political risks in their business strategies.
		exogenous	National strategy for renewables/ hydrogen	Name of strategy and year of implementation	Reflect governments' priorities and commitments to transitioning to cleaner energy sources and reducing carbon emissions. These strategies signal a shift towards low-carbon energy sources, which can create pressure on steel companies to adopt cleaner technologies, improve energy efficiency, and reduce emissions to align with government objectives.
		exogenous	Climate policies (e.g. ETS, carbon taxes)	Name of policy and year of implementation	Government efforts to internalize the external costs associated with carbon emissions and mitigate climate change. For example, carbon taxes, increase the cost of emitting carbon dioxide, which can significantly impact steel company's financial performance. This creates pressure on steel manufacturers to invest in cleaner production processes to avoid or minimize the financial burden of carbon taxes.
	Society	exogenous	Protests, social movements	Type of organization, year and number of protests	Public sentiment and demands for change including environmental concerns related to steel production. When communities organize protests or social movements against steel companies, it often indicates dissatisfaction with their environmental practices, such as pollution, emissions, or land use. These protests can create significant pressure on steel companies by drawing attention to their environmental impact and prompting public discourse on the need for stricter regulations or corporate responsibility.
		exogenous	Carbon Disclosure Project (CDP)	Climate change score	Global initiative aimed at driving environmental transparency and accountability among corporations. Participation in the CDP involves disclosing carbon emissions data, climate-related risks, and environmental management strategies. Steel companies that choose to participate in the CDP demonstrate their recognition of the growing importance of environmental issues, including climate change, and their willingness to engage with stakeholders on these matters.
Economic environment	**Customers**	exogenous	Demand for low-carbon steel	Increase in requests for low-carbon steel	Shifting market preferences and regulatory requirements towards environmentally sustainable products. Steel companies that fail to meet this demand risk losing market share and facing decreased competitiveness as consumers and businesses prioritize environmentally friendly alternatives.
	Suppliers	exogenous	Price of coking coal	US$/ton	Coking coal is a crucial raw material used in the production of steel through the traditional blast furnace method, where it serves as a source of carbon

(*continued on next page*)

Table 1 (*continued*)

TEF	Pressures	Type of pressure/ response	Indicator	Indicator description	Pressure-indicator link
					for the reduction of iron ore. When the price of coking coal rises, it increases the production costs for steel companies, as coking coal typically represents a significant portion of their expenses. This can squeeze profit margins and reduce the competitiveness of steel products in the market. The price of coking coal is influenced by a variety of factors, including supply and demand dynamics, geopolitical events, currency fluctuations, and regulatory changes.
		exogenous	Price of iron ore	US$/ton	Iron ore is a primary ingredient in steelmaking, to produce molten iron, which is then converted into steel. As for coking coal, when the price of coking coal rises, it increases the production costs for steel companies, as coking coal typically represents a significant portion of their expenses. This can squeeze profit margins and reduce the competitiveness of steel products in the market. The price of coking coal is influenced by a variety of factors, including supply and demand dynamics, geopolitical events, currency fluctuations, and regulatory changes.
Industry regime	**Mission**	company response	Emission reduction targets/Net-zero strategy	Year and target	Internal efforts and initiatives undertaken by companies to address environmental concerns and align with global and national climate goals. By setting emission reduction targets and developing net-zero strategies, steel companies proactively respond to environmental challenges and position themselves as leaders in sustainable business practices. Moreover, emission reduction targets and net-zero strategies can drive innovation and technological advancements within the steel industry, fostering the development of low-carbon steel production methods.
	Mindset/ Beliefs	company response	Publication of sustainability report	Sustainability report has been published. Year of publication, and the report dealing with climate topics (keyword: climate)	Steel company's internal efforts to transparently communicate their environmental, social, and governance (ESG) performance to stakeholders. When steel companies publish sustainability reports, they demonstrate a commitment to corporate responsibility and accountability.
		company response	Mission statements of CEOs	Keyword "climate" in annual reports	Internal commitment and strategic direction set by top leadership in addressing climate-related challenges and opportunities. When CEOs include statements about climate in their mission statements within annual reports, it signifies a recognition of the importance of climate change as a business issue and a commitment to integrating climate considerations into the company's overall strategy and operations.
	Technical Knowledge	company response	Choice of low-carbon technology	Energy efficiency, hydrogen-based, scrap-based or CCU/S	Proactive approach to addressing climate change and embracing sustainable practices. The choice of low-carbon technology also reflects strategic considerations, such as cost-effectiveness, competitiveness, and long-term viability.
		endogenous	Readiness of low-carbon technologies	TRL, costs, steel markets	Internal dynamics and capabilities within the steel industry to adopt and implement low-carbon practices. Furthermore, the readiness of low-carbon technologies can create internal pressure within the industry regime, as steel companies may face expectations from peers, customers, investors, and regulatory authorities to adopt these technologies.
	Capabilities	company response	GHG emissions intensity	CO_2eq/ton crude steel	Internal efforts and effectiveness of these companies in reducing their carbon footprint. The emission intensity per ton of steel is a crucial metric for assessing the inherent production process, as it reveals the underlying structural aspects that enable emission reduction. This metric goes beyond simply capturing emissions reductions resulting from external factors such as economic or geopolitical shocks.
		company response	Investments in low-carbon technologies	US $ and year of expenditures	Internal willingness, decisions and actions taken to transition towards low-caarbon production methods. Investments in low-carbon technologies signal a

(*continued on next page*)

Table 1 (*continued*)

TEF	Pressures	Type of pressure/ response	Indicator	Indicator description	Pressure-indicator link
					long-term commitment to addressing climate change and reducing their carbon footprint.
	Industry Standards	endogenous	Guidelines and initiatives from steel associations	Name of guideline and year of implementation	Collective efforts and commitments of the industry to address common challenges and opportunities. Adherence to industry guidelines and initiatives may enhance the credibility, reputation, and competitiveness of steel companies by demonstrating their commitment to responsible business practices and meeting industry standards.

different system state. This qualitatively different system state can be described by low CO2 emissions and the use of low-carbon technologies while maintaining the function that the steel industry is providing. On the macro-scale, this different system can be assessed based on the development of its carbon emissions. However, such a fundamental change can only occur when a certain number of companies adopt low-carbon technologies to reduce their emissions (Lei et al., 2023; Xu et al., 2023). As a result, multiple decisions at both meso- and micro-scales are necessary to initiate a PTP at the macro scale (see also Sharpe and Lenton, 2021 for tipping cascades). As such, in order to unlock potential reinforcing feedbacks on a sectoral level, first single steel companies need to be incentivized to adopt the new technology, becoming front-runners (de Villafranca Casas et al., 2024).

Therefore, we particularly focus on the operationalization of PTPs at meso-scale. As such, when defining a company as a system in transformation, it is necessary to explore what a PTP at the company level could really constitute and which interventions might allow a company to reach a PTP. Thus, it is crucial to understand steel companies and their embeddedness in their socio-economic system for which the Triple Embededdness Framework (TEF) guides our analysis.

2.3. *The Triple Embeddedness Framework*

The Triple Embeddedness Framework (TEF) has become a useful approach that can be applied to analyse transformation processes in industries and individual companies, illustrating socio-political (e.g. policy, social movements, public discourse) and economic (e.g. new entrants, new technologies, market developments) pressures experienced by incumbent industries and the behavior of such industries (Geels, 2014). The TEF also helps to understand which factors need to be changed to break off carbon lock-ins. This approach has been applied to analyze processes in various industries, including the coal sector (Brauers et al., 2020; Turnheim and Geels, 2013), electricity systems (Kungl and Geels, 2016), oil companies (Canal Vieira et al., 2022) and the steel sector in the UK (Geels and Gregory, 2023).

Geels and Gregory (2023) show that it is useful to analyse steel companies embedded in the steel industry regime, as well as their interactions with suppliers and customers, regulatory groups (policy-makers), special interest groups and social movements (Fig. 2). In the transition to net-zero emissions, pressure is applied from two directions: competitive economic forces within the industry regime and formal institutions (policies, regulations) and informal institutions (public values, expectations). Geels (2014) concludes that these pressures may stimulate changes in routines, technologies, core beliefs and values in firms,

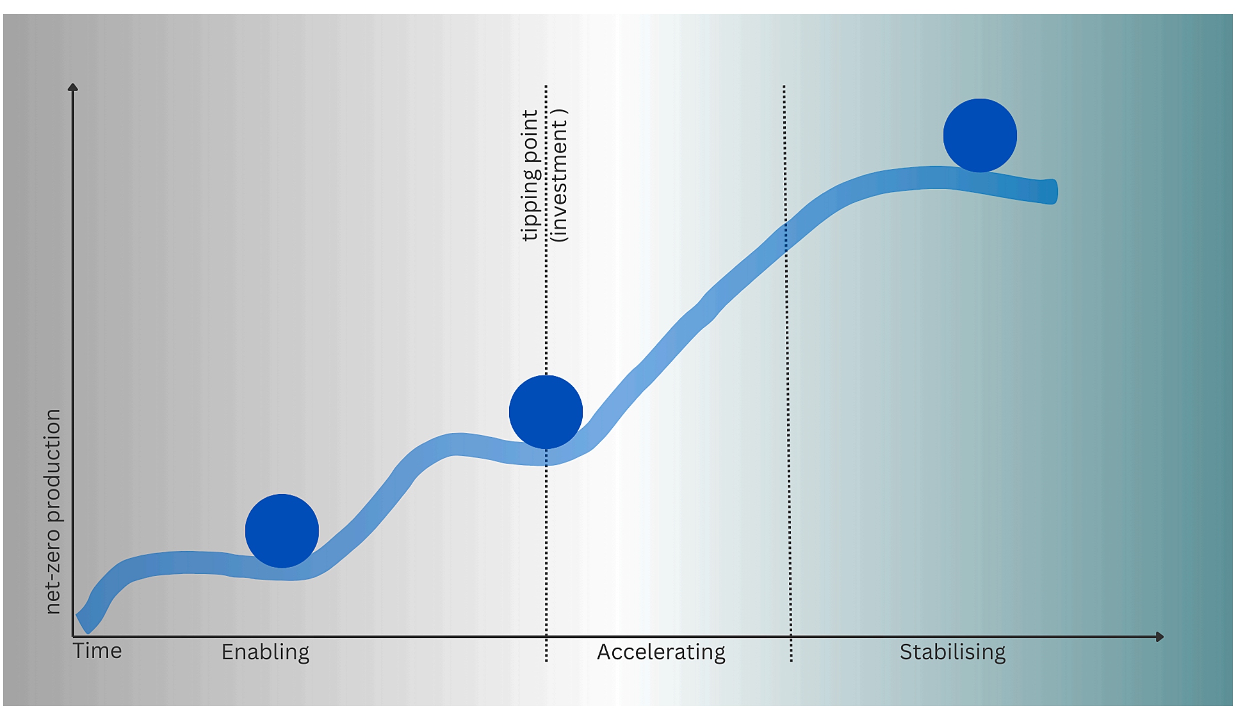

Fig. 3. Tipping process of a steel company inspired by Lenton et al. (2023). In the enabling phase various socio-political, economic and industry pressures effect the company leading to destabilization within the company system. A final trigger in form of investments then kick-off a reinforcing feedback that is stronger than existing balancing feedbacks leading to non-linear change until the company stabilizes again in a low-carbon production regime.

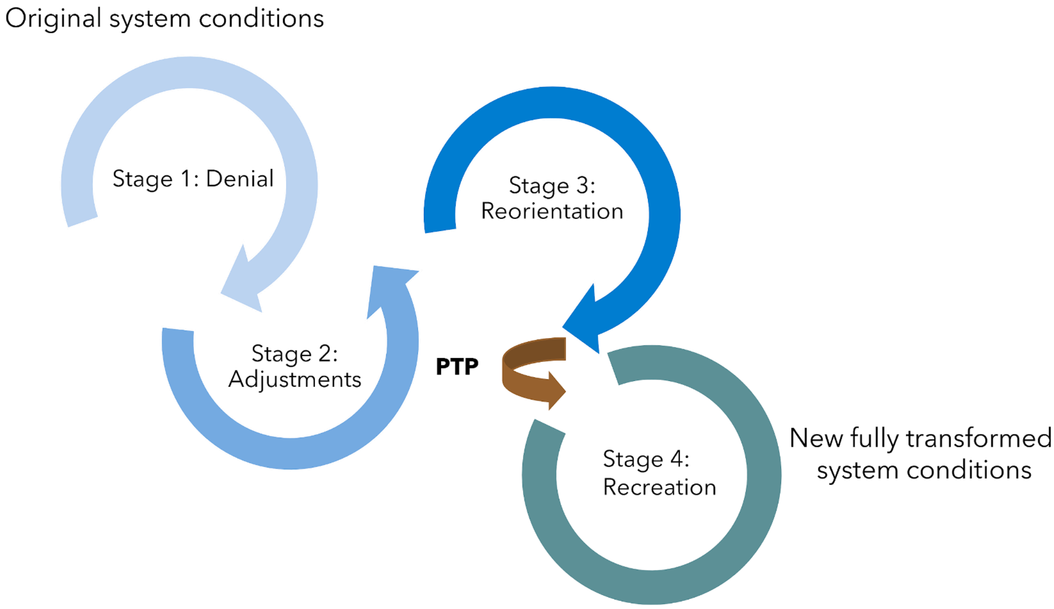

Fig. 4. Positive Tipping Point (PTP) in the transition stages and dynamics of strategic reorientation of a company inspired by Tàbara et al. (2018) and Geels (2014).

encouraging individual firms to strategically revise the established industry regime paradigms.

Schematically, companies move through different stages during their transition: denial, adjustments, reorientation and recreation (Geels, 2014). In stage 1, economic and political pressures (i.e., exogenous pressures) increase, but are not perceived as threats. As a result, companies downplay the problem or even deny its existence. In stage 2, exogenous pressures further increase, leading to performance problems in companies. Companies respond by making incremental and symbolic changes. By the time they have reached stage 3, exogenous pressures have accumulated, and companies have recognized that the problem is structural and not temporary, leading them to alter the company's strategy. This means that new technologies and capabilities are explored. Finally, in stage 4, the company faces exogenous pressures, prompting them to critically reevaluate their core beliefs and mission. As a result, the company undergoes a significant restructuring process (Geels, 2014).

3. Methods

3.1. Operationalizing Positive Tipping Points in the Triple Embeddedness Framework

PTPs are typically operationalized by analyzing the development of selected system indicators over time and potential non-linearities in their development (Lenton et al., 2022; Milkoreit et al., 2018). Such indicators comprise, among other factors, demographic, economic and political developments (Tàbara et al., 2018; Lenton et al., 2022; Otto et al., 2020; Winkelmann et al., 2020). The TEF informed our selection of system indicators upon we determined our analysis of tipping dynamics. The TEF includes the socio-political and economic environment as exogenous pressure as well as the industry regime as endogenous pressure, including a company's response to these pressures (Geels, 2014). Geels (2014) further specified these different pressures and responses as listed in Table 1 (see column *pressures*). Based on this list, we then selected various indicators that are descriptive for all exogenous and endogenous pressures and potential responses from a company (see Table 1). These indicators can be used to explain various tipping dynamics (see Fig. 3 for tipping process). Exogenous and endogenous pressures can serve as enabling conditions: pressures arising from policies and laws, economic circumstances and markets, as well as developments within the global steel industry. As such they influence a company and possibly destabilizes a company's functioning until a final trigger leads to a PTP at company level. In addition, indicators of a company's response to pressures and the possible interaction of them helped us to derive a definition of a potential PTP at the company level. These indicators include a change in the company's mission, the company's net-zero targets and strategies, their technology choice to achieve these targets, investments in these technologies and a change in emissions per ton of steel. Thus, exogenous pressures and endogenous industry pressures enable a company to rethink their production processes, leading to a company decision on a future net-zero pathway by replacing (substantial parts of) old with new infrastructure. This decision is usually demonstrated by the company's net-zero targets and strategies and their technology choice to achieve these targets. However, when the company invests in new technology, it triggers reinforcing feedbacks through capacity building (learning-by-doing, economies of scale) and new technology dependencies (e.g., hydrogen infrastructure), and ultimately activates a PTP at company level. After a certain period of time and restructuring, the company stabilizes again in a qualitatively different system state characterized by a low-carbon production process. This can be proved by investigating the change in emissions per ton of steel, which may be at a much lower level in the new system state compared to the initial system state.

In addition, we applied the transition stages from the TEF to identify when a PTP occurs at the company level. As shown in Fig. 4, we hypothesize that the PTP signifies the moment when a crossover from reorientation (stage 3) to recreation (stage 4) takes place. This crossover occurs because, by stage 3, a process of reassessment and reconsideration is already underway, causing self-amplifying feedback effects that finally result in the company reevaluating its core beliefs and mission. Such a shift in core beliefs and the company mission can then materialize in a fundamental restructuring of production processes.

3.2. Company case selection

For the choice of company cases, we applied three criteria. First, regional diversity was crucial to ensure that different socio-political and economic environments were considered and to enable us to identify structural differences in the cases by examining common patterns. Second, we focused on primary steel producers who are using primarily conventional blast-furnace technology, as their transition to low-carbon

Table 2
Yearly production volume, revenue and employees and emission intensity of each company. Data received from annual reports and yearly exchange rates from (The World Bank, 2023).

For 2020/21	BlueScope (Australia)	POSCO (South Korea)	Voestalpine (Austria)	U.S. Steel (USA)
Revenue (mio US $)	12,873	48,965	11,266	20,275
Production (tsd tons crude steel)	3.1	42,960	6,882	16,390
Employees	14,000	63,000	48,654	24,540

production is more difficult than that of secondary steel producers. Third, the companies' headquarters are in the respective country, as we assumed that the influence from national developments had a greater impact if it is locally based in the case of multi-national companies. In addition, we chose countries that are located in developed economies, as these have a frontrunner role under the Paris Agreement (UNFCCC, 2015).

We selected primary steelmakers in Australia (Bluescope), South Korea (POSCO) and the United States (U.S. Steel), while excluding major steel producers from, for example, China, India, and Germany. The exclusion of these countries was primarily due to the unique socio-political landscapes of emerging economies like China and India, which differ significantly from the industrialized nations under consideration. Moreover, given the stronger commitments to emission reductions mandated by industrialized countries under the Paris Agreement, we prioritized analyzing steel companies from nations with established first-mover obligations. Additionally, we decided to chose only one company within the European Union. Although SSAB is seen as a world forerunner in the transition to net-zero emission production, we chose a similar-sized but different company in Austria (voestalpine), as SSAB is already well-studied (Arens et al., 2021; Kushnir et al., 2020; Öhman et al., 2022). Table 2 summarizes the yearly production volume, revenue and employees for each case study (see Appendix A for further case study descriptions).

3.3. Data collection

We reviewed the positioning of each company in the transition process by using system indicators for the period of 2005, when the Kyoto Protocol was ratified and the climate change debate became more prominent in societal discussions, until 2021 or, if data were available, until 2022.

For the data collection, we followed the TEF (see section 3.1). The list of indicators was also adjusted throughout the collection process. For example, we planned to collect data on low-carbon steel sales to certain customers to assess customer demand. This information, however, was not available at the time of study, as the production of low-carbon steel had just begun. Instead, we included qualitative information about potential pressure from customer demand by looking for statements in company reports or press releases that reported an increase in the demand for low-carbon steel. Similarly, if a specific topic garnered significant attention in one of the case studies, for example, it was mentioned in annual reports and had not yet been considered, we incorporated it into our indicator list and expanded the data collection process across other case studies accordingly. Quantitative data were collected for prices, investments and emissions, whereas mainly qualitative information was compiled for other indicators.. The data were collected from publicly available documents, including annual reports and sustainability reports of companies, press releases, governmental reports and documents, studies from international research institutes such as the International Energy Agency (IEA) and other databases (e.g., International Monetary Fund). Overall, a total of 234 documents were

Table 3
Number of documents analyzed per type of document for each case study.

	BlueScope (Australia)	POSCO (South Korea)	Voestalpine (Austria)	U.S.Steel (USA)
Annual reports	2005–2022 [22, some reports have two parts]	2005–2021 [17, since 2011 annual report and sustainability reports were merged]	2009–2022 [13]	2010–2022 [12]
Sustainability reports	2011–2022 [11]	2005–2021 [17, since 2011 annual report and sustainability reports were merged]	2013, 2015/6, 2018–2022 [7]	2017, 2019–2022 [5]
Global policy and government documents	[4]			
National policy and government	[10]	[17]	[39]	[21]
Press releases	Public Press [1] Bluescope press [0]	Public Press [9] POSCO press [1]	Public Press [2] Voestalpine press [1]	Public Press [16] U.S. Steel press [1]
Guidelines and initiatives from steel associations	[15]			
Others	[10]			

analyzed (see Table 3 for number and type of documents per case study and Table A.1. in Supplementary Material A for a detailed list of documents per indicator and respective sources).

3.4. Empirical analysis

In order to answer our research question, we described and summarized the main developments for each case study drawing on our indicator analysis. This allowed us to directly compare differences and similarities among the companies on the basis of one indicator. However, we color-coded our qualitative findings to keep an overview of the developments per case study. By following a traffic-light system, each indicator was ranked green, orange, or red. Regarding indicators of a company's response to exogenous and endogenous pressures, green indicates a high response, orange, some response and red, little or no response. Regarding indicators of exogenous and endogenous pressures, green indicates high pressure from the indicator on the company, orange, medium pressure and red, little or no pressure. If an indicator was ranked green for at least two case studies, and these case studies were also close to reaching a PTP, we assessed the indicator as applying strong pressure. At the same time, if an indicator was ranked red, but no correlation to a potential PTP could be made, we considered this as applying rather weak pressure for the transition to net-zero emissions.

4. Results

4.1. Exogenous pressures

4.1.1. Socio-political environment

Steel companies have broadly resisted policy pressures to pursue net-zero primary steel production for a long time. In this study, we found that the four steel companies had taken little action before the Paris Agreement materialized in the form of national commitments (see Table 4 for a full list of political events for each case study). Government

Table 4
International and national Policy developments relevant for each case study from 2005 to 2022.

Year	Bluescope (Australia)	POSCO (South Korea)	U.S.Steel (USA)	voestalpine (Austria)
2002	–	Kyoto Protocol ratified	–	Kyoto Protocol ratified
2005	–	–	Kyoto Protocol *not* ratified	EU ETS Phase 1 started
2006	–	–	–	–
2007	Kyoto Protocol ratified, National Greenhouse and Energy Reporting Act	Stockholm Convention	U.S. Supreme Court decision: EPA is authorized to set emission limits for GHG emissions beyond local air pollution	Update of Austrian Climate Strategy Est. Austrian Climate and Energy Fund
2008	White Paper Carbon Pollution Reduction Scheme	First Energy Master Plan	–	EU Climate and Energy Package 2020 EU ETS Phase II
2009	UN Copenhagen Accord: GHG emission reduction target: 5 % up to 15 % or 25 % by 2020 compared to 2000	–	UN Copenhagen Accord: GHG emission reduction target: 17 % by 2020 and 83 % until 2050 (Obama Administration)	UN Copenhagen Accord: GHG emission reduction target: 30 % by 2020 compared to 1990 EU Renewable Energy Directive
2010	–	Global Superior Energy Performance Partnership	–	EU Low-Carbon Economy Roadmap Austrian Energy Strategy
2011	Clean Energy Act	GHG and Energy Target Management Scheme	–	Austrian Climate Protection Act
2012	Carbon Pricing Mechanism established under the Clean Energy Act	Act on the Allocation and Trading of GHG Emission Permits	–	–
2013	Introduction and repeal of ETS	–	–	EU ETS Phase III Austrian Energy Efficiency Act
2014	–	Second Energy Master Plan	–	EU Climate and Energy Package 2030
2015	–	ETS started	Clean Power Plan	–
2016	Paris Agreement ratified, Australian safeguard mechanism	Paris Agreement ratified Roadmap for GHG Emission Reduction by 2030	Paris Agreement ratified (Obama Administration)	Paris Agreement ratified
2017	–	–	Withdrawal from Paris Agreement announced, Repeal Clean Power Plan and Clean Air Act (Trump Administration)	Revision EU RES Directive
2018	–	Update Roadmap for GHG Emission Reduction by 2030 Plan for 2nd phase of ETS	–	National Climate and Energy Plan Austria (#mission2030)
2019	–	Third Energy Master Plan	–	EU Green Deal and target for climate neutrality by 2050
2020	Long-term strategy for green steel industry	Long-term low-carbon development strategy	Withdrawal from Paris Agreement	EU Fit-for-55 package, Industrial Strategy, H2 Strategy and Innovation Fund; Austrian target for climate neutrality by 2040
2021	Hydrogen strategy at state level (NSW),Renewable Hydrogen Industry Development Plan (Victoria)	–	Re-joining the Paris Agreement (Biden Administration), 2030 GHG Reduction Target, US net-zero strategy 2050	European Climate Law, IPCEI for H2, ETS Phase IV; RES Expansion Act Austria
2022	Government change; update of safeguard mechanism	–	Inflation Reduction Act ($391 billion for climate and energy), clean hydrogen initiative, green public procurement (Buy Clean Task Force), revision of Infrastructure Law, carbon-based trade policy for clean steelmaking, industrial decarbonization research initiative	RePower EU; Austrian H2 Strategy, climate and transformation offensive Austria

measures following the previous international climate accords were too weak to produce substantial measures at the company level. For example, the European Union (EU) pre-empted the Paris Agreement by introducing the Emission Trading Scheme (ETS) in 2005. However, these pressures led to discussions about carbon leakage and a potential loss in terms of global competitiveness instead of triggering the application of net-zero strategies (Anger and Oberndorfer, 2008; Boutabba and Lardic, 2017; Okereke and McDaniels, 2012). In this context, voestalpine also voiced their consideration to move their production to regions that did not have such strict climate policies (voestalpine, 2009, p. 15) as an argument to evade substantial actions. U.S. steel expressed similar sentiments regarding their steel plant in Slovakia (U.S. Steel, 2010; U.S. Steel Kosice, 2010).

The Paris Agreement appears as a watershed moment for steel companies. Since 2015, national climate policies have tightened, increasing the pressure on major emitters. This effect is most strongly observed in Austria and South Korea. The EU launched various policy strategies, including the European Green Deal in 2019 (European Commission, 2019) and the Fit-for-55 package including a Carbon Border Adjustment Mechanism (proposed in 2021 and agreed on in 2022, European Commission, 2021), that should guide EU countries towards achieving climate neutrality by 2050. In 2020, the Austrian Government became even more ambitious and set a climate neutrality target for 2040. South Korea committed to climate neutrality by 2050 (D'Ambrogio, 2021) and updated its strategy for GHG emission reduction by 2030. In addition, an ETS was implemented in 2015 (ICAP, 2022).

In contrast, US and Australian energy and climate policies remained

Table 5
Yearly scores of case study companies in the carbon disclosure project retrieved from CDP (2023).

Year	BlueScope	POSCO	U.S. Steel	Voestalpine
2010	submitted – not scored	A	submitted – not scored	no response (F)
2011	declined	A-	D	submitted – not scored
2012	declined	B	C	declined
2013	declined	B	B	no response (F)
2014	no response (F)	B	B	no response (F)
2015	declined	B	C	declined
2016	F	A-	no response (F)	F
2017	F	A-	no response (F)	C
2018	F	B	N/A	B
2019	F	A-	N/A	A-
2020	F	B	C	B
2021	F	B	C	B
2022	D	B	C	A-

Note: the scores describe the level of action in achieving environmental stewardship: A = leadership in action on climate change (e.g., science-based targets, climate transition plan), B = good environmental management, C = awareness of environmental issues, D = companies just started their disclosure by being scored, F = requested company fails to disclose; the differentiator (−) indicates different levels within one score; N/A = not available.

erratic and did not demonstrate that substantial efforts were being made to reduce emissions even after 2015 (see Table 4) (Crowley, 2021). Only with new governments, in the US in 2021 and Australia in 2022, is new ambition in climate policy. Both countries have now set a target to achieve net-zero emissions by 2050 (Australian Government, 2021; U.S. Department of State, 2021), leading to a consequential strategy change at the company level (BlueScope, 2022a; U.S. Steel, 2021).

Furthermore, we found that direct societal pressures from protests or social movements on the four steel companies to reach net-zero steel production are limited. Rather than influencing climate target setting in individual companies, public bodies and not-for-profit organizations play an important role in observing compliance with government regulations and reporting requirements. For example, the Environmental Protection Agency and the Allegheny County Health Department brought U.S. Steel to court for violating the Clean Air Act. The issue was settled with a $1.5 million penalty levied against the company and official requirements issued for them to improve their steel production facility extensively in 2022 (EPA, 2022). Although emission reporting has been a long-standing requirement by governments to increase environmental transparency and track progress towards international climate targets for decades, climate-related reporting has only become the norm since 2015, after which it has been taken more seriously by large steel companies. One indicator for this observation is the record of steel companies reporting in the Carbon Disclosure Project (CDP). Table 5 shows that all but POSCO either neglected or inconsistently pursued emission reporting in the early 2010s.

4.1.2. Economic environment

While global steel demand is rising (worldsteel, 2022), a growing demand for low-carbon steel in particular is a crucial signal to steel producers and can exert pressure that supports the decarbonization of primary production (Energy Transitions Commission, 2021). Early markets for low-carbon steel are most likely to emerge in the automotive, energy, construction and white goods sector, as these sectors are being required to reduce their carbon footprint (Energy Transitions Commission, 2021). Such developments are mentioned in three out of our four case studies. POSCO has already launched two brands focusing on eco-friendliness regarding the automotive and energy sector (POSCO, 2021, p. 10). voestalpine also reported increasing numbers of communications with customers about the sustainability performance of their products (voestalpine, 2022a, p. 20), and U.S. Steel clearly stated that customers are demanding low-carbon solutions (Business Wire, 2023; U.S. Steel, 2022). In contrast, BlueScope did not explicitly mention the demand for low-carbon steel as a driving factor for climate action.

Table 6
Global initiatives and standards for the steel industry.

Year	Standard/Initiative	Description	Participation
2008	Climate action data collection programme	Reporting of on-site or company-level CO_2 emissions.	BlueScope, POSCO U.S.Steel, voestalpine
2009	CARES Sustainable Constructional Steels	Certification scheme with the objective of improving the environmental, social and economic management of steel manufacturers and processors as well as improving the performance of products.	none
2019	ResponsibleSteel Standard	To recognize steel sites that operate in a responsible manner.	BlueScope (founding member), POSCO U.S.Steel, voestalpine
2021	worldsteel: Net-Zero Steel Pathway Methodology	Aim: to facilitate companies to become consistent in how they measure and set GHG reduction targets, in line with the contribution needed from the sector.	BlueScope (steering member), POSCO, voestalpine
	Science-based targets initiative	Science-based targets provide companies with a clearly-defined path to reduce emissions in line with the Paris Agreement goals.	voestalpine
2022	Update of ResponsibleSteel Standard	Incorporates additional requirements on GHG emissions and the sourcing of input materials.	BlueScope, POSCO U.S.Steel, voestalpine
	worldsteel's Sustainability Charter	Organization commits to a vision where steel is a material for a sustainable world and takes leadership for a positive impact on people, the planet and society.	BlueScope, POSCO U.S.Steel, voestalpine

Price developments in essential input materials and transport are major considerations for steel companies, as these development affect their economic viability. Since iron ore and coking coal are traded globally, their prices are subject to change in the supply chain. In addition, a company's location can determine the costs of raw materials, as transportation costs often contribute a high share to the final commodity price (Hummels, 2007). However, none of the four cases indicates that decisive climate actions are being taken towards material price pressures. All companies mentioned the challenging period since the outbreak of the COVID-19 pandemic and the Russian invasion of Ukraine, but emphasized their resilience in the economic environment (BlueScope, 2022b; POSCO, 2021; U.S. Steel, 2022; voestalpine, 2022b) (see Appendix B for more information).

4.2. Endogenous pressure

4.2.1. Industry norms and standards

Globally, the need for coordinated climate action within the steel industry has become more prominent since 2008, and collaborationhas intensified since 2019 (see Table 6).

Table 7
Technology routes for steel production and their emission reduction potential based on Energy Transitions Commission (2021), Fan and Friedmann (2021), Harpprecht et al. (2022) and Vogl et al. (2021b).

New technologies	Emission reduction compared to blast furnace and type of disruption	
Blast furnace with best available technology The best available technology meets the prescribed output standards for a specific process and is approved by legislator or regulators (see e.g. (Remus et al., 2013)	−20–40 %	incremental
Smelting reduction-basic oxygen furnace Iron ore is reduced by smelting reduction	−35 %	incremental
Blast furnace with carbon capture and storage (CCS) CO_2 from the blast furnace and coke plant are captured	−50–95 %	breakthrough
Hydrogen direct reduction with electric arc furnace (H2-DRI-EAF) Low-CO_2 hydrogen is used as the reducing agent to reduce iron in a direct reduction plant. An EAF using renewable electricity is applied to further process into steel.	−99 %	breakthrough
Scrap-EAF with renewable energy EAF operated with renewable electricity for secondary production	−99 %	breakthrough
Ore electrolysis Iron ore is reduced by using electrons as reducing agent	−99 %	breakthrough

following TCFD recommendations in 2020 (POSCO, 2020). Jointly with five leading Korean companies, POSCO signed the Carbon Neutrality Joint Declaration 2050 from the Committee for Green Metallurgy Development – a science and industry-government partnership – in February 2021. In the same year, POSCO hosted the first Hydrogen Iron & Steel Making Forum jointly with the worldsteel technology committee. The second forum was held in Sweden in 2022 and was conjointly organized by POSCO and SSAB. The forum brought together various steelmakers, including voestalpine, and representatives from several governments (e.g., Australia, Korea, US, EU).

At the same time, the Australian Steel Association and the Green Building Council of Australia developed the Environmental Sustainability Charter to improve the environmental footprint of its certified steelwork fabrication companies (ASI, 2023). Furthermore, lead investors have been engaging BlueScope through Climate Action 100+ in an open and productive dialogue since early 2018, requesting disclosures and increased investments in net-zero primary production (Climate Action 100+, 2022). Investors held several meetings with BlueScope in 2021, including an investor roundtable, with the priority engagement topics being short- and medium-term targets and the longer-term net-zero pathway for the steel sector.

Additional efforts by U.S. Steel have been rather limited. In 2008, U. S. Steel engaged in the promotion of cost-effective environmental strategies through the American Iron and Steel Institute, the Canadian Steel Producers Association, worldsteel and EUROFER (U.S Steel, 2008, p. 24). In 2021, the company expanded their engagement by forming collaborations with universities and research institutes as well as associations as a means of transitioning to net-zero steelmaking while remaining rather vague about its involvement (U.S. Steel, 2021).

4.2.2. Technology readiness and low-carbon breakthrough technology projects

Various low-carbon technology practices are evolving within the industry regime and have been adopted differently on the global market.

Table 8
Regional diffusion of low-carbon breakthrough technology projects in the steel industry based on Energy Transitions Commission (2021) and Vogl et al. (2021b).

Technology	Asia&Oceania	Europe	America
Blast furnace & CCS	TATA Steel (India), HBIS (China),	Arcelor Mittal (Norway, France)	U.S. Steel (USA)
H2-DRI-EAF	Liberty (Australia), HBIS (China), Fortescue (Australia), Metalloinvest (Russia), POSCO (South Korea), Baosteel (China)	Arcelor Mittal (Belgium, France, Germany, Spain), Salzgitter (Germany), Thyssenkrupp (Germany, Netherlands), Voestalpine (Austria), SSAB (Sweden), Liberty (Romania, France), TATA Steel (Netherlands), Tenaris (Italy), H2 Green Steel (Sweden, Spain)	Arcelor Mittal (Canada), Paul Würth and SHS (Canada), Compañia Siderúrgica Huachipato SA (Chile),
Scrap-EAF with renewable energy	–	SSAB (Finland)	Algoma Steel (Canada)
Ore electrolysis	–	–	Boston metals (USA)

This is demonstrated, for example, by voestalpine's decision to join the science-based targets initiative in 2021 (SBTi, 2023). Furthermore, the European Confederation of Iron and Steel Industries (EUROFER) published its first low-carbon steel roadmap in 2012 (EUROFER, 2012), followed by a low-carbon roadmap including pathways to a CO_2-neutral European steel industry in 2019 (EUROFER, 2019). These roadmaps were partly mentioned in annual reports to provide a perspective on the sector's goals.

POSCO took a proactive role in the global industry regime in 2003 when worldsteel launched the worldsteel's CO_2 Breakthrough Programme (worldsteel, 2009). Among the participants mentioned above, POSCO actively engaged in the Global Steel Sectoral Approach discussion to find a sector-specific response to climate change in 2007. In 2010, POSCO published the world's first carbon report in the steel industry (POSCO, 2010). The company was Korea's first manufacturing company to become a TCFD (Task Force on Climate-Related Financial Disclosure) supporter and published an annual Climate Action Report

Steel companies tend to make incremental improvements and adopt efficiency measures to reduce their emissions. However, these strategies only achieve limited reductions in emissions. For example, implementing even the best available technology in the blast furnace route or adopting smelting reduction in combination with a basic oxygen furnace, can only lead to a maximum emission reduction of up to 40 % (see Table 7). In contrast, so-called breakthrough technologies can achieve an up to 99 % emission reduction. Such technologies include the installation of Carbon Capture and Storage (CCS) technology in addition to the use of the blast furnace route or the switch to either hydrogen-based direct reduction in combination with the use of an electric arc furnace (H2-DRI-EAF) or the direct electrolysis of iron ore with electricity.

While incremental technology improvements already have a high

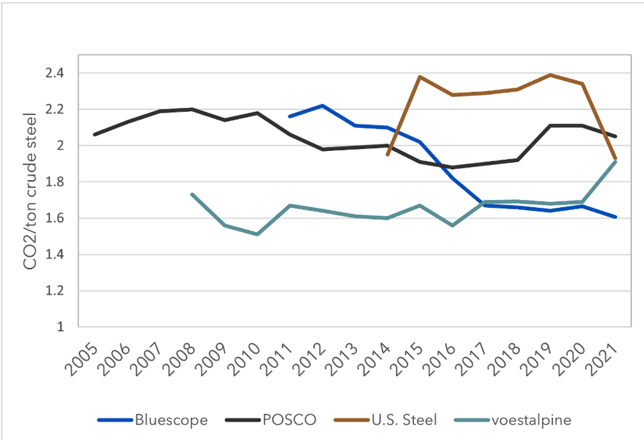

Fig. 5. Development of specific CO2 emissions per ton crude steel for case study companies from 2005-2021.
Source: Annual Reports and Sustainability Reports

technology readiness level (TRL),[1] breakthrough technologies are less mature (Harpprecht et al., 2022). CCS, either for the blast furnace or natural gas-direct reduction route, have a similar TRL as compared to the hydrogen-based steel production (Agora Energiewende and Wuppertal Institute, 2021, pp. 166–173). However, CCS routes tend to raise levelized production costs by around 8–9 % as compared to the existing production practices, while the H2-DRI route is about 35–70 % more expensive (IEA, 2020b). The limiting factor for this technology is the access to low-cost renewable electricity and the cost development of the electrolyzer (Wang et al., 2021; Way et al., 2022). An alternative to hydrogen-based steelmaking is the direct electrolysis of iron ore, which does not require the prior production of hydrogen. However, this technology is still at an early developmental stage (Agora Energiewende and Wuppertal Institute, 2021, pp. 166–173).

Although the H2-DRI-EAF route hinges on CCS options regarding its production costs, European steel makers, including voestalpine, have concentrated on the hydrogen-based technology option (see Table 8). On the one hand, CCS has a rather short history in Europe (Lockwood and Bertels, 2022) compared to other world regions, such as the US (Wilcox et al., 2021), although it has received increasing amounts of attention here since 2023 (European Commission, 2023). On the other hand, the European industry wants to strategically position itself as a technology leader for low-carbon steel (EUROFER, 2019). This positioning increases its competitiveness not only in the global market but also within Europe. POSCO is pursuing a similar strategy and wants to maintain its competitiveness by being a frontrunner in the field of hydrogen-based steelmaking (POSCO, 2023, 2021). Interestingly, in the US, only two projects for low-carbon breakthrough technologies are currently underway. U.S. Steel is exploring the CCS option while Boston Metals is investigating direct ore electrolysis. BlueScope is the only case study not listed among the ongoing low-carbon breakthrough technology projects, although Australian competitors are actively developing the hydrogen-based route.

4.3. Companies' responses

4.3.1. Sustainability reporting and GHG emission intensity

The company-level responses to the increasing pressure are revealed by the frequency and quality of their reporting (see Table 3 for available reports). POSCO is a frontrunner in terms of sustainability reporting, having published its first sustainability report before 2005 and emphasizing transparent climate disclosures in its 2020 reports (POSCO, 2020). BlueScope and voestalpine followed suit with sustainability reporting, albeit with varying degrees of ambition and focus on climate action over the years. U.S. Steel, while also adopting sustainability reporting in recent years, only outlined emission reduction targets in its 2019 report after disclosing emissions in 2017 (U.S. Steel, 2019, 2017).

The companies' CO_2 emissions per ton of crude steel (see Fig. 5) have not substantially changed over the last decade. The emission intensity drop observed at BlueScope and U.S. Steel can mainly be attributed to the acquisition of secondary steelmaking capacities (BlueScope, 2021, 2015; U.S. Steel, 2021) and the closure of primary steel production plants (U.S. Steel, 2016). The emission intensity of voestalpine started to increase in 2020 – a trend that can also be observed for POSCO – because the calculation method has changed. Overall, no deep emission cuts have been achieved by any of the four companies so far.

4.3.2. New missions and visions

To assess whether these companies are already in the process of reorientation, we examined changes in their corporate missions and visions. Our analysis of the four companies' sustainability and climate reports revealed that climate pledges and emission disclosure became the new norm in the industry in the mid- to late-2010s. Previously, climate action had widely been considered a business risk, resulting in reactive approaches. For example, voestalpine considered climate policies as an economic threat until 2010, only acknowledging their need to take climate action in 2014. However, from that point onwards, climate protection had become a more important topic for the company. The government pressure triggered a change in the mission of the company, which also set climate protection as a goal in 2021 (voestalpine, 2022a, p. 6). This commitment is also reflected in their increasingly active role in R&D for low-carbon technologies and the publication of a net-zero strategy "greentec steel" (voestalpine, 2023a).

POSCO has been proactive with respect to sustainability issues since 2005. POSCO developed a CO_2 credit calculation system for its steel products by introducing an life cycle assessment in 2005 (POSCO, 2005). The company voluntarily agreed to reduce air pollutants and, in 2013, announced that its goal is to develop and apply a next-generation production method that does not require coal and is CO_2-free. Over the observed period, POSCO was also actively engaged in the steel industry's efforts to achieve more sustainable production and is the first company to publish a climate action report acknowledging the company's responsibility (POSCO, 2020, p. 5). Specific emission reduction targets were announced in 2020, along with a technology roadmap for achieving these. Based on the measures taken by POSCO and voestalpine, the two companies seem to be taking on a frontrunner role in the transition of the global steel industry.

BlueScope started early on to report their GHG emissions (BlueScope, 2009), demonstrating an awareness of their climate responsibility. However, for a long time, their concrete measures did not go beyond adjustments by increasing scrap steel production. The company has only recently announced specific emission reduction targets. The company also plays an active role at the regime level as a founding member of the ResponsibleSteel initiative and led the development of the Net-Zero Steel Pathway Methodology. However, BlueScope's pledges lack a concrete strategy and evidence of investment decisions (BlueScope, 2022a).

Comparably, U.S. Steel hesitated regarding climate action until 2014 and took on an observer role, especially concerning international climate policy. Climate policy, in general, was criticized and presented as a business risk. For example, as the operator of a steel plant in Slovakia, the implementation of the EU ETS was of major concern. Although the company paid for certificates in the first phase of EU ETS, it made windfall profits from the second phase onwards, leading to higher policy acceptance. The company finally committed to emission

[1] The TRL is an internationally used rating system for the maturity of technologies. The classification is as follows: research and laboratory stage: TRL 1 to 3; pilot stage: TRL 4 or 5, demonstration phase:TRL 6 or 7. Mature technologies: TRL 8 to 9.

Table 9
Assessment of companies' responses for different criteria describing a PTP. Green: high response, orange: some response, red: little/no response.

Indicator	BlueScope	POSCO	U.S. Steel	voestalpine
Emission reduction targets/Net-zero strategy	2030 target is weakm 2050 targets announced in 2022 but lacks a concrete strategy	goals for 2030, 2040 and 2050 announced in 2020 including technology strategy	weak target for 2030 and net-zero target for 2050 announced in 2021, without long-term technology strategy	first emission reduction goal in 2019; in 2020 goals for 2030 and 2050 including technology strategy were announced
Publication of sustainability report	sustainability reports since 2011 but unspecific until 2015	consistent sustainability reports since 2005	inconsistent frequency und unspecific until 2018	inconsistent frequency und unspecific until 2019
Mission statements of CEOs	yearly reporting on GHG emissions but no emphasis in mission statements	emphasis of actions for climate protection since 2005	climate protection is not emphasized but emission reduction targets are announced	climate protection since 2014
Choice of low-carbon technology	2030 and 2050: technology neutral	2030: phase-in H2-DRI, 2050: H2-DRI, CCUS	2030: scrap-based steel production; 2050: technology neutral	2030: EAF, 2050; H2-DRI, CCUS
GHG emissions intensity	no structural change	no structural change	no structural change	no structural change
Investments in low-carbon technologies	mainly in blast furnace relinement	low investment rate	investments in scap-based steel plant	investment decision for two EAF to achieve 2030 goal

reduction targets in 2021. Still, the transformation to a net-zero company does not seem to define the business conduct and the long-term strategy of U.S. Steel so far.

4.3.3. *Decisive decisions: emission targets, net-zero pathways and new technologies*

The emission reduction targets for 2030 range from 10 % to 30 % among the companies examined here. However, all companies pursue climate neutrality by 2050. In its emission reduction strategy, BlueScope remains technology neutral and wants to cut emissions by 12 % by 2030. BlueScope views the H2-DRI-EAF technology pathway as highly uncertain despite acknowledging that it is internationally demonstrated, but only considers it economically viable from 2040 onwards (BlueScope, 2022a). The company also justified a re-investment in a conventional blast furnace in 2021 – investing 682 million US$ – due to the perceived early development stage of low-carbon technologies (BlueScope, 2022a, p. 43). Although the company announced emission reduction targets, measures for implementing a breakthrough technology have been limited to their first research activities at Port Kembla (BlueScope, 2022a, p. 42). Instead, the recent investment decision in a blast furnace plant might delay the phase-out of conventional emission-intensive technologies.

U. S. Steel set a comparably higher emission reduction target of 20 % for 2030 with its "best for all" strategy. Its main strategy they will apply to reach this goal is to shift from primary to secondary steel production (U.S. Steel, 2021, p. 67), reflected by a $450 million investment in the newly acquired Big River Steel recycling plant (U.S. Steel, 2023). The company acknowledges that all primary steel production facilities must be transformed beyond efficiency improvements between 2030 and 2050 and made 2050 net-zero commitments in early 2021. The 2022 sustainability report provides a first overview of available technology options beyond 2030, including DRI, CCS, direct electrification and offsetting. Nevertheless, the company has not committed to an alternative technology pathway to achieve this target, nor has it announced any relevant investments or stepped-up its R&D efforts.

In contrast, POSCO announced a three-step strategy to cut emissions and phasing in the H2-DRI-EAF technology, in 2020 with specific targets including a 10 % decrease by 2030, a 50 % reduction by 2040, and net zero by 2050. To reach these targets three phases are determined: starting with incremental improvements, then deploying bridge technologies such as more scrap-use, CCS and partial hydrogen technology deployment and, ultimately fully shifting to hydrogen-based steelmaking (POSCO, 2020, p. 22). The company plans to establish a joint green hydrogen production plant with the Australian iron ore supplier Fortescue Metal Group (FMG) (Min-hee, 2021). In February 2019, POSCO announced investments of 169 million US $ to set up more environmentally friendly production facilities and cut emissions (Chung, 2019). The deep decarbonization of the company should be made possible by a systematic switch to hydrogen as the reducing agent, for which a million-ton demo plant will be built in 2023 and operational by 2027. The company claims that a complete transformation to a net-zero steel mill would cost the equivalent of 33.8 billion US$ (Chang-Won, 2021).

Since 2016, voestalpine has increased its efforts to achieve net zero. In the 2018 Corporate Responsibility report, voestalpine emphasized its responsibility to contributing to the national GHG emission reduction target. However, its strategy aimed solely for an incremental approach toward achieving net-zero emissions (voestalpine, 2018, p. 39). A year later, voestalpine had already set a target to reduce GHG emissions by 80 % by 2050 as their commitment to the Paris Agreement (voestalpine, 2020, p. 71). Hence, in 2020/21, the company set an emission reduction target of 30 % by 2030 and a net-zero target for 2050 (voestalpine, 2020, p. 15). In 2021/22, voestalpine's net-zero plan called "greentec steel" was launched, which comprises a 10 % emission reduction in the short-term by optimizing input material and reducing agents and a 30 % emission reduction by 2030 by installing two electric arc furnaces, which equals a 5 % reduction in Austrian national GHG emissions (voestalpine, 2023a). Hence, the company runs several R&D projects, including a pilot facility to produce green hydrogen from water by electrolysis using renewable energy sources (H2Future), a test facility

Table 10
Assessment of exogenous and endogenous pressures that influence a company's response. Green: high pressure, orange: some pressure, red: little/no pressure.

Indicator	BlueScope	POSCO	U.S. Steel	voestalpine
Global climate agreements/targets	global climate agreement ratified but no further implications	global climate agreement ratified followed by more climate policies	global climate agreement first ratified, then withdrawn, then ratified again and no further implications	global climate agreement ratified followed by more climate policies and mentioned in CEO letters of reports
National climate targets	climate neutrality by 2050 (set in 2022)	climate neutrality by 2050 (set in 2020)	climate neutrality by 2050 (set in 2021)	climate neutrality EU 2050 , climate neutrality in Austria 2040 (set in 2020)
National strategy for renewables/hydrogen	no renewable energy strategy but hydrogen strategy (in 2021) in place	renewable energy (in 2014) but no hydrogen strategy in place	renewable energy strategy (in 2015) and hydrogen strategy (in 2022) in place	renewable energy strategy (in 2011) and hydrogen strategy (in 2022) in place
Climate policies	some policies in place, ETS introduced but repealed, started in 2016	many policies in place, ETS since 2015	policy ambiguity and no substantial policies until 2022	many policies on EU and national level, ETS since 2005
Protests, social movements	no movements claiming net-zero transition	no movements claiming net-zero transition	many lawsuits on air pollution violations, no movements claiming net-zero transitions	no movements claiming net-zero transition
Carbon Disclosure Project	no disclosure until 2015, low scores since then	disclosure since 2010 and high scores achieved	inconsistent disclosure over time and low scores when disclosed	no disclosure until 2015, high scores achieved since then
Demand for low-carbon steel	company does not report increasing demand for low-carbon steel products	company reports on increasing demand for low-carbon steel products	company reports on increasing demand for low-carbon steel products	company reports on increasing demand for low-carbon steel products
Price of coking coal	company does not report on pressure of raw material prices for climate action	company does not report on pressure of raw material prices for climate action	company does not report on pressure of raw material prices for climate action	company does not report on pressure of raw material prices for climate action
Price of iron ore	company does not report on pressure of raw material prices for climate action	company does not report on pressure of raw material prices for climate action	company does not report on pressure of raw material prices for climate action	company does not report on pressure of raw material prices for climate action
Technology readiness and low-carbon projects	does not compete for technology leadership but involved in first-mover projects	competes for technology leadership and involved in first-mover projects	neither compete for technology leadership nor involved in first-mover projects	competes for technology leadership and involved in first-mover projects
Guidelines and initiatives from steel associations	participate in global standard initiatives but no pressure for further actions	participate in global standard initiatives and drives industry regime developments	participate in some global standard initiatives but no pressure for further actions	participates in global standard initiatives but no pressure for further actions

for reduction processes with hydrogen plasma, the Sustainable Steel (SuSteel) project and a project that examines hydrogen-based fine ore reduction (Hyfor). Although the company focuses on the H2-DRI-EAF technology, it also investigates CCS and CCU (carbon capture and utilization) options (voestalpine, 2022). In order to achieve its 2030 emission reduction goal, the first investment ("*amount in the three-digit millions*" (voestalpine, 2022a, p. 38) was approved in 2022, followed by an investment decision of 2 billion US$ for two electric arc furnaces in March 2023 (voestalpine, 2023b).

4.4. Finding PTPs in case studies

According to the definition made in section 3.1, our empirical findings show that voestalpine is very close to reach a PTP with its investment decisions, followed by POSCO with a concrete technology pathway, while U.S. Steel and BlueScope are lagging behind (see Table 9). All four companies are at different stages in the transition, with voestalpine standing out as the frontrunner on the verge of crossing from the reorientation into the recreation stage in the decarbonization process. This assessment is supported by voestalpine's decision to speed up emission reductions until 2030 by replacing parts of the conventional blast furnace route with the H2-DRI-EAF route by installing two EAFs for green hydrogen-based steel production. Although this investment only covers 30 % of the emissions related to the company's output, it indicates the onset of a positive feedback dynamic, which can further propel the company along the net-zero trajectory when technology normalization creates new path dependencies. For example, the approval for the investment decision also entails increasing expert knowledge and the companies capacities to adopt and operate the new technology (voestalpine, 2023b). POSCO shows a similar pattern along their net-zero pathway, demonstrating early commitments towards sustainability and investigations of low-carbon technologies. The company is also dedicated to following a hydrogen-based technology route while advocating for sector-level green hydrogen deployment. However, POSCO's low emission reduction commitments in the mid-term and their lack of decisions to invest in commercial installations indicate a more cautious approach towards recreating their production process.

In contrast, U.S. Steel and Bluescope remain in the adjustment stage. Both are strongly pushing for a switch to secondary production and efficiency gains by optimizing the existing blast furnaces in order to meet their 2030 reduction targets. Neither has defined a clear strategy nor made a technology commitment to achieving net-zero emissions. Indeed, BlueScope's announcement that it would refurbish an old blast furnace in 2022 entrenches a high carbon-emission technology for decades, which indicates that it can only reach a PTP if it accepts their latest blast furnace investment as stranded assets.

Our findings on company PTPs are also in line with developments in the socio-political, economic and industry environment (see Table 10). Regarding voestalpine and POSCO, we observe higher pressure in particular from policymaking on a national level, whereas BlueScope and U.S. Steel were confronted with national policy ambiguity, particularly after the Paris Agreement. These findings indicate that frontrunners are characterized by robust national policies, whereas for all steel companies, their decision-making is influenced by global climate goals and agreements. This is particularly pertinent as domestic steel companies operate within a global market landscape and in order to remain competitive need to align with global political developments. All companies except BlueScope also reported experiencing a customer demand to supply low-carbon steel. Within the industry regime, voestalpine and POSCO also experienced strong influences from regional steel markets and respective steel associations, where competitors drive the development of hydrogen-based production processes. In contrast, U.S. Steel and BlueScope do not experience that regional market pressure. Overall, we find that the companies that are exposed to higher pressure in their environments have progressed farther in their change process.

Finally, due to the pressures from the economic and socio-political environment, it can happen that companies reorient their strategy for single sites, which then reach a PTP. At the same time the company as a whole does not arrive at this transition stage. Therefore, in particular, the company's size is a critical factor. voestalpine is a comparably small steel producer (see Table 2) with two locations (and respective plants) in one country. In contrast, POSCO is one of the largest producers globally (see Table 2) with subsidiaries in 53 countries; hence, it has a much more leeway regarding how and where it can adapt first. Consequently, POSCO or U.S. Steel with multiple subsidiaries could reach a PTP at individual sites, while the company as a whole may not shift.

5. Discussion

Our results show that one out of the four companies is very close to reach a PTP which is defined by the company's investments that allow the company to move along a pathway to achieve net-zero emissions in the future by replacing (substantial parts of) old with new infrastructure. This one is voestalpine, which demonstrated their commitment to transition to adopting net-zero emission practices by instigating a concrete technology plan and making investments decisions that enable them to reduce their emissions by 30 %. POSCO is also nearing a PTP and has made significant progress in aligning their operations with low-carbon technology pathways. In contrast, both BlueScope and U.S. Steel have yet to make concrete decisions regarding their technology pathways and have not fully aligned their business conduct with the goal of achieving net-zero emissions.

Based on our case studies, we found that pressures from the policy environment and the customer demand for low-carbon steel constitute decisive exogenous factors in the company's reorientation process. The Paris Agreement served as a catalyst for change in the steel industry, but primarily national policies had a tangible impact on transforming companies. This is noticeable in the quality and frequency of sustainability reporting, which significantly improved in the late 2010s, when emission disclosure also became the new norm. Furthermore, the four companies responded to increasing normative societal and political pressures by specifying their climate commitments and setting mid- and long-term emission targets. Similarly, in a study of the UK steel industry, Geels and Gregory (2023) found, that increased decarbonization efforts in the socio-political environment exerted pressure on steel companies to switch technologies since 2015 and Brauers and Oei (2020) underlined that pressure from the EU can inject new impetus for change in the Polish coal industry. In our study, only voestalpine and POSCO outlined concrete net-zero strategies in response to the further tightening of climate targets and more stringent national (and EU) policies. In contrast, Australia's weak and erratic climate policies enabled BlueScope to remain in a holding pattern for decades while creating political legitimacy through business adjustments and announcements of early explorations of low-carbon technologies. Similarly, U.S. Steel has shown little action due to the absence of incentives or consistent pressures from the national government. Hence, the primary distinction lies in how national policies stimulate innovation and propel frontrunners, while global climate policy have a greater leverage by influencing producers who operate in a less stringent national policy context. This is particularly pertinent for catalyzing a macro-scale tipping point in the steel industry, which would be highly needed considering the current status of emission reduction targets among major steel companies worldwide (de Villafranca Casas et al., 2024). This observation also correspond to findings from Fesenfeld et al. (2022) who emphasize the importance of using politics to trigger tipping points by designing conditions that foster behavioural and technological change. In that regard, the introduction of a global climate club for steel that fosters transnational cooperation to overcome technical, economic, and political uncertainty could accelerate the transition on a sectoral level (Hermwille et al., 2022).

In addition, three of four case studies mentioned the customer demand for low-carbon steel as a main motivator for transitioning. This underlines the significant impact of implementing GHG emission regulations for end-users of steel, for example, mandatory emission reporting or the establishment of low-carbon steel markets, and constitutes a powerful lever for policymaking (Bataille et al., 2018; Kim et al., 2022; Muslemani et al., 2021).

When analyzing endogenous pressures, we found similar responses from companies. Those companies that take over a frontrunner role due to higher pressure from national policy frameworks are those that proactively shape the industry regime. For example, voestalpine and POSCO, who position themselves as technology frontrunners are those that rather influence the industry regime and therefore put pressure on other companies than being influences by the industry regime. This also holds true for industry norms and standards. The frontrunners participate and even drive forward the implementation of standards while laggards such as BlueScope and U.S.Steel only comply to them if it is ultimately necessary in order to maintain their reputation and competitiveness in the global steel market.

Additionally, the age structure of existing infrastructure can play a critical role in overcoming lock-ins within socio-technical systems. For instance, at voestalpine, certain blast furnaces need to be replaced by the year 2030 when reaching the end of their operational lifespan (voestalpine, 2023c). Indeed, most European steel plants are comparably old, while the bulk of global steel mills mainly located in China or India have only been installed in the 2000s and later (Vogl et al., 2021). Hence, concerns have been raised that the age factor will further delay the decabonization of the global steel sector (OECD, 2022). However, Vogl et al. (2021) found that the mitigation potential in the global steel sector is driven by the deployment pace of breakthrough technologies and the accessibility to renewables rather than by the lifespan of long-lasting capital. Furthermore, recent studies showed that, with the implementation of innovation policy and international cooperation in technology development, the transition of China's and India's iron and steel sectors can potentially be accelerated (An et al., 2018; Mallett and Pal, 2022; Yu and Tan, 2022).

Finally, our findings come with some caveats. First, the study was conducted during the invasion of Russia into Ukraine and the COVID-19 pandemic. Both crises had a disruptive impact on global supply chains and the energy system. Although our observations could not confirm that these events accelerated the transition within companies, caution in interpreting these results is required because, in hindsight, these crises could have led to significant pressures, pushing change within the company. Hence, continued research is necessary to map the trajectories of steel companies and observe PTPs by applying our definition within the steel sector or other hard-to-abate sectors (e.g., the cement industry). Further, our research explored new territory for empirically investigating PTPs relying on several qualitative and quantitative indicators. As we analyzed ongoing transition processes in steel companies, we were not able to proof a PTP by demonstrating a non-linear development in a relevant control variable. However, our findings contribute empirical evidence to the evolving theory of PTPs, while our methodology enriches the emergence of a standardized analytical framework (Lenton et al., 2022). Furthermore, in this study, we chose to exclusively utilize publicly available documents, particularly company reports, as we consider them to be a comprehensive representation of the entire company. Still, we encourage future studies to expand on our selection of case studies and indicators (including e.g. cultural factors and leadership changes) and consider in-depth qualitative investigations drawing on primary data (e.g., interviews) across long timeframes. Finally, this study focuses on supply-side tipping points connected to the switch of production technologies. Although, global steel demand is expected to increase in upcoming decades (OECD, 2019), future studies need to address potential demand-side tipping points in terms of reducing steel demand, and particularly in developed economies, and, therefore, directly avoiding CO_2 emissions in the steel sector.

6. Conclusions

This study explored PTPs at the company level in the global steel sector by empirically analyzing secondary data and using the Triple Embededdness Framework and Positive Tipping Point concept as a theoretical basis. Our research indicates that a company reaches a PTP when it decides to restructure their production processes by adopting low-carbon breakthrough technologies as a result of reorienting their vision. This decision unfolds along concrete net-zero technology pathways in combination with investments that enable the deployment of infrastructure for low-carbon breakthrough technologies.

According to this definition, voestalpine, a steel producer in Austria, is close to reaching a PTP with investment decisions made, whereas POSCO (South Korea) is also close to crossing one but is still missing substantial investments in the new technology pathway. In comparison, BlueScope (Australia) and U.S. Steel (USA) are lagging behind and have yet to decide on their concrete technology pathways or to align their business conduct towards net-zero emissions.

We found that while global commitments such as the Paris Agreement provide a necessary framework and momentum, national policies are critical to accelerate the transition towards low-carbon steel production for the frontrunners, voestalpine and POSCO. Based on this observation, we conclude that global climate policy wields greater influence over producers operating in regions with less stringent national policy frameworks. Therefore, the development of a global carbon club for steel could intensify transnational cooperation and enable a PTP in the steel sector. Moreover, the demand from customers for low-carbon steel can act as a driving force for innovation and encourage steelmakers to produce and supply low-carbon products. As such, the establishment of a market for green products need to be prioritized in policy-making.

Future research can add to our results by expanding the scope with more primary data, such as interviews, and by exploring the implications of demand-side strategies. Additionally, the approach developed for operationalizing PTPs can be extended to other hard-to-abate industries with similar network structures, such as cement, plastics, or paper and pulp.

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CRediT authorship contribution statement

Raphaela Maier: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. **Timo Gerres:** Formal analysis, Investigation, Supervision, Writing – review & editing. **Andreas Tuerk:** Formal analysis, Investigation, Supervision, Writing – review & editing. **Franziska Mey:** Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Case study descriptions

Each case study represents an interesting case due to its regional characteristics. Australia ranks among the top 30 major steel producing countries globally (worldsteel, 2022) and possesses significant reserves of iron ore (Australian Government, 2022). Nonetheless, the primary focus of steel production in the country lies in meeting domestic demand rather than actively contributing to the global market (worldsteel, 2022, p. 18). BlueScope, the largest steel producer within Australia, plays a pivotal role in fulfilling the nation's steel requirements. Austria has a long-standing history in the iron and steel industry, with iron

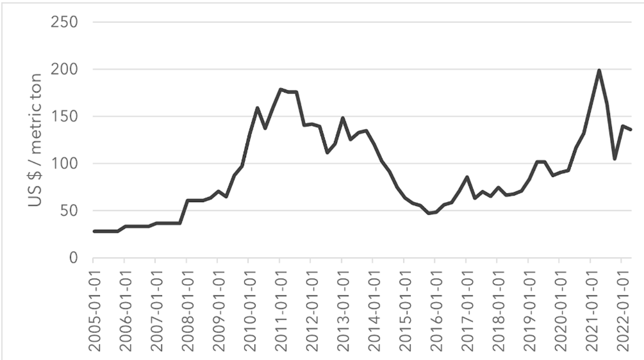

Fig. B1. Development of global wholesale iron ore prices from 2005 to 2022. Source: (IMF, 2023)

manufacturing dating back to the 11th century (Bamberger et al., 1995). Voestalpine is the largest iron and steel producer in Austria, operating six blast furnaces in the country and, therefore, contributing to almost 15 % of national GHG emissions (Umweltbundesamt, 2020). In contrast, South Korea has a rather young steel industry with the establishment of POSCO in 1973 sparking the crude steel production; this was the 6th largest steel producer in the world in 2022 (KOSA, 2023). Furthermore, South Korea has the highest per capita consumption of steel worldwide (worldsteel, 2022). The United States, despite being the world's largest economy, also exhibits a significant per capita steel consumption (worldsteel, 2022). However, this is in stark contrast to the declining state of primary and secondary steel production in the country, which ranks second worldwide as a net importer of steel (worldsteel, 2022, p. 26). Within the US, most companies concentrate on secondary steel production, such as Nucor, whereas U.S. Steel is the biggest primary steel producer (Swalec Caitlin, 2022).

Appendix B. Economic environment

In recent years, iron ore and metallurgical (met) coal prices[2] fluctuated strongly due to global economic recovery and supply chain disruptions. The supply chain disruptions due to the COVID-19 pandemic saw iron ore jump from 88 US$/ton in March 2020 to a record high of 215 US$/ton in July 2021 before falling back to 96 US$/ton in November 2021 and rising again to 160 US$/ton only five months later (IMF, 2023) (see Fig. B.1). Met coal prices followed a similar trend: low at the beginning of COVID-19 pandemic due to weak steel production and the Chinese ban on Australian coal imports (IEA, 2020c). In 2021, prices rose again as demand recovered and extreme weather events constrained supply (storms and floods in Australia, wildfires in Canada). Shortly before the Russian invasion of Ukraine in 2022, the price reached an all-time high of 658 US$/t (Australian low-volatile coking coal) (IEA, 2022b, p. 73).

In addition, transportation costs of raw materials are a determining costs factor. Freight rates have also been rising with the pressure on global logistics. Austria and South Korea import iron ore and met coal, while Australia and the US benefit from domestic mining. Until 2020 Europe mainly imported their coking coal from the US, whereas from 2021 onwards, more coal was imported from Australia (IEA, 2022b, p. 68). South Korea mainly imported from Australia in the last decade. Freight rates for overseas shipping on the Australia-Rotterdam route fluctuated between 4 and 16 US$/t until 2020, not including further transportation to the final destination and increased since 2020, peaked at the end of 2021 at 40 US$/t and decreased since July 2022 down to 12 US/t (IEA, 2022b, 2020c). Similarly, coal transport costs within the US were responsible for about 40 % of the final commodity price (EIA, 2020).

[2] Metallurgical (met) coal, which includes coking coal (hard, medium and semi-soft) and coal for pulverized coal injection (PCI) is a primary ingredient in steelmaking.

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2024.102846.

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