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Identification of barriers to decarbonise the German steel industry as a basis for a feasibility assessment

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ABSTRACT

Decarbonising the German steel industry requires not only mature low-carbon technologies, but also framework conditions that make their deployment feasible in practice. This study identifies the most critical barriers using a mixed-methods approach: 1) a systematic review of 42 publications and 2) semi-structured interviews with experts from all German primary steel producers. The review results in a comprehensive inventory of barriers associated with feasibility dimensions, which serves as a structured basis for the interviews. Experts weighted each barrier and highlighted the most important obstacles.

The resulting ranking by practitioners differs markedly from rankings inferred from literature, suggesting that frequency of mention may be a weak indicator of practical relevance. Barriers with high consensus and importance relate to energy costs and the long-term availability of low-carbon electricity and hydrogen, regulatory certainty (EU ETS, CBAM, support schemes), international competition with global overcapacities, and the creation of lead markets for green steel. Socio-cultural barriers appear comparatively minor in this sectoral context.

Methodologically, the study demonstrates a structured diagnostic approach: capturing the barrier landscape via literature, refining and prioritising through expert input, and translating top barriers into actionable indicators. The results provide policymakers and energy systems modellers with an empirically grounded, prioritised set of barriers for designing more realistic and feasible decarbonisation pathways for the steel industry.

1. Introduction

The steel industry is among the most energy- and emissions-intensive sectors. In Germany, primary steelmaking accounts for a substantial share of national greenhouse gas (GHG) emissions (6.6% in year 2023 (UBA, 2025)), while globally the sector is responsible for around 7% of anthropogenic GHG emissions (Rumsa et al., 2025). As a basic materials industry embedded in numerous value chains, steel production passes its carbon footprint on to downstream products such as automobiles, machinery, and construction materials (Rissman, 2024). Decarbonising steel production is therefore not only essential for achieving sectoral climate targets, but also a key prerequisite for deep emissions reductions across the wider economy. There are major challenges in this transformation process and the question of barriers to feasibility and how they can be systematically assessed is central for the implementation of effective solutions.

The German steel industry operates today under increasing decarbonisation pressure driven by climate policy, carbon pricing, and changing market expectations, while simultaneously facing intense international competition, volatile energy prices, and tight margins (Reuters, 2025). Steel is a systemically relevant material underpinning key industrial value chains and enabling core infrastructure, transport, and energy systems (IEA, 2020). In Germany, the sector supports several million jobs and a broad industrial base (WV Stahl, 2025a). Maintaining domestic production capacity may therefore contribute to supply chain resilience and economic stability (European Parliament, 2025), even though steel production itself relies heavily on imported raw materials such as iron ore. Navigating this tension requires investment decisions of unprecedented scale and irreversibility (Naujok et al., 2024). Hydrogen-based direct reduction (H2-DRI) is widely regarded as the central, technologically mature route to near-zero emissions in primary steelmaking, promising also to maintain industrial value creation and employment in Germany (Harpprecht et al., 2022; Rumsa et al., 2025). Alternative options—such as continued Blast Furnace (BF) operation with CCS, smelting-reduction concepts like HIsarna, iron electrolysis—are currently less technologically advanced or offer significantly

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lower mitigation potential than large-scale deployment of H2-DRI (Algers et al., 2025).

Despite technological readiness and ambitious policy targets, the pace of transformation remains insufficient to align the sector with national and European climate goals (Grigsby-Schulte et al., 2025). A wide range of potential barriers to decarbonisation is discussed in the literature and policy debate, including high and volatile energy costs, regulatory uncertainty, limited investment security, international competition, and constraints related to energy carriers and raw materials (e.g. (BMWK, 2023; Maschke, 2025; Senkpiel et al., 2025; Vogel and Bauknecht, 2025)). Socio-cultural and organisational factors, such as skilled labour force availability and internal change capacities, may further affect implementation (e.g. (Demary et al., 2024b; Gieschen et al., 2023; Senkpiel et al., 2025)). Together, these interlinked barriers can undermine confidence in future framework conditions and delay or prevent investment decisions.

Energy systems analysis and scenario modelling aim to support such high-stakes decisions by exploring possible transformation pathways under different technological and policy assumptions (Hanna and Gross, 2021). However, scenarios that insufficiently account for real-world implementation constraints risk to overestimate the speed and scale of industrial decarbonisation (Jewell and Cherp, 2023). Feasibility assessments address this challenge by explicitly focusing on the implementability of transformation pathways and the barriers that shape them (Shukla et al., 2022). A critical prerequisite for such assessments is a clear and empirically grounded understanding of which barriers are most relevant in a given sector and context (König et al., 2025).

For the German steel industry, no systematic and stakeholder-informed prioritisation of current decarbonisation barriers exists yet (cf. Section 2.2). Existing studies typically focus on individual aspects or provide qualitative discussions without a structured assessment of relative importance. This limits the ability of energy systems models and scenario studies to adequately reflect the sector's most critical implementation constraints. This article addresses this gap with two objectives. First, it aims to identify and prioritise the barriers currently hindering the decarbonisation of the German primary steel industry based on scientific literature and stakeholder perspectives. Second, it seeks to describe and demonstrate transparently the applied mixed-methods approach for systematically deriving and prioritising implementation barriers, thereby supporting more realistic and implementation-oriented energy systems and industrial transformation research.

Accordingly, the study addresses the following research questions:

1. Which barriers are currently perceived as most important in hindering the decarbonisation of the German primary steel industry?
2. What different prioritisations of barriers can be identified from a systematic literature review and from semi-structured interviews with stakeholders?
3. How can the combination of a systematic literature review and semi-structured interviews improve the empirical basis for subsequent energy systems modelling and policy analysis in order to increase the feasibility of the study?

The authors are convinced that the resulting methodological approach, decarbonisation barrier inventory and prioritisation have relevance for the energy systems modelling research community and for stakeholders in policy and industry. While the analysis focuses on the German primary steel industry, the proposed approach is designed to be applicable to other energy-intensive sectors and national contexts.

The remainder of this paper is structured as follows. Section 2 gives insights in current literature. Section 3 describes the methodological approach. Section 4 presents the empirical findings and the conclusions drawn from them. Section 5 discusses these results in a broader context, and Section 6 concludes by reflecting on their implications for both practice and theory.

2. Theory and background knowledge

This chapter situates the study within the current scientific discourse and clarifies its knowledge base. Section 2.1 introduces the concept of feasibility assessment and the specific component underpinning this work. Sections 2.2 and 2.3 summarise the state of research on decarbonisation barriers in the German and international context respectively, with the German perspective informed by the systematic literature review conducted in this study (see Section 3.1).

2.1. Conceptual foundations of feasibility assessment

Feasibility assessment was introduced by the Intergovernmental Panel on Climate Change (IPCC) in its Fifth Assessment Report (AR5) and applied in detail to all sectors in AR6, with the notable exception of the industry sector (IPCC, 2018; Shukla et al., 2022). A likely reason is the pronounced heterogeneity of industrial subsectors and regional contexts, which makes sector-wide feasibility assessments difficult to interpret. This challenge underlines the need for more context-specific feasibility approaches, such as the one pursued in this study for the German steel sector. In this context, feasibility assessment focuses on identifying and characterising drivers (enabling factors) and barriers (hindering factors) that shape the implementation of decarbonisation measures and pathways (Shukla et al., 2022). Feasibility is thus understood not as the solvability of an optimisation problem, but as the practical implementability of transformation pathways under given political, social, economic and environmental conditions (König et al., 2025).

To capture this broader understanding, feasibility assessments consider a wide range of influencing factors, which are grouped into six dimensions: economic, technological, institutional, geophysical, socio-cultural and environmental feasibility (Brutschin et al., 2021; König et al., 2025; Shukla et al., 2022). Each dimension comprises specific criteria that can either foster or hinder the feasibility of mitigation options and therefore requires transdisciplinary assessment approaches (König et al., 2025).

To structure this methodological diversity, König et al. (2025) propose the “*feasibility loop*”, an overarching procedural framework with five iterative steps, ranging from an initial analysis of the current and the future target situation to a detailed feasibility evaluation along the different dimensions. The present study focuses on the first step of this loop, which aims to establish the knowledge base for all subsequent stages by systematically mapping context conditions, transformation goals and constraints in the specific study setting (König et al., 2025). This includes clarifying the target situation, contrasting it with the current situation, and identifying the key drivers and barriers that shape the transformation between the two.

To date, there is no detailed and operationalised procedure for implementing this first step of feasibility assessment in practice, particularly for industrial decarbonisation. This study addresses this gap by applying a structured approach to identify, categorise and synthesise decarbonisation barriers in the industrial sector as a foundation for subsequent feasibility assessment.

2.2. Transformation context of the German steel industry

The German steel industry is currently caught between increasing pressure to decarbonise, driven in particular by the EU Emissions Trading System (EU ETS) (European Commission, 2025), and a strained economic situation characterised by high energy prices, global overcapacities and substantial investment needs in new technologies (WV Stahl, 2025a). As a basic materials industry, steel production is of fundamental macroeconomic and strategic importance (WV Stahl, 2025a). Accordingly, policymakers have signalled their ambition to support the sector's transformation and maintain domestic production capacity, as illustrated, for example, by the high-level political event

"*Stahlgipfel*" on steel decarbonisation held in 2025 (CDU, 2025).

Achieving decarbonisation targets requires long-term decisions at both political and corporate levels, which are associated with considerable uncertainty (Hanna and Gross, 2021; Shukla et al., 2022). Scenario studies using energy system models (e.g. Harpprecht et al. (2022)) aim to provide orientation for decision-makers under such uncertainty.

For the German steel industry, a range of information sources on decarbonisation and transformation is available, from academic and industry reports to policy documents, media coverage and consultancy studies (cf. Table 1). These heterogeneous sources yield a rather fragmented picture of the barriers currently prevailing in the German steel sector. According to the literature review conducted in this study, there is currently no scientifically grounded study that systematically synthesises this evidence, derives an integrated inventory of existing barriers and prioritises them in a transparent manner. This lack of a consolidated evidence base hampers the ability of energy systems modellers to address the most relevant implementation barriers in a targeted way.

2.3. From barrier identification to ranking: methodological practices in decarbonisation research

To situate our work within the broader global debate and exploit potential substantive and methodological synergies, we added a simplified review of international literature in this field. We applied a search strategy analogous to that used for German barriers (see Section 3.1), but restricted to English-language queries, without a German focus, and limited to Scopus and Google Scholar.

Across the reviewed international literature, a converging methodological pattern emerges for identifying and assessing barriers to decarbonisation across sectors and regions. The first group of studies relies on systematic or structured literature reviews to establish a comprehensive knowledge base. These studies collect and categorise barriers, often drawing on both peer-reviewed publications and grey literature such as policy reports and roadmaps. For example, Emodi et al. (2022) integrate scientific and grey sources to derive 36 barriers to clean energy investment in greenfield contexts, and Rumsa et al. (2025) review global iron and steel decarbonisation roadmaps to extract implementation barriers. Similarly, Das and Malik (2025) synthesise barriers to decarbonisation in India from academic and grey sources, while Faerber et al. (2026) analyse 273 publications on energy-sector innovation, extracting drivers and barriers from 64 key studies. Comparable sectoral reviews exist for hydrogen-based industrial decarbonisation (Griffiths et al., 2021; Jayachandran et al., 2024), pulp and paper (Joyo et al., 2025), basic materials industries such as steel and cement (Löfgren and Rootzén, 2021), global governance of energy-intensive industrial decarbonisation (Oberthür et al., 2021), net-zero transitions in supply chains (Singh et al., 2023) and near-zero emissions pathways in global iron and steel roadmaps (Rumsa et al., 2025). These reviews typically produce structured barrier inventories, sometimes complemented by frequency counts, but rarely provide context-specific rankings grounded in stakeholder evidence.

A second group consists of empirical, primary-data-based studies that identify and often prioritise barriers through interviews, surveys or focus groups. Bolz et al. (2024), for instance, use focus group workshops in a Northern German hydrogen region to deductively extract an innovation barrier category system from transcripts, assign decision levels, analyse controversy among participants, and assess the perceived importance of barriers for hydrogen technology adoption. Gao et al. (2025) conduct exploratory interviews to identify barriers to hydrogen-based decarbonisation in the Scottish whisky industry, resulting in a descriptive barrier set. Compared to pure reviews, such empirical approaches typically work with fewer barriers but generate fine-grained, context-specific assessments of which barriers matter most in practice.

Particularly relevant are hybrid designs that combine literature

Table 1
Comparison of the considered literature in terms of study type and sectoral scope.

Type of literature		Sources: Steel specific	Sources: Broader industry
Peer-reviewed publications		(Maschke, 2025; Wachsmuth et al., 2023)	Tholen et al. (2021)
Research reports		(Adisorn and Kobayashi, 2022; Agora et al., 2021; Aydemir et al., 2024; Köhnke et al., 2025; Küster Simic and Schönfeldt, 2022; Verpoort et al., 2024)	(Agora Industrie and Bertelsmann Stiftung, 2025;Bunde and Freuding, 2022; Caviezel et al., 2024; Cluster Dekarbonisierung der Industrie, 2025; Feld et al., 2025; Fraunhofer, 2024; Gieschen et al., 2023; Grimm, 2025; Mohnen et al., 2022; Raupach-Sumiya, 2024; Senkpiel et al., 2025; Vogel and Bauknecht, 2025)
Grey literature	**Newspaper reports**	(Hartbrich, 2023; Pitel et al., 2025; Spiegel, 2025)	(Euroforum, 2021, 2022, 2023, 2024)
	Reports from industry associations, consultancies and individual corporates	(Albrecht et al., 2022; Hönig and Zink, 2025; Naujok et al., 2024; WV Stahl, 2025b)	(BCG, 2021; BDI, 2024; Beland and Bolay, 2025; Demary et al., 2024a; Demary et al., 2024b; Fahrenholz and Farin, 2025; Goßlau and Hechelmann, 2024; Kraus & Partner, 2024)
	Governmental and intergovernmental publications	-	(BMWK, 2023; Wachsmuth et al., 2021)

reviews with stakeholder interaction. Hafner et al. (2022) review barriers and drivers of industrial decarbonisation in Switzerland and then use 17 semi-structured firm interviews to validate and rank the most relevant barriers. Mishra et al. (2023) integrate a literature review with semi-structured interviews and expert surveys to identify and prioritise barriers to adopting Industry 4.0 technologies for decarbonisation in the steel industry. Similar designs are found in Kuo et al. (2022) for electric vehicle transition, Ohene et al. (2023) for net-zero carbon buildings in Ghana, Gangadhari et al. (2025) for overarching industrial barriers, and Zhang et al. (2022), who combine a supply-chain-oriented literature review with interviews of first-mover firms to derive both a general barrier set and firm-specific rankings. Across these studies, a shared logic is visible: a broad, literature-based barrier inventory is constructed for completeness, which is then refined and ordered through stakeholder-based weighting or ranking procedures. Hybrid approaches thus combine the strengths of both methods by maintaining the comprehensiveness of systematic reviews while generating context-specific rankings that reflect perceived barrier relevance in practice.

Across energy, industry, buildings, transport and supply chains, a methodological consensus emerges: barriers are first systematically identified and structured via literature reviews (often including grey literature) and then empirically validated and prioritised through stakeholder-based methods. The present study explicitly builds on this consensus by combining a systematic barrier inventory with stakeholder interaction to derive a context-specific, ranked set of decarbonisation barriers.

3. Methods

The mixed-methods approach enabled a triangulation of perspectives from academic literature and industrial practice (Flick, 2009), thereby ensuring that subsequent feasibility assessments in energy systems modelling are based on empirically grounded and practitioner-validated insights. The German steel industry serves as the case study for this analysis. In Fig. 1, the overall study context is defined using the 5W1H method adopted by König et al. (2025). This context specification determines both the scope and structure of the literature review and the design of the interviews.

3.1. Systematic literature review

The systematic literature review identifies and categorises existing barriers to the implementation of industrial transformation scenarios in Germany. The review was conducted in August and September 2025. Approximately 450 search results were initially considered, of which 42 studies were ultimately deemed relevant and analysed. The overall process of literature identification, screening, and selection is depicted in Fig. 2 as a PRISMA-based flowchart (Page et al., 2021) and is described in more detail in the following sections.

3.1.1. Search strategy for the identification of literature

The literature search aimed to capture a broad and policy-relevant evidence base on barriers to the decarbonisation of the German steel industry. Both peer-reviewed and grey literature were included, following Adams et al. (2017), who define grey literature as material published outside traditional academic peer-review processes. This was necessary because many practically relevant insights on industrial transformation are documented in research and industry reports, association papers, policy documents and consultancy studies rather than in academic journals.

The review targeted studies that address barriers to decarbonisation in the German steel industry, complemented by analyses of the wider German industrial sector to allow for comparison across sectors. The literature search was restricted to documents published from 2021 onwards. This time frame was selected to ensure that the review reflects the most recent policy developments, market conditions and regulatory frameworks relevant to industrial decarbonisation in Germany, including both the current and the previous legislative period. Literature written in German or English were considered.

Scientific and semi-academic literature was searched using SCOPUS,[1] Web of Science,[2] Semantic Scholar[3] and Google Scholar.[4] Grey literature was identified via Google Advanced Search[5] and by systematically screening the websites of key stakeholders, including major German primary steel producers (ArcelorMittal,[6] Salzgitter AG,[7] Stahl-Holding-Saar,[8] thyssenkrupp Steel[9]), relevant industry associations (e.g. WV Stahl[10], VDEh,[11] WSM,[12] BDI,[13] VDMA,[14] DIHK[15]), the federal economic ministry (BMWE and its predecessors BMWi/BMWK) ,[16] and selected consultancy and research institutes (e.g. IW and EY).

Based on an initial conceptual mapping, keywords were grouped into thematic categories and translated into German and English synonyms (Appendix 1). Keywords explicitly related to scenarios or modelling (e.g. "scenario", "pathway", "roadmap", "modelling") were intentionally excluded from the core search strings. This was done to avoid biasing the sample towards scenario and modelling studies and to ensure that the review captures a broader set of empirical, conceptual and policy-oriented work on barriers. Scenario-based studies were not excluded a priori; rather, they could enter the sample if identified through other, barrier-related keywords.

Platform-specific search strings were then constructed, adapting syntax and operators to each database; all queries are documented in Appendix 2. Across all platforms, a publication date filter from 2021 onwards was applied. Additional filters were applied to Google Scholar (disabled citation inclusions), Google Advanced Search (restriction to PDF files) and Semantic Scholar (exclusion of medical literature). For each database and search query, up to the first 50 results sorted by relevance were screened. This limit was chosen to keep the review workload manageable and to focus on the most visible and widely cited documents, which are likely to shape the current debate. If fewer than 50 results were returned, all available documents were considered. All collected references were subsequently merged into a single database and de-duplicated.

3.1.2. Screening of literature

The screening and selection of documents followed a multi-stage procedure designed to ensure both relevance and quality of the included sources, particularly in light of the substantial share of grey literature.

In a first step, all retrieved documents were screened on the basis of title, abstract (where available), and basic metadata. Given the prominence of grey literature in this field, particular attention was paid to assessing source quality. The CRAAP test (Currency, Relevance, Authority, Accuracy, Purpose) was used as a heuristic framework, especially for non-peer-reviewed documents (California State

[1] Weblink: https://www.scopus.com
[2] Weblink: https://www.webofscience.com/
[3] Weblink: https://www.semanticscholar.org
[4] Weblink: https://scholar.google.com
[5] Weblink: https://www.google.de/advanced_search
[6] Weblink: https://germany.arcelormittal.com/
[7] Weblink: https://www.salzgitter-ag.com/en
[8] Weblink: https://www.stahl-holding-saar.de/shs/en/home/
[9] Weblink: https://www.thyssenkrupp-steel.com/en/
[10] Weblink: https://www.wvstahl.de/
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[12] Weblink: https://www.wsm-net.de/
[13] Weblink: https://english.bdi.eu/
[14] Weblink: https://www.vdma.eu/en/
[15] Weblink: https://www.dihk.de/
[16] Weblink: https://www.bundeswirtschaftsministerium.de/Navigation/EN/Home/home.html

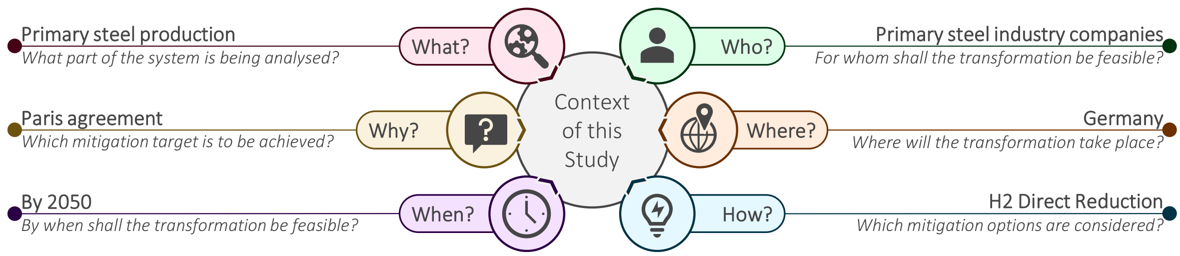

Fig. 1. Context of the feasibility study according to the 5W1H method as adopted by König et al. (2025).

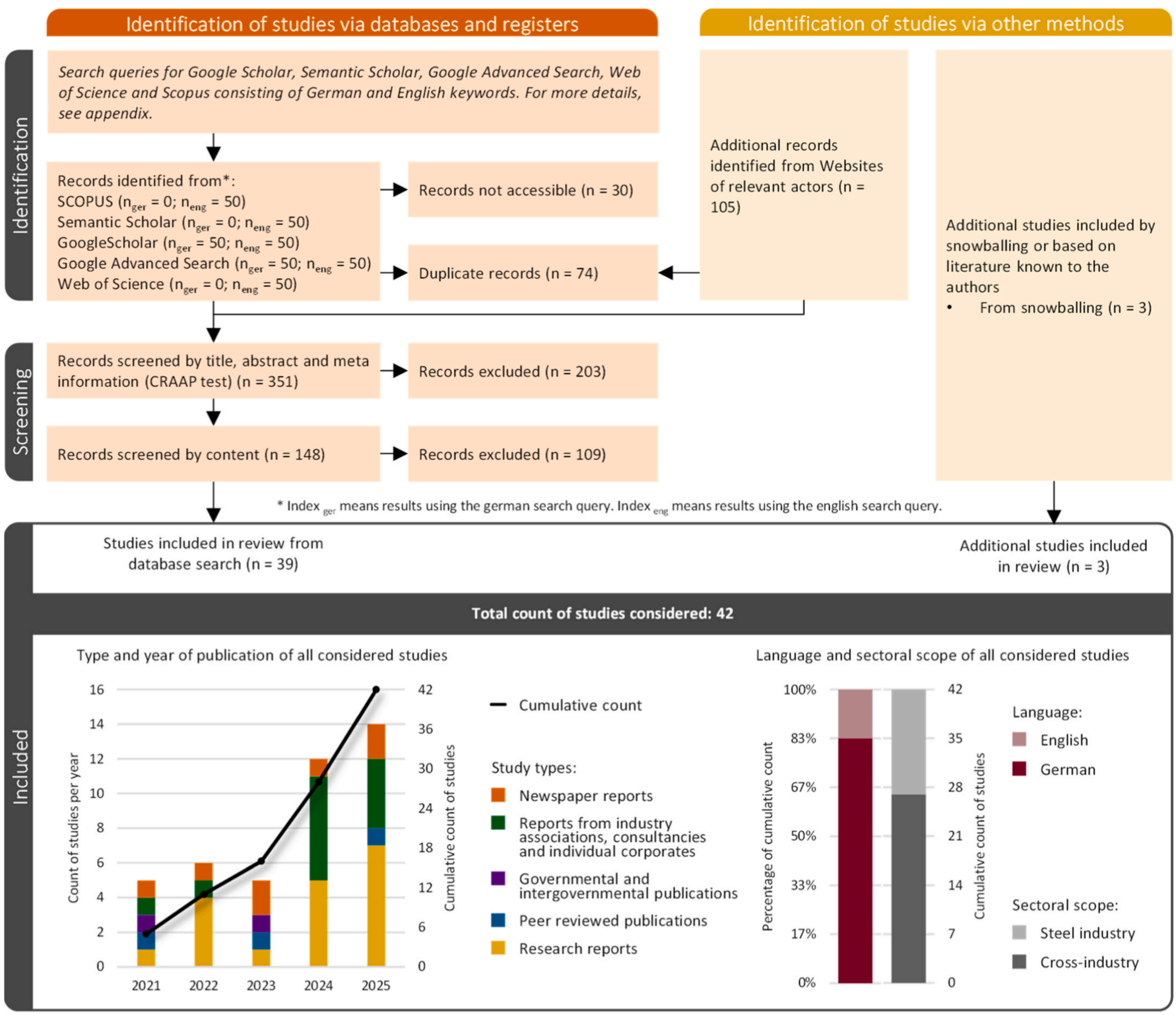

Fig. 2. Adapted PRISMA Flowchart for the systematic literature review within this study.

UniversityChico. Meriam Library, 2010). Sources were excluded if they clearly failed in at least one of these dimensions, for example due to the absence of publication dates, lack of identifiable authorship or institutional backing, or the presence of unverifiable or implausible claims. The CRAAP test was not applied as a formal scoring system but as a structured guideline to support consistent inclusion decisions.

This first step served to rapidly filter out obviously unsuitable or low-quality sources and thereby reduce the volume of literature to be examined in detail during the subsequent content screening. In addition, documents were excluded if they were clearly outside the conceptual or geographical scope of the study. Specifically, the following exclusion criteria were applied additionally to the ones provided by the CRAAP test:

- Pure technology specifications without contextual or systemic information

- No specific relevance to the German context
- Purely theoretical work without empirical or practical application
- Analyses of other industrial sectors without a clear link to either the steel industry or the industrial sector more broadly
- No discussion, analysis, or explicit mention of barriers to decarbonisation
- Low credibility or authority of the source

In a second step, all documents that passed the initial filter underwent a full content screening. Each source was read in detail to determine whether it contained information relevant to the research questions. At this stage, the content was not yet systematically analysed; rather, the potential usefulness of each document for the subsequent in-depth analysis was assessed. Both textual information and material presented in figures and tables were taken into account.

3.1.3. Analysis of included literature

After completion of the full screening process, the remaining 42 sources were systematically examined for barriers to the decarbonisation of the German industrial sector.

The subsequent content analysis followed a multi-step procedure:

1. Extraction: All explicitly mentioned barriers were identified and extracted from the results sections of the respective studies. Also implicitly discussed issues were extracted. Each barrier mention was recorded and listed in a structured table.
2. Aggregation: Conceptually identical or closely related barriers across different sources were grouped and consolidated.
3. Mapping to feasibility dimensions: Each aggregated barrier was then mapped to the six feasibility dimensions and 34 subcategories defined by (König et al., 2025). This ensured a structured, theory-informed classification of the barriers and facilitated subsequent comparison and interpretation.
4. Synthesis: The final set of barriers was compiled into a comprehensive matrix that summarises all identified barriers, sorted by their frequency of occurrence in the literature and differentiated by feasibility dimension. This matrix forms the basis for the subsequent analysis and visualisation of the barrier landscape.

3.2. Interview design and rationale

Semi-structured expert interviews were conducted to complement the systematic literature review and validate the identified barriers against practical experience in the German steel industry. They served to contextualise and confirm literature-derived barriers from a practitioner perspective and to elicit a practitioner-based weighting of their importance. The interviews thus form a central element of a triangulated validation strategy (Flick, 2009), integrating theoretical insights with experiential knowledge.

3.2.1. Research design and interview format

The interviews were designed as semi-structured expert interviews (Kruse, 2015), following established principles of qualitative interviewing (Brinkmann and Kvale, 2018; Kuckartz and Rädiker, 2024a, 2024b). Methodologically, they drew on the problem-centred interview approach (Mayring, 2023), which combines an open, semi-structured format with a clear thematic focus. The openness of the format allows for unrestricted response forms and typically yields more honest, reflective, precise and nuanced statements than standardised questionnaires (Mayring, 2023). This format enabled both the exploration of complex organisational and technological challenges and a structured comparison across interviews. The combination of open narrative prompts and more structured questions reflects a principle of methodological pluralism in expert interviews (Bogner et al., 2014), balancing inductive exploration with deductive validation.

3.2.2. Sampling and recruitment

In total, six expert interviews were conducted with actors directly involved in the transformation of the German primary steel sector. Sampling followed a purposive strategy (Palinkas et al., 2015), aiming to capture relevant expertise along key decision-making and value-creation structures. All companies operating primary steelmaking sites in Germany (ArcelorMittal, Salzgitter AG, Stahl-Holding-Saar, thyssenkrupp Steel) as well as the German steel industry association (WV Stahl) were contacted and interviewed. In one case, a company was represented by two interviewees. As these individuals held different roles and responsibilities within the organisation, they were treated as distinct expert perspectives rather than duplicate organisational responses. Their interviews were conducted independently and showed no indication of coordinated answers.

Recruitment followed two channels: (1) direct outreach via existing professional contacts, and (2) initial contact through general corporate email addresses. In the latter case, companies internally designated a suitable participant, such that final interviewee selection was partly shaped by internal organisational processes. This access pattern is typical for expert research (Bogner et al., 2014). In all cases, interviewees had demonstrable expertise in decarbonisation strategies or strategic transformation planning.

3.2.3. Data collection and interview guide

All interviews were conducted online between October and November 2025. Each interview lasted between 45 and 90 min, which is widely recommended for expert interviews as it provides sufficient depth while remaining feasible for time-constrained participants (Bogner et al., 2014). The expected duration was communicated in advance to support focused yet comprehensive discussions.

The interview guide comprised eight thematic blocks and combined open narrative questions, deductive probes and reflective tasks. Interviewees were invited to reflect on the desired target situation of the German steel sector, including the expected technological pathway and the future location of key value-creation steps. This initial discussion served to establish a shared reference point for the subsequent barrier analysis, as barriers can only be meaningfully assessed in relation to a specified target situation. The approach also helped to open the interview with a constructive and future-oriented perspective, in line with solution-focused interviewing practices (de Shazer, 1988). This was followed by a more detailed exploration of problems and barriers, following an inductive–deductive logic inspired by qualitative content analysis (Kuckartz and Rädiker, 2024b). The guide thus enabled both the emergence of new themes and the systematic examination of barriers identified in the literature. The interview guideline was tested prior to interview conduction in a piloting interview in accordance to Mayring (2023). The final version of the interview guideline is provided in Appendix 4.

To support the validation and weighting of the literature-derived barriers, a visual representation of the barrier ranking was presented as stimulus material during the interview. Participants were asked to assess and prioritise individual barriers, thereby creating a practitioner-based ranking. The use of stimulus material is well established in semi-structured expert interviews, as it facilitates reflective comparison and structured evaluation (Bogner et al., 2014).

3.2.4. Ethics, transcription and data protection

All interviews were conducted in accordance with established standards of qualitative research ethics, including transparency, voluntary participation and informed consent (Brinkmann and Kvale, 2018). With explicit permission, interviews were audio-recorded.

Recordings were transcribed verbatim and the transcripts were lightly cleaned (e.g. removal of filler words, correction of repeated words) following the transcription principles outlined by Kuckartz and Rädiker (2024b). To ensure confidentiality, all personal identifiers, company names and sensitive project details were fully anonymised.

Data storage and processing complied with General Data Protection Regulation (GDPR) requirements (European Union, 2016) and institutional data protection guidelines. In line with these strict data protection provisions, results are reported only in aggregated form, preventing any attribution to individual companies or persons.

4. Results

This chapter presents the study's substantive and methodological results. Section 4.1 reports the findings of the systematic literature review, Section 4.2 the interview results. Section 4.3 synthesises both outcomes, compares them with existing literature and derives implications for energy system modelling and feasibility assessments, thereby clarifying the added value of the interview component.

4.1. Literature based decarbonisation barriers for the German steel industry

The systematic literature review yielded 42 relevant studies, listed and differentiated by sectoral scope and type in Table 1.

Fig. 3 presents the resulting barrier landscape. It lists all identified decarbonisation barriers and ranks them by absolute frequency of mention, distinguishing between steel-specific and cross-industry sources and assigning each barrier to a feasibility dimension following König et al. (2025).

The barriers display a heterogeneous distribution across three applied ranking indicators: (1) total count, (2) steel-specific count and (3) relative count, the latter indicating what proportion of all mentions stems from steel-specific sources. Each indicator produces a different ranking, suggesting that barriers are not equally critical across subsectors and that not all feasibility aspects are equally relevant for every industrial branch. The subsequent analysis therefore examines whether any of these indicators aligns with practical experience and is suitable as a ranking basis.

Fig. 3 also shows that no barrier is classified under environmental feasibility. In industrial practice, environmental impacts are mediated via other factors—such as regulation or social acceptance—which do appear in the list. Environmental feasibility thus acts as an indirect dimension, influencing implementation only through other feasibility dimensions. Accordingly, it is crucial that environmental impacts are adequately translated into regulatory frameworks to ensure sufficient effectiveness.

Socio-cultural barriers play a comparatively minor role in the industrial sector, as reflected by their mid-to low-level frequency in the literature (cf. Fig. 3), and rank even lower when considering steel-specific studies only. This suggests, that acceptance of industrial transformation is generally high among the public, customers, and within companies, while a shortage of skilled labour remains a challenge, albeit one that appears less pronounced in the steel industry than in other sectors.

Brief definitions of all identified and ranked barriers are provided in Appendix 3.

4.2. The interview results

This section presents the interview results building on the literature review. Section 4.2.1 synthesises perceptions of the current and target state of the transformation, while Section 4.2.2 analyses the stakeholder-based barrier ranking using a four-quadrant map of importance and consensus. Sections 4.2.3 and 4.2.4 further examine barriers with high importance and/or low consensus, providing detailed insights from the interviews.

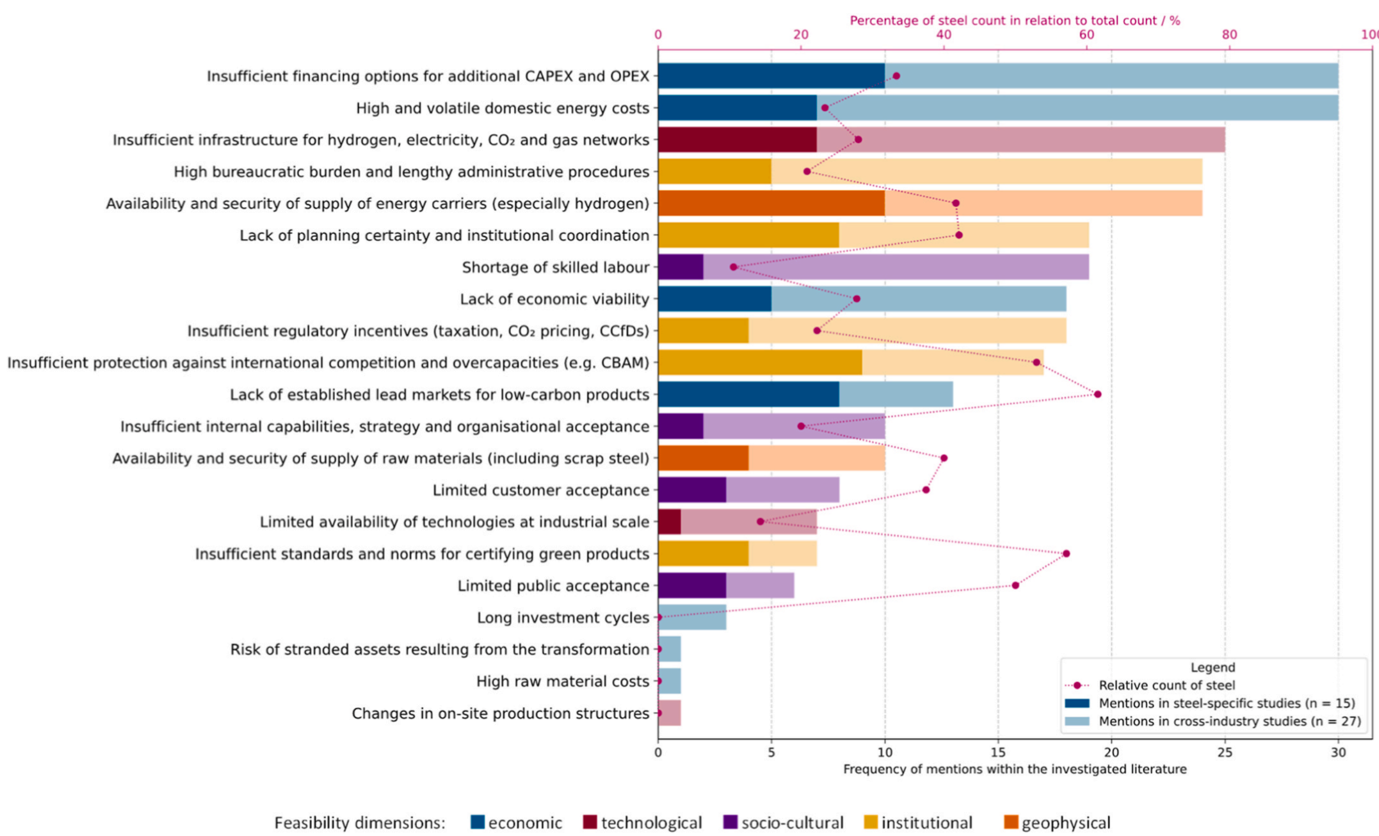

Fig. 3. List of all decarbonisation barriers, resulting from the systematic literature review, sorted by total count. CAPEX = Capital Expenditures; OPEX = Operating Expenditures; CCfDs = Carbon Contracts for Difference; CBAM = Carbon Border Adjustment Mechanism.

4.2.1. *The current and target situation*

The interviews reveal a consistent understanding of both the current and target situation of the transformation in the German steel sector. The target situation is driven by the EU policy framework, particularly the EU ETS, which increases decarbonisation pressure as free allocation is phased out by 2034 (European Parliament, 2022). Since the BF–BOF route is technologically optimised and offers little further mitigation potential, a technological shift is unavoidable. Hydrogen-based direct reduction (H_2-DRI) is consistently identified as the only commercially mature option with substantial emission-reduction potential, making a full transition to DRI operated with hydrogen the agreed target situation.

At the same time, several interviewees suggested that a diversified technological mix may be desirable in the longer term, as greater diversity is associated with higher system stability and resilience. One possible element of such a mix would be the relocation of direct reduction abroad combined with imports of hot briquetted iron (HBI). Here, views diverged: some interviewees regarded this as a plausible option, provided that a reliable global HBI market emerges, while others stressed the importance of retaining the full value chain in Germany. Despite these differences, there was broad agreement that downstream steelmaking steps, particularly those involving alloying and quality adjustment, and thus a substantial share of industrial know-how and value creation, should remain in Germany.

The current situation remains dominated by the blast furnace route, with only 0.1 Mt of 24.3 Mt pig iron production realised via direct reduction in 2024 (Worldsteel Association, 2025). While several large-scale hydrogen-based DRI projects have been initiated, notably µDRAL (Salzgitter AG, 2025), Power 4 Steel (Stahl-Holding-Saar, 2025) and tkH2Steel (thyssenkrupp, 2025), their implementation has recently faced delays and uncertainties (Steitz and Kackenhoff, 2025). In particular, ArcelorMittal has cancelled its planned DRI investments in Germany despite substantial public funding, citing unfavourable economic conditions (Reuters, 2025). These developments indicate that, although the technological transition has begun, its pace and scale remain uncertain and strongly dependent on the evolution of framework conditions.

4.2.2. *Relevant barriers from industries perspective*

To close the gap between the current and target situation, the interviews identified the most relevant barriers. A German version of Fig. 3 served as the discussion and ranking basis, with the “relative count” plot removed for clarity. Interviewees prioritised each barrier, which was assigned a weighting from 1 (low) to 3 (high), and also indicated their top three barriers. Fig. 4 shows the resulting ranking based on average weighting, with top-three nominations marked by stars as qualitative indication.

The weighted ranking of barriers derived from the interviews clearly deviates from the ranking based on the frequency of mentions in the literature, even if the top 10 selection has a large overlap. This suggests that all three literature-based indicators —*total count, steel-specific count*, or *relative count*—are not sufficient for a well-founded ranking of the barriers and, by extension, for identifying the most relevant aspects for further investigation. Methodologically, this finding can be explained by the lack of a consistent barrier list across the analysed literature sources, in contrast to the approach taken in the present interviews. In the literature, mentions typically relate to those barriers that are most salient within the specific focus of each study. By comparison, the interviews were conducted on the basis of a standardised and comprehensive barrier list, providing a uniform discussion basis. This allowed for directly comparable responses and the derivation of a more robust and meaningful ranking.

A literature review alone is therefore not sufficient to identify the most relevant aspects for analysis within a feasibility assessment. It

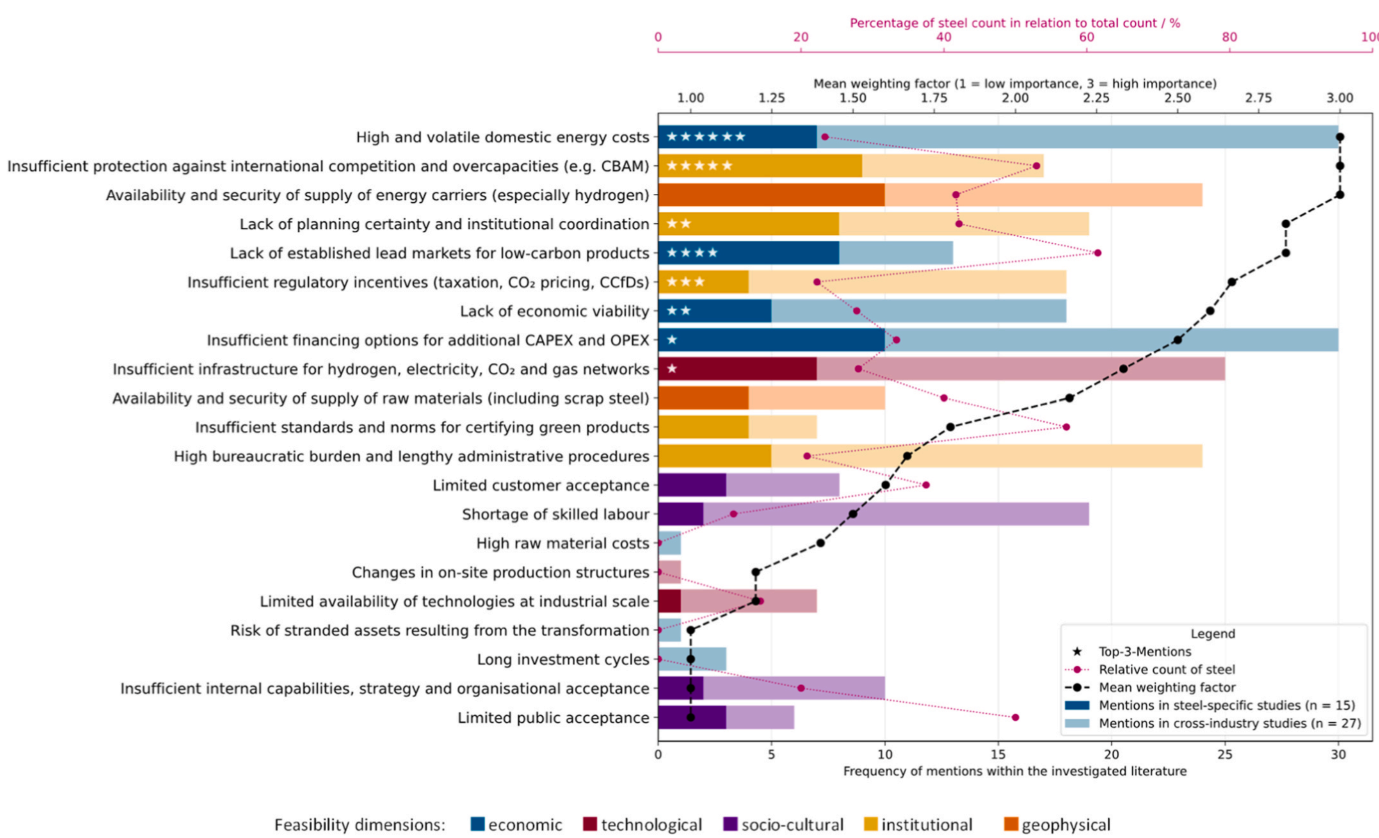

Fig. 4. Decarbonisation barriers of the German steel industry ranked by average weighting factor derived from the interview results. CAPEX = Capital Expenditures; OPEX = Operating Expenditures; CCfDs = Carbon Contracts for Difference; CBAM = Carbon Border Adjustment Mechanism.

requires a combination of both: a literature review that establishes a common basis for discussion, followed by stakeholder interaction to distil those aspects that are most relevant in practice.

To assess the degree of consensus among interviewees regarding the importance of each barrier, we use the statistical measure of variance σ^2. A low variance indicates high consensus, i.e., a broad agreement on how a barrier should be weighted, whereas a high variance signals low consensus.

Combining the two indicators—variance and mean weighting factor—yields Fig. 5, which positions each barrier according to its perceived importance and the degree of consensus among interviewees. Four quadrants are distinguished. The upper-left quadrant A contains all barriers that are rated as highly important with a high level of consensus. The lower-left quadrant C, by contrast, comprises barriers that are consistently assessed as having low importance and is therefore not examined in greater depth in the subsequent analysis.

The further a barrier is located to the right in the figure, the lower the consensus regarding its weighting. Their actual relevance remains less clearly established and therefore require closer examination, also reflected in the colour scheme of the figure.

4.2.3. *Critical high-consensus barriers: insights from quadrant A*

The quadrant A of Fig. 5 comprises those barriers that all interview participants consistently regard as particularly important. This strong empirical prioritisation aligns closely with the core political demands of the German steel industry, as articulated for example at the "Stahlgipfel" (WV Stahl, 2025c). These demands should not be read as pointing to a complete absence of policy action. Rather, they largely relate to policy fields already addressed by German and EU institutions, but which interviewees perceive as insufficiently aligned, reliable or effective in their current form. From the perspective of subsequent feasibility assessments, this quadrant therefore constitutes the logical starting point.

A key barrier is the markedly higher cost of electricity and hydrogen in Germany compared with international competitors. These prices substantially increase the cost of producing green steel and undermine the competitiveness of German sites. The announced industrial electricity price (BMWE, 2026) is viewed by interviewees as only partially effective, as it is time-limited and covers only a share of total electricity demand (WV Stahl, 2025d). They therefore call for: (i) a systematic analysis of the drivers of high energy costs, (ii) an international comparison of successful mitigation strategies, and (iii) a long-term, reliable concept for structurally reducing energy costs.

Closely related is the financing of the required investments. Both the literature and the interviews concur that the transformation cannot be funded by the steel industry alone. Existing support instruments are described as too fragmented, overly specific and insufficiently aligned with actual investment projects. In the absence of a robust support architecture, even technologically well-defined transformation pathways cannot in practice be realised.

Planning certainty is highlighted as an overarching precondition. Given the very long investment cycles in steel, stable policy frameworks extending beyond individual legislative periods are crucial. Interviewees emphasise, in particular, the need for reliable EU ETS rules, a predictable design and further development of CBAM, consistent national and European support schemes, and credible ramp-up paths for green electricity and hydrogen. The current design of carbon contracts for difference is likewise regarded as inadequate to effectively de-risk transformation investments in the steel sector.

International competition is seen as another central feasibility risk. Without effective trade defence, there is a danger that domestically produced green steel will be displaced by cheaper, CO_2-intensive imports. While CBAM is generally considered an appropriate instrument, interviewees stress that potential loopholes must be identified and closed at an early stage if it is to deliver the intended level of protection.

In addition, the interviews point to the current absence of a sufficiently developed market for green steel. Production-side subsidies alone are considered insufficient as long as public and private demand continues to focus primarily on conventional imported steel. The creation of national or European lead markets—through green public procurement, quota systems or voluntary market standards—is therefore called for by the stakeholder in order to establish reliable demand for low-carbon steel.

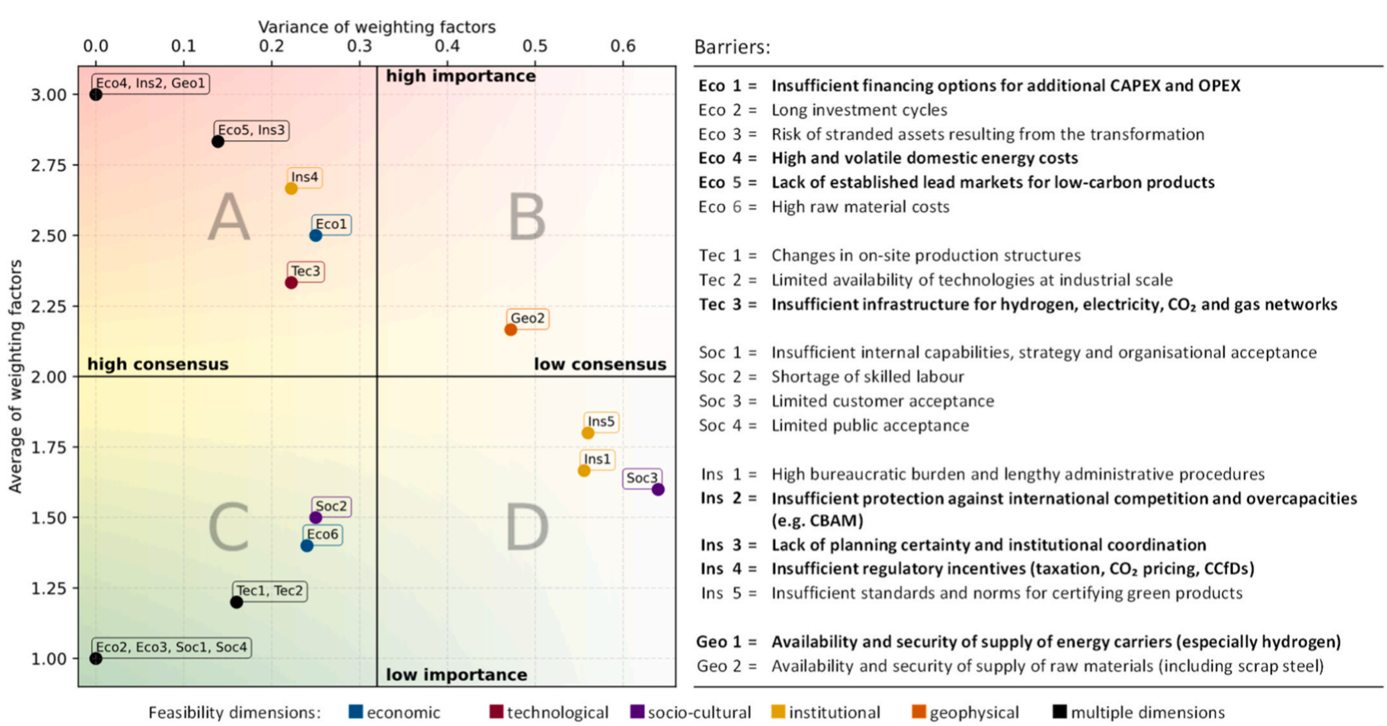

Fig. 5. Relevance of feasibility barriers for the transformation of the German steel industry, shown as position in a grid defined by value and variance of weighting factor. CAPEX = Capital Expenditures; OPEX = Operating Expenditures; CCfDs = Carbon Contracts for Difference; CBAM = Carbon Border Adjustment Mechanism.

Finally, energy infrastructure and hydrogen availability are described as tightly coupled key barriers. The development of an adequate hydrogen transport infrastructure remains unresolved in many regions, but is decisive for supply security. Sufficient volumes of hydrogen must be available at the required quality and in compliance with support scheme criteria. Particularly problematic is the linkage of funding schemes to actual hydrogen use: if infrastructure roll-out is delayed, committed funds cannot be fully or timely accessed.

Overall, the barriers identified in Quadrant A do not concern the technological feasibility of decarbonisation—hydrogen-based direct reduction is largely accepted as the target route—but rather the surrounding economic, regulatory and infrastructural framework conditions. The results indicate that these barriers are strongly interlinked: high energy costs, lack of planning certainty, inadequate support structures, an uncertain market ramp-up and an unsecured hydrogen supply mutually reinforce one another and cumulatively influence investment decisions. It is thus not so much individual factors as the consistency and reliability of the overall framework that determine whether transformation pathways for the steel industry are perceived as implementable. The high degree of convergence in interview responses also suggests that these barriers are understood as structural and sector-wide rather than site-specific. A central implication for future work is the development of suitable, measurable indicators for these barriers and their integration into energy and sector models, in order to enable robust assessments of the feasibility of transformation scenarios in the steel sector.

4.2.4. Context-dependent barriers: understanding low-consensus assessments in quadrants B and D

In contrast to quadrant A, the right-hand quadrants B and D comprise barriers whose importance is assessed very differently by the interview participants. This low level of consensus does not imply low relevance, but rather indicates strong context dependence in how these barriers are perceived.

A recurring pattern is that many of these barriers are shaped by firm-specific strategies and local conditions. This is particularly evident for raw material availability. Assessments vary depending on the chosen decarbonisation pathway and its technological configuration, including different combinations of DR, EAF, smelting reduction and continued BOF operation. As a result, the perceived importance of DR-grade pellets, BF-grade pellets, scrap and iron ore differs substantially across firms, reflecting divergent technological strategies rather than conflicting views.

Customer acceptance shows a similarly context-dependent pattern. While some firms report strong willingness to pay and clear demand signals for green steel, others primarily face price-driven customers with limited sensitivity to CO_2 performance. The relevance of this barrier therefore depends largely on the customer structure and existing supply relationships.

Differences in assessment are also pronounced with respect to bureaucratic requirements. Additional administrative and regulatory obligations are perceived as manageable by some firms, but as a significant obstacle by others. These differences are closely linked to internal capacities and organisational structures, as well as site-specific factors such as local permitting rules or environmental protection requirements.

Low consensus is likewise observed for standards and norms. In 2024, the Low Emission Steel Standard (LESS) emerged. It is initiated by the German Steel Association (WV Stahl) together with member companies and can be applied by steel companies to certify their green products (LESS aisbl, 2026). While the LESS standard is generally recognised as an important initial step, its current European scope limits its perceived relevance for a globally traded commodity such as steel. The dispersion in assessments reflects differing views on how critical the absence of internationally harmonised standards currently is, rather than disagreement about the importance of standardisation as such.

Overall, the barriers in quadrants B and D are best characterised as context-specific rather than sector-wide constraints. Their relevance depends on company strategies, location characteristics and market environments, which explains the observed dispersion in assessments. Unlike the high-consensus barriers in quadrant A, these issues do not point to uniform bottlenecks, but highlight heterogeneity within the sector and potential areas for further empirical investigation.

4.3. Synthesis and implications of the results

Methodologically, the findings highlight the complementary value of combining a systematic literature review with expert interviews. The review provides a comprehensive inventory of relevant barriers and structures the field of investigation, while the interviews largely confirm the comprehensiveness of this list. Only the lack of secured long-term energy supply contracts was added, integrated into the barrier of high national energy costs. Literature-based indicators, such as frequency of mentions, alone do not seem to allow robust prioritisation; a meaningful assessment of practical criticality emerges only through weighting by industry actors. The added value thus clearly lies in the combination of both approaches.

Substantively, the study consolidates and refines the existing literature. Core barriers to decarbonisation are generally known, yet a systematic consolidation for the German steel sector that links these barriers to a feasibility framework and validates them empirically with stakeholders has been lacking. A key contribution is the distinction between barriers with high consensus and structural relevance, and those with strongly divergent assessments, which primarily reflect company- and site-specific factors, such as strategy, business model or regional context.

Deviations from the literature mainly occur where cross-sectoral studies dominate. Bureaucracy and skilled labour shortages are weighted higher across industries than in steel, reflecting differences in firm size, labour intensity, and administrative capacity. Conversely, the availability of key technologies is perceived as a minor constraint in steel, due to long-standing experience with direct reduction. However, the interviews indicate that limited engineering and construction capacity, including specialised machinery, may become bottlenecks.

The results yield clear implications for energy system modelling and policy analysis. Framework conditions that stakeholders rate as highly important should be represented explicitly. These include, first, economic and regulatory parameters such as the level and volatility of electricity and hydrogen prices in international comparison, the design and reliability of support instruments, long-term regulatory pathways in the EU ETS and CBAM, and international trade conditions and CO_2 cost differentials. Second, demand and market mechanisms—such as lead markets, quotas, green public procurement and potential price premia for low-carbon steel—should be incorporated as explicit demand and price signals. Third, infrastructure pathways for electricity and hydrogen networks, storage and import infrastructure should be modelled consistently with support schemes, as delays in infrastructure roll-out can directly affect the effectiveness of funding programmes.

At the same time, the findings do not imply that German and EU policy fail to address these areas altogether. Rather, most of the highly prioritised barriers correspond to policy fields that are already the subject of active intervention, including carbon pricing (European Union, 2023a), CBAM (European Union, 2023b), hydrogen infrastructure planning (Bundesnetzagentur, 2024), industrial support schemes (BMWK, 2024) and emerging discussions on lead markets (European Commission, 2026). The interviews suggest, however, that the central deficit lies in the adequacy and coherence of the current policy mix. Existing measures are often perceived as too short-term, too fragmented, too narrowly designed or insufficiently coordinated to provide the level of certainty required for large-scale, irreversible investment decisions in the steel sector.

Beyond this, the findings sharpen the understanding of economic viability in the context of steel sector transformation. The interviews clearly show that “lack of economic viability” does not constitute an independent barrier, but the aggregate outcome of interlinked barriers. For this reason, it no longer appears as a separate barrier in Fig. 5. However, a competitive steel price remains the central objective for firms. Transformation pathways should therefore be evaluated not only for emissions reductions but also for resulting steel prices relative to international benchmarks and realistic willingness to pay. A pathway yielding non-competitive prices can only be deemed feasible if policy or market instruments close the viability gap.

Finally, the interviews emphasise that the steel sector, as a systemically relevant basic materials industry, should not be analysed in isolation. The potential macroeconomic and geopolitical consequences of substituting domestic production with imports are critical, particularly given dependencies on politically unstable supply regions and steel's key role in infrastructure, construction, healthcare, and defence. These aspects could be addressed in future by dedicated raw material risk assessments, building on recent work on material and supply risks, for example Schlosser and Naegler (2025) or Naegler et al. (2025).

5. Discussion: limitations and scope for future research

The findings align closely with international evidence. Rumsa et al. (2025) identify similar global barriers, including investment risks for low-carbon technologies, demand creation despite a green premium, weak policy signals, availability of renewable electricity and hydrogen, certification gaps, skilled labour shortages, and limited availability of DR-grade iron ore. However, there are deviations in the assessment of their relevance in the present study mainly concerning certification, raw-material availability, and labour shortages. Germany appears to benefit from the emerging LESS standard, skilled labour is perceived as less critical, and raw-material concerns show low consensus, indicating remaining uncertainty rather than universally acknowledged constraint.

A key contribution of the study lies in distinguishing between barriers with high consensus and structural relevance, and barriers with low consensus whose importance depends strongly on company-specific, regional, or strategic conditions. In this respect, low-consensus barriers partly reflect the inherent subjectivity of expert interviews, which may limit the evidential strength of the findings. To address this, the analysis makes subjectivity explicit by reporting the variance of weighting scores. This turns subjectivity into an analytical asset: variance distinguishes barriers that are widely regarded as clearly important or unimportant from those whose relevance is context-dependent and may indicate potential blind spots. The recruitment strategy further supported this aim by including at least one representative from each company engaged in primary steel production in Germany, thereby capturing an industry-wide spectrum of perspectives.

Methodologically, the findings highlight the value of combining a systematic literature review with expert interviews. The review ensured a comprehensive and structured barrier inventory, while the interviews validated and prioritised these barriers under current conditions. This is particularly important because barrier perceptions and policy debates are dynamic. Although the review was restricted to publications from 2021 onwards to ensure topicality, some temporal mismatch between the literature base and the 2025 interviews remains unavoidable. The findings should therefore be interpreted as reflecting the current transformation context rather than a time-invariant barrier structure. In this sense, the interviews not only validate the literature-based barrier set but also update it against current stakeholder perceptions in a rapidly evolving policy and market environment.

A related methodological question is whether similar results might have been achieved through interviews alone. While this is possible with regard to the final ranking, an interview-only design would have shifted the focus from systematic identification to practitioner-based prioritisation. The literature review was therefore important not only for completeness, but also for ensuring that the interviews were not limited to the barriers most salient at the time of data collection. The added value of the mixed-methods design lies precisely in this combination of breadth and contextual relevance.

Several limitations should nevertheless be acknowledged. The review was restricted to post-2021 publications, to 50 hits per query, and to the German context, which enhances topicality and relevance but may exclude foundational or lower-ranked studies. The CRAAP test was used as a heuristic rather than a formal quality-assessment tool. These limitations do not undermine the findings, but they should be borne in mind when considering their scope and generalisability.

The approach proposed here is conceptually transferable to other sectors and national contexts, as it follows a generic logic of barrier identification, stakeholder-based prioritisation, and feasibility mapping. However, its implementation depends on context-specific factors such as data availability, maturity of the literature, and stakeholder access, which may require methodological adaptations, including broader expert samples or additional data collection. Transferability therefore applies primarily to the overall design rather than to its exact implementation.

Future work should further operationalise feasibility assessments, e.g. based on the feasibility-loop framework (König et al., 2025), by deriving measurable indicators for prioritised barriers and embedding them in energy-system and sectoral models, enabling scenario analyses that link barrier configurations to decarbonisation pathways. Future research could also examine how barrier perceptions evolve over time, for example through longitudinal interview studies or repeated stakeholder surveys. In addition, barriers with high variance merit further investigation through qualitative case studies (e.g. firm-level governance or regional infrastructure constraints) and broader quantitative surveys.

Finally, future work should examine more explicitly under which economic, geopolitical, and supply-security conditions HBI imports might constitute a viable complement or alternative to domestic upstream production, and which stages of steel value creation are strategically important to retain domestically. This would also allow a more differentiated assessment of whether different configurations of domestic and imported upstream inputs weaken or potentially enhance resilience under varying geopolitical conditions.

6. Conclusion

In summary, this study consolidates and structures previously fragmented knowledge on decarbonisation barriers in the steel sector, empirically prioritises these barriers from a stakeholder perspective, and derives implications for energy systems modelling and energy policy. Using a mixed-methods approach that combines a systematic literature review of 42 relevant studies with semi-structured expert interviews comprehensively covering all German primary steel producers, the study identifies and weights key barriers across six feasibility dimensions. The comparison of literature-based and interview-based rankings shows that practical relevance cannot be inferred from frequency of mention alone. Barriers with high importance and consensus include energy costs, the availability of low-carbon electricity and hydrogen, regulatory certainty, international competition, and lead-market creation, while socio-cultural barriers appear comparatively less critical.

6.1. *Practical implications*

For energy and climate policy actors, this study offers a structured and empirically grounded picture of what currently hinders the decarbonisation of the German steel sector. It goes beyond a generic barrier list by (i) providing a stakeholder-validated prioritisation, aligned with the demands articulated in recent policy dialogues (e.g. the *Stahlgipfel*), and (ii) distinguishing between structurally critical barriers with high consensus and context-specific issues with divergent assessments.

Barriers with high importance and high consensus (Section 4.2.3) define the core agenda for policy action, particularly in five closely linked areas: (1) energy supply and costs, (2) financing structures, (3) regulatory certainty, (4) international competition and trade defence, and (5) lead-market creation. In contrast, low-consensus (Section 4.2.4) barriers vary strongly with firm-specific and regional conditions, indicating that uniform policy measures may be ineffective and that more targeted, flexible instruments are required.

Energy and climate policy actors can use this study as a reference for an indicative mapping of the most critical obstacles and as a scientific validation of the issues already prominent in the current policy debate.

6.2. Theoretical implications

The study advances feasibility and energy-modelling research in three ways. First, it demonstrates a concrete, empirically grounded approach to structuring the diagnostic phase of feasibility assessments by combining comprehensive literature mapping with expert weighting. Second, the quadrant-based representation of barriers (Section 4.2.2) refines the feasibility concept by systematically distinguishing between high-consensus, structurally critical barriers and context-dependent issues with divergent stakeholder views. Third, it translates sector-specific expert knowledge into a structured input for energy system modelling, providing validated framework conditions that should be explicitly modelled rather than treated as background assumptions (Section 4.3). This improves the empirical basis for energy systems modelling and policy analysis and supports the design of transformation pathways that are not only technically and economically sound, but also more likely to be feasible in practice.

Use of generative AI-assisted technologies

During the preparation of this work the authors used ChatGPT-5.1 as an assistant to content organisation and improving language and readability. Individual wording suggestions and recommended background knowledge from the AI tool were reviewed and edited before they were adopted so that the authors take full responsibility for the content of the publication.

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CRediT authorship contribution statement

Robin König: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Thomas Pregger:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing. **Stefan Kronshage:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing. **Patrick Jochem:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Robin Koenig reports financial support was provided by Federal Ministry for Economic Affairs and Energy. Thomas Pregger, Stefan Kronshage, Patrick Jochem reports financial support was provided by Federal Ministry for Economic Affairs and Energy. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2026.115373.

Data availability

The data that has been used is confidential.

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