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From waste to value? Valuation and materiality in geographies of industrial by-product use

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A B S T R A C T

Discussions about the environmental impacts of production and consumption are fuelling interest in strategies to transform industrial regions. While economic geography and regional development research extensively cover sustainable innovation and green regional development, innovation diffusion, demand-side aspects, and market emergence are often neglected. This paper illustrates how an enhanced valuation perspective that integrates materiality more directly helps to assess dynamic social processes of valuation in the case of low-carbon, resource efficient solutions. Through a path tracing approach, the paper assesses how two industrial by-products, slag sand and fly ash, evolved into highly valued secondary resources in Germany's Ruhr. Regional availability, market devices, and institutional work influence different dimensions of market valuation in waste-to-value processes. Insights on different phases of the development provide hint on how to organise and foster regional circular solutions. Findings may inform research and policy to advance emerging green industries, market creation for sustainable resources, and industrial decarbonisation, where the materiality of technologies and resources plays a key role.

1. Introduction

Adverse environmental impacts of production and consumption and strategies to address them, such as decarbonisation (Coe & Gibson, 2023) and circular economy (Bourdin et al., 2021; Bourdin & Torre, 2020), resonate with economic geography and regional development research, which deal extensively with green industrial development and green restructuring (Zhou et al., 2023; Fløysand et al., 2022). A closer look, however, reveals a notable emphasis on the emergence of eco-innovations (Hansmeier & Kroll, 2024; Hansmeier & Losacker, 2024) and regional green development (Jakobsen et al., 2021; Zhou et al., 2023) and less attention on innovation diffusion, demand side aspects, and markets (Rekers, 2016; Mazzucato, 2016). These topics are, however, crucial for creating resource-efficient and low-carbon regional economies (Flanagan et al., 2022; Jakobsen et al., 2021). This imbalance does not stem from a lack of analytical concepts in geography, as past research adopting a valuation perspective demonstrates.

The valuation perspective was adopted from neighbouring social sciences in the 2010s and deemed existing concepts, such as clusters and territorial innovation models, overly productionist (Jeannerat, 2013; Carvalho & van Winden, 2018). Consequently, the focus on economic valuation practices offered a suitable perspective to overcome the reduction of markets to black boxes (Berndt and Boeckler, 2011) and allowed to include markets and market actors more directly (Jeannerat, 2013; Beckert & Aspers, 2011). Today, there is a large corpus of research on valuation as a practice by which various market actors attribute value to goods or services.

Central aspects of valuation are often connected to non-technical, less-tangible characteristics of market objects such as authenticity, producer-consumer relationships, and their social status (Carvalho and van Winden, 2018). Research in geographical valuation studies, thus, shows a strong focus on status markets, and high-value commodities (Haisch and Menzel, 2022; Müller et al., 2021; Jeannerat, 2013). In status markets, technology and materiality are incorporated indirectly when they relate functionality to quality or authenticity. Status cannot be derived from the materials or compositions of materials from which specific goods are made. It is the result of processes comparing specific goods and their qualities (Ibert et al., 2019).

This article picks up Barad's (2003, p. 801) general criticism of the social sciences, "Language matters. Discourse matters. Culture matters. But [...] the only thing that does not seem to matter anymore is matter", that proves highly relevant in the context of climate change, biodiversity

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loss and other consequences of resource use. Responding to recent calls to re-incorporate materiality in economic geography (Njøs et al., 2024), I demonstrate how valuation studies can more directly integrate material concerns. In doing so, I align with Jeannerat's (2024) advocacy for a "new material geography in market valuation" by engaging in a reevaluation of research considerations in valuation studies in the field of economic geography that is necessary in the light of grand societal challenges.

To illustrate the benefits of a valuation perspective incorporating materiality, I assess the emergence process of low-carbon, resource-efficient solutions based on by-product utilisation. Using path tracing, I analyse two case studies from Germany's Ruhr region, where industrial residues like slag and fly ash have developed into valuable secondary resources for cement and concrete production. In both cases, utilising industrial by-products reduces primary resource use and CO_2 emissions. Analysing how value is established in markets highly influenced by the materiality of primary and secondary resources allows to better grasp valuation processes in the context of decarbonisation and circularity.

Two research questions structure the article: RQ1) What are the social mechanisms and regional dimensions influencing the evolution of residual materials into valuable resources? RQ2) How does materiality as a notion central to understanding the transformation of industries can be employed to broaden the valuation perspective?

Section 2 introduces central aspects of the valuation perspective in economic geography. Section 3 illustrates how the notion of materiality helps to enhance comprehension of valuation processes in low-carbon industries. Sections 4 and 5 describe methods and data acquisition. In Section 6, two case studies of waste-to-value processes exemplify the approach and illustrate how an extended valuation perspective helps to grasp current developments in circularity and decarbonisation. Section 7 discusses the findings and illustrates how a focus on materiality enhances research on valuation. Chapter 8 concludes the article.

2. A geographical perspective on valuation

In evolutionary economic geography (EEG), markets are often treated as external structures that producers and consumers passively respond to MacKinnon et al. (2019). Therefore, social processes that shape markets for innovation are still not fully understood (Uyarra, 2021). The valuation perspective facilitates an enhanced understanding of markets as "constructed, practically organised social or socio-technical mechanisms" (Flanagan et al. 2022, p. 1002) constituted by different agents, such as market actors and networks. Actors coordinate and mobilise resources to allocate a specific socioeconomic value to different market objects (Jeannerat, 2013), network structures facilitate cooperation and trust, and institutions reduce uncertainty and resolve coordination problems in the exchange of goods and services (Beckert, 2009; Flanagan et al., 2022). Valuation as a dynamic social process brings these agents together (Jeannerat, 2013). Markets are "constantly in the making " (Müller et al., 2021) as they are highly influenced by valuation practices. Understanding valuation processes, thus allows to understand how value is attributed to different market objects and the emergence of markets for new goods.

Jeannerat (2013) proposed three central analytical dimensions of market valuation that help to dissect valuation processes as processes of qualification and commercialisation in more detail: relational, conventional, and transactional value construction.

- The relational construction of market value is the process of qualification, wherein manufacturers, intermediaries, and consumers participate in qualifying a commodity or amenity through direct comparison with other commodities or indirectly by referring to market devices (e.g. certifications, standards and awards) as means of identification, acknowledgement, and recognition of market value.
- Conventional construction of market value involves aligning contractual principles within an institutional context that governs a specific market. This includes the assessment, experimentation, adaptation, and innovation of the institutional framework by the involved actors. Conventional market construction is therefore closely connected to institutional work (Fløysand et al., 2022), the "physical and mental effort aimed at affecting an institution or set of institutions" (Lawrence et al., 2011, p. 53), so the changing or bottom-up creation of regulative, normative, and cognitive institutions (Sjøtun, 2019).
- The transactional dimension concentrates on establishing equivalency regarding the market object, the monetary exchange for it, and other forms of transactions. It predominantly encompasses the commercialisation and commodification of a product or service.

Valuation is substantially embedded in institutional contexts: Market design, positioning of products in political contexts, societal values, and the existence of market devices play vital roles (Jeannerat, 2024). When a new good or service enters a social and economic system, actors must determine its worth, dangers and potential (Hutter & Stark, 2015). Valuation processes require information to reduce uncertainty. Here, market devices facilitate individual and collective action by providing comparability, signalling differences between market objects, and reducing cognitive deficits (Aspers & Beckert, 2011). The embeddedness of valuation processes in institutional contexts makes them highly place-dependent for some goods (Flanagan et al. 2022).

From this backdrop, a valuation perspective in economic geography is crucial as it underscores the negotiation and coordination of economic significance among producers, intermediaries, and consumers. This perspective highlights that the economic value of products is contingent not only upon production systems but also on the interconnections across various geographical, organisational, and institutional contexts and levels (Carvalho and van Winden, 2018).

In most cases, valuation is influenced by multiple levels. Actors may refer to various frameworks of valuation, some predominantly regional, while others are external yet adapted to local processes. International trade agreements, tariffs, and national policies influence how regional and non-regional goods are valued. This multiscalar nature is evident in geographical indications (GI), like Prosciutto di Parma and Champagne, which tie products and qualities to specific regions, are connected to international trade regulations, and, thus, impact the valuation of certain goods beyond their region of origin.

The place-contingency of different goods varies depending on the product type in question: standardised products are produced for global mass markets, and customised products often closely connected to local contexts, where they depend on territorially embedded symbolic meanings (Binz & Truffer, 2017; Jeannerat & Kebir, 2016). In this context, technical and experiential market valuation pose two contrasting models of valuation, closely connected to differences in regional economies: Technical market valuation is central for export-based manufacturing, where regional systems occupy strategic niches of production, while experiential market valuation is mainly relevant for service-oriented sectors such as leisure, entertainment and visitor-based activities, where the quality of goods and services is associated with the quality of the place where they are experienced (Jeannerat, 2013). In between these two, a third model, authenticity market valuation, is based on the coupling between consuming and producing milieus through connoiseurs, legitimising third parties and the control of the discourse about a product (Jeannerat, 2013; Jeannerat & Crevoisier, 2011). For high quality goods, this leads to a coupling with places (anchoring), where the place or region of production denotes certain qualities, such as aestheticity, reliability or specific taste in the case of Swiss watches, German cars or Cuban cigars.

Scholars analysing valuation from a spatial perspective have been particularly interested in status markets as opposed to standard markets. Standard markets rely on quality metrics to indicate a commodity's value, so individual relationships between market actors are largely irrelevant (Macneill & Jeannerat, 2016). Status markets comprise goods whose valuation processes are less objective, highly influenced by non-tangible criteria (e.g. taste, aesthetics, attention) and, therefore, by relationships between market participants (Ibert et al., 2019; Müller et al., 2021). Prominent case studies include the surfing industry, watchmaking, art, and fur trade (Carvalho and van Winden, 2018; Jeannerat, 2013; Müller et al., 2021; Haisch and Menzel, 2022). Most status markets are end-user markets, while producers and processors rely on standard markets (Aspers, 2005). This is why the better part of valuation studies in economic geography focuses on business-to-consumer relationships and valuation processes in end-user-oriented goods and services, often overlooking upstream activities.

Aspers (2005, p. 6) claims that "historically, the role of the material base has diminished, and symbolic meaning has become more important for value production. As a consequence, status is likely to be an even more frequently encountered principle governing social order in markets in the future". Amid concerns about resource use and consumption, this idea must be taken with precaution. In the past, innovation has been seen as increasingly disconnected from materiality and production, however, sustainability objectives bring these aspects back into the spotlight (Jeannerat and Crevoisier, 2022). Although *green products* may be traded on status markets, heightened awareness of the necessity to produce and consume in a more sustainable manner has led to a resurgence of interest in upstream activities and their environmental impact. Resources, product life cycles, and the material base gain significance (Njøs et al., 2024). Consequently, the symbolic value of *green products* is directly connected to the direct and indirect environmental impact of producers, processors, and basic industries' upstream activities.

In the context of resource efficiency, decarbonisation and circular economies, valuation is highly influenced by chemical and physical properties as well as by geography. While resources and commodities may be standardised concerning their quality, factors such as regional disposition and transportability lead to differences in availability, influencing valuation processes. Green solutions might be available in some regions (e.g. renewable energy or biomass), influencing territorial development (e.g. locational choices for battery or semiconductor production). However, especially for emerging sectors, sustainable resources are not ubiquitously available.

In addition to the availability of *green* resources, valuation processes for sustainable market objects are highly influenced by the territorial scale, especially due to regional industrial - or national defossilisation strategies, policies and international commitments that influence producers and demand on the national and regional scale (e.g. the EU's Carbon Border Adjustment Mechanism). Market institutions and quality conventions are pivotal in the systemic transformation towards sustainability as they aim to shape markets for green solutions (Jeannerat, 2024). Valuation practices for certain market objects are due to change because of controversies about "technologies, activities and qualities that should or should not be adopted" (Jeannerat, 2024, p.2). Following the idea of *(global) place-less standard markets* omits these aspects and their consequences for valuation processes.

3. (Socio)materiality in the valuation of 'green' market objects

The notion of materiality allows to bring together valuation studies and the impact of resource extraction and consumption. Materiality refers to a technology's intrinsic aspects, the "arrangement of an artefact's physical and/or digital materials into particular forms that endure across differences in place and time and are important to users" (Leonardi, 2012, p. 42). The materiality of an artefact, technology or resource can be separated from the sociomaterial context of usage. The term sociomateriality comprises the "enactment of a particular set of activities that meld materiality with institutions, norms, discourses, and all other phenomena we typically define as social" (Leonardi, 2012, p. 42). It describes the practices in which a specific technology is embedded (Orlikowski, 2007), reflecting an ontology of separateness where entities exist independently before and after their interaction (Orlikowski & Scott, 2008; Faulkner & Runde, 2012). Consequently, technological objects exist independently of their social positions and technical identities and once produced, become a part of the external world with all positive, harmful, intended, and unintended impacts (Faulkner & Runde, 2012). A pragmatic perspective, thus, promotes an understanding where "materiality depends entirely on the context and consequences" (Pentland & Singh, 2012, p. 287). Especially in a sustainability context, not only tangible properties but also non-tangible, physical properties connected to the production and use of resources or technologies matter, such as energy consumption or CO_2 emissions (Bansal & Knox-Hayes, 2013).

In previous geographical research on valuation, materiality is, at best, integrated implicitly, when functional qualities of a technology are considered. Due to the predominant focus on status markets that often means a shift away from physical or functional characteristics, its role is, however, rarely elaborated in-depth and consequences of materiality outside the valuation process in question are seldom reflected thoroughly (for a notable exception, see Müller et al., 2021).

Materiality is, however, crucial in understanding the environmental impacts of economies. The interaction between a technology's or resource's material properties and social context, such as institutions and market dynamics, significantly shapes valuation as a dynamic process. Territorial institutional contexts influence valuation by implementing policies to combat pollution (e.g., embargoes or technology bans) and promoting sustainable practices (e.g., tax exemptions or incentives). Changes in these contexts can lead to the re-evaluation of market goods, highlighting previously less relevant qualities of resources in valuation practices.

A focus on materiality, thus, facilitates the integration of embodied energy, carbon intensity and industrial decarbonisation as well as technology lock-ins in geographical research (Coe & Gibson, 2023). It is crucial for understanding regional transformation processes, as sustainability transitions are intertwined with existing industrial bases and influenced by infrastructure and resources (Zhou et al., 2023). Despite its marginal role in economic geography (Gibson, 2016, Swanton, 2013), materiality has been effectively integrated into research on waste, extractive industries or emission allowance trading (Gregson and Crang, 2010; Franz et al., 2018, Bansal and Knox-Hayes, 2013).

In this paper, I build on these three complementary perspectives of a) materiality as intrinsic properties that are b) relevant in specific sociomaterial contexts and c) matter due to the consequences they may cause. For this, I align these with the three dimensions of valuation (Jeannerat, 2013), see Table 1. Incorporating these perspectives into valuation research addresses challenges mentioned above as it allows to resolve issues related to geographical association and dissociation of production and consumption processes and their consequences (Jeannerat, 2024).

Integrating materiality and sociomateriality into market valuation research connects two analytical levels. It first considers how the physical and social contexts of market objects influence valuation. Material properties enable valuation by allowing to refer to market devices, such as standards, that aid comparability. Secondly, this approach examines the implications of technologies and resources within planetary boundaries. While inherent material properties remain constant, they are continually re-evaluated in social-institutional contexts, which leads to different outcomes in valuation processes across different territorial contexts.

Reintegrating materiality in valuation research, thus, allows for assessing valuation processes from a sustainability perspective without focusing exclusively on production. This complements research on eco-innovation by expanding the focus to include mechanisms of demand-making and market creation (Martin et al., 2019; Flanagan et al., 2022; Jakobsen et al., 2021). It offers an analytical perspective to enhance research on the geography of innovation and sustainability

Table 1
Integrating materiality perspectives and valuation dimensions (informed by Jeannerat, 2013, Jeannerat, 2024, Pentland and Singh, 2012, Leonardi, 2012).

Valuation Dimension	Underlying Valuation Practices	Role of Materiality
Relational	Qualifying a commodity or amenity through direct comparison with other commodities or indirectly via market devices (e.g., certifications, standards)	• Materiality enables direct comparison • Sociomateriality is the basis for the (re)interpretation of material properties in different contexts • Consequences of materiality are either recognised or externalised by market actors
Conventional	Aligning contractual principles within institutional contexts that govern markets.	• Materiality that endures across differences in place and time provides the foundation for the establishment of market devices (e.g. standards) • Sociomaterial contexts tend to prioritise specific material attributes, while market participants actively influence these contexts. • Consequences are (partially) acknowledged by institutional contexts (e.g. in the sustainability transformation).
Transactional	Establishing equivalency regarding market objects, monetary exchanges, and other transactions to convert symbolic value into market terms (commercialisation and commodification)	• Materiality is crucial for commodification and commercialisation • Sociomateriality governs specific transactions • Consequences of Materiality can be integrated into transactions through direct recognition (actors' pricing them in), indirect recognition by institutions (e.g., waste fees), or a combination of both (passing on costs)

transitions, facilitating insights into spatial factors relevant to the emergence of alternative resource use.

4. Methods

The regional utilisation of by-products has been frequently observed in geography since the late 19th century (Desrochers & Leppälä 2010). It is, however, still highly relevant today as industrial regions strive for energy- and resource efficiency. Therefore, assessing shifts in the valuation processes of industrial by-products necessitates a mixed-method approach: To understand the contemporary situation, an additional historical perspective is needed to grasp how spatial-economic configurations have evolved (Martin & Sunley, 2022). I analyse two case studies, the utilisation of ironmaking slags as well as the use of fly ash from coal-fired power plants.

The Ruhr, a densely populated and industrialised area in western Germany, offers itself for analysis: Historically significant for coal mining and heavy industry, the region transitioned into a diverse economic hub of industrial heritage, technology, culture, and innovation in the late 20th century. Today, various initiatives and industries advance industrial defossilisation, hydrogen-based solutions, and circular economy approaches.

This paper employs path tracing, an ideographic approach, to uncover mechanisms connected to the valuation processes of regional, secondary resource-based solutions. Path tracing, derived from process tracing, explores changes in "material and social worlds" (Sotarauta & Grillitsch, 2022, p. 5). As with process tracing, it can be used for historical explanation to identify mechanisms that influence processes "that have already occurred" (Mahoney, 2015, p. 202).

For this, it is key to distinguish between the larger process and underlying mechanisms (Yeung, 2019). Therefore, the overall shift in the valuation of two specific by-products (from waste to secondary resource) is defined as the process in question, while factors influencing, encouraging, or alleviating it are the underlying mechanisms. Following an analyticist understanding, mechanisms are conceptualised as distinct analytical devices, allowing the study of their impact within and generalisation across cases (van Meegdenburg, 2023).

To identify the different process stages and mechanisms that lie behind the shift in valuation that occurred in these two specific by-products, I sequenced historical events to identify subsequent developments influencing the larger process as proposed by Sotarauta and Grillitsch (2022). As change is most often a gradual transformation over a longer period of time, the main focus was on different phases of the process, the "identifiable and distinct period[*s*] between critical junctures " (Sotarauta and Grillitsch, 2022, 7). While this does not allow for a generalisation of the findings for other waste-to-value processes, it helps to identify key factors and conditions that also may apply partially in other cases.

5. Data collection

Data was collected in three steps. Firstly, 17 semi-structured qualitative interviews were conducted with representatives from the steel, energy, and cement industry (Table 2). Main topics were current and past developments in by-product distribution and utilisation. Secondly, archival documents such as contracts, internal strategy papers, correspondence, and industry handbooks from the late 19th century to the mid-1990s were analysed. Data was obtained in six visits to the ThyssenKrupp Corporate Archives (TkA), which preserve historically significant documents of the Thyssenkrupp Group, Germany's largest steel producer, and its former subsidiaries and holdings in the Ruhr. Thirdly, recent industry documents, including decarbonisation roadmaps and resource strategies were analysed.

This comprehensive approach provided a deep understanding of contemporary valuation processes and their evolution over decades. Inclusion of two cases allowed to not only grasp the development in a single sector but to generalise findings. Data was consolidated, chronologically sorted, and coded using MaxQDA. Analysing data along the three dimensions of market valuation (Jeannerat, 2013) provided insights into the valuation processes' evolution.

Table 2
Interviews conducted in 2022/2023.

Interview	Region	Sector	Role
CC1	Germany	Cement & Concrete	Association
ST1	Ruhr	Steel	Company
ST2	Ruhr	Steel	Company
FA1	Ruhr	Fly Ash	Company
FA2	Ruhr	Fly Ash	Company
RS1	Ruhr	Steel & Cement	Research
RS2	Ruhr	Steel	Research
RS3	Ruhr	Steel	Research
CC2	Switzerland	Cement & Concrete	Company
ST3	Belgium	Steel	Company
CC4	Germany	Cement & Concrete	Company
FA3	Ruhr	Fly Ash	Association
ST4	Germany	Steel	Association
CC5	Germany	Cement & Concrete	Company
ST5	Germany	Steel	Company
RS4	Germany	Steel	Research
CC6	Germany	Cement & Concrete	Company

6. By-product utilisation as a strategy to decarbonise cement and concrete-making

Cement and concrete production contribute significantly to global greenhouse gas emissions. Although alternative fuels address some thermal energy needs, chemical processes cause the majority (2/3rd) of CO_2 emissions, releasing up to 400 metric tons per metric ton of cement (Verein Deutscher Zementwerke e.V., 2020). To reduce environmental impact, the industry can replace shares of CO_2-intensive clinker with alternative cementitious components. Different cement types, such as Portland cement (CEM I), Portland composite cement (CEM II), Blast furnace cement (CEM III), Pozzolanic cement (CEM IV), and Composite cement (CEM V), vary in clinker ratio.

In recent years, market shares of CEM II and CEM III cement incorporating large shares of alternative resources have steadily grown (Fig. 1). Today, alternative cementitious resources comprise 19 % of the resources used in cement making (Verein Deutscher Zementwerke e.V. , 2022). A large share of these resources are industrial by-products like granulated blast furnace slag (slag sand) and fly ash, which are crucial in reducing the environmental impact of cement and concrete production.

The following case studies illustrate how these two industrial by-products emerged as alternative cementitious materials in the Ruhr and experienced a change in valuation from discarded industrial residues into highly valued, regionally traded resources.

6.1. Ironmaking slag: from residue to alternative cementitious material

Integrated steelworks convert primary resources into pig iron, which is later processed into steel. The most common technological route is Blast Furnace-Basic Oxygen Furnaces, which accounts for 70 % of global pig iron production (World Steel, 2023, p.1). In the process, iron ore, coke, oxygen, and other resources react under high temperatures, producing pig iron and non-ferrous slags. These slags solidify into lump slag or can be granulated into slag sand when rapidly cooled. Approximately 300 kg of slag originate in producing 1000 kg of pig iron (RS3), resulting in 7.6 million tons of blast furnace slags annually in Germany (FEhS - Institut für Baustoffforschung e.V, 2022, p.114). Steel producers cannot utilise these slags; however, the latent hydraulic material properties of granulated blast furnace slag make it a valuable alternative cementitious material.

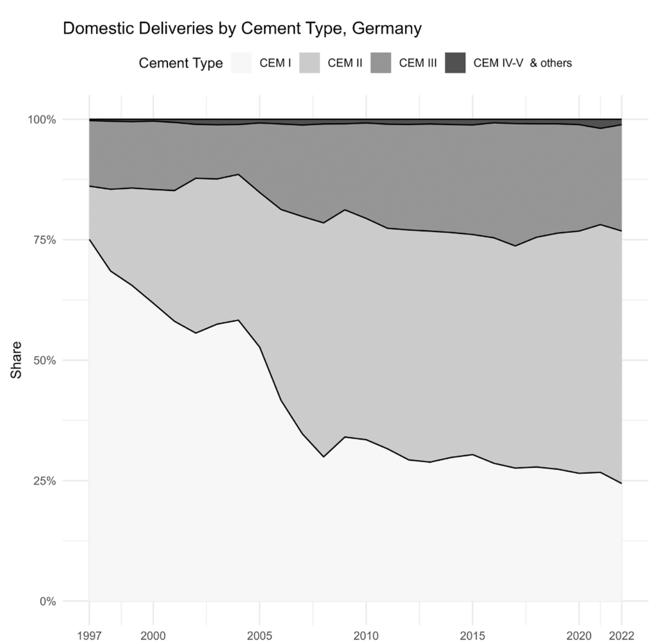

Fig. 1. Market Shares of the different cement types in Germany 1997–2022 (VDZ Data, own depiction[1]).

[1] Original data and data sources are indicated in the supplementary materials.

The first case study explores how once discarded residues evolved into a secondary resource in Germany's Ruhr, with a focus on Germany's largest steel plant of the Thyssenkrupp Steel Europe in Duisburg (formerly known as August Thyssen Hütte and Thyssen Stahl AG).

6.1.1. Disposing of industrial wastes

Slag sand has been used as an alternative cement-making resource since the late 19th century. Initial attempts to fully replace cement clinker with slag led to problems with structural integrity and durability. However, the first patents combining Portland cement clinker and slag sand paved the way for using slags. Two cement types, Portland Blast Furnace Cement and High-Slag Blast-furnace Cement, were developed to utilise steel production residues. The first cement mills in the Ruhr utilising slags were either operated by steelmakers or contractors in the cement sector (Bäume, 1948). First construction pilot projects using new types of cement acted as positive examples.

In this early stage, steelmakers encountered opposition from traditional Portland cement associations: *"When the slag cement industry was being established, the Portland cement industry initially only noted […] a competing product that would penetrate its market." (*Möllhoff, 1942*, p.1, own Translation).* As a response, they founded the "Verein Deutscher Eisenportlandzementwerke" (VEPZ) in 1901 and the "Verein Deutscher Hochofenzementwerke" (VHOZ) in 1907 as associations that advocated for, certified, and monitored slag-based cement. Their combined efforts led to the recognition of slag-based types of cement and the establishment of standards that proved the equivalence of slag-based cement with conventional Portland cement in 1917 (Grün, 1928). Despite these advancements, traditional cement suppliers resisted recognising new cement types to a full extent, engaging in practices that discredited alternative cement, withholding them from the market or selling them at lower prices (Bäume, 1948).

In this first period, ironmaking slag was initially qualified as resources for concrete making while pilot construction projects proved its viability. Although the materiality of slag initially posed a challenge for steelmakers, that had to dispose of it, its properties made it a viable resource for cement production. Market actors made salient that its material properties meant that it could easily be integrated in current production processes and proved this by initiating successful pilot projects. Changes in the conventional construction of value, in the form of early standards for its use, and the relational construction of value, in the form of first contracts between willing actors from the steel and cement industry, lead to an initial shift in the valuation of a material that was formerly seen as waste.

6.1.2. Commodification of by-products

In the first half of the 20th century, iron- and steelmakers and their associations strongly advocated for slag-based cements in order to counter the Portland cement industries reluctance to incorporate slag and their attempts to impede its distribution as they wanted to to safeguard their market shares. These associations for the distribution enabled a step away from the initial strategy of direct contracts with single cement makers towards commodification.

The associations' efforts to change the sociomaterial context were successful in 1932, when the newly introduced German cement standard (DIN 1164) incorporated the previously independed standards for slag-based cement (Verein Deutscher Zementwerke e.V. , 2002). In the following years, the production of slag sand-based cement in the Ruhr increased, as data from 'Vereinigte Stahlwerke AG', Germany's largest iron- and steel company at the time and a precursor to the Thyssen Stahl AG, shows (Bäume, 1948).

In the 1940's, steelworks in the Ruhr actively engaged with the national government to secure a conductive sociomaterial context for utilisation, presenting a variety of arguments for slag sand utilisation, such as technological advancement, logistical advantages, the proximity to markets and energy efficiency. In addition, the macroeconomic importance of the iron- and steel sector was highlighted and it was emphasised which challenges the sector would face if there were no large scale solutions to dispose of by-products (Möllhoff, 1942). During World War II, these arguments resided well with the national government, which led to political pressure on conventional cement producers to further incorporate alternative resources (Schulze-Fielitz, 1943).

After 1945, the slag-based cement associations merged with the Portland Cement Industries Association to form the 'Verein Deutscher Zementwerke e.V.' (VDZ), while slag research intensified with the establishment of the 'Forschungsgemeinschaft Eisenhüttenschlacken' (FEhS). Furthermore, Institutional support continued after the war: „Today, the production of slag-based cement is promoted by the authorities because it requires less electricity and coal" (Keil, 1949, p. 95, own translation).

Since the 1970's, iron- and steelmakers in the Ruhr actively progressed slag utilisation. While slag was in some cases still used to fill mining pits, decreased mining activity, growing by-product outputs and limited storage capacities led to challenges for slag disposal. This development was accelerated by the introduction of stricter waste management legislation in Germany in the 1970's, which lead to a search for solutions to dispose large quantities of slag and, thus, the extension of granulation facilities by the Ruhr steel industry (Ottenheym, 1972; Ottenheym, 1980; Thyssen AG, 1980). While lump slag had been the major form of distribution in the early 1970's, the decision to increase the share of granulated slag in order to distribute it as an alternative cementing material lead to slag sand distribution surpassing lump slag distribution at Thyssen Stahl AG in the following decades (Fig. 2).

From a demand perspective, this development was aided by challenges of the energy crisis in the 1970's. While primary resources needed thermal processing, slag sand offered latent hydraulic properties without the need for further thermal processing, which positively influenced valuation of slag sand in times of high fuel costs.

This second period encompassed a further shift in the valuation of slag sand. One important driver was institutional work by the steel industry and its associations that influenced the sociomaterial context and lead to the establishment of standards that facilitate slag sand use. This signified an important change in the conventional dimension of value construction. Concurrently, there were changes in the relational dimension, the comparison of different products with similar functionalities: In times of energy scarcity, the material qualities of slag sand as a resource for energy-efficient cement production were highlighted as being particularly beneficial and, thus, played a pivotal role when it was compared to conventional resources. As steelmakers invested into new granulation infrastructure to comply with disposal in an increasingly restrictive environmental legislation context, slag sand availability increased.

Although standards permitted the nationwide use of slag sand in cement production, its distribution and utilisation remained highly regionalised. The Ruhr region, with a concentration of steelworks and high demand for construction materials, absorbed the slag sand locally. Industry documents highlight geographical distance as a key factor, noting that regions without local steelworks, like southern Germany, had lower use rates and higher prices for slag sand (Phoenix-Rheinrohr, 1965).

6.1.3. Increasing demand for secondary resources

Even though the value of slag sand as a resource had been recognised by most actors in the late 20th century, there were still reports of reluctance among conventional cement- and concrete makers to use it. As vertically integrated companies owning the resources extraction sites for clinker production they profited from conventional cement production. In the early 2000's this changed, especially due to developments in the sociomaterial context:

> "Blast furnace slag based cements were initially a small area […] but the value of blast furnace slag and its utilisation in the cement industry has of course become increasingly important in recent years, because the issue of CO_2 has been recognised" (ST1, own translation).

Emerging debates about greenhouse gas emissions and the introduction of CO_2 emission allowances in the European Union increased demand for sustainable cement, particularly cement based on by-products (Fig. 1). The attribution of emissions to iron- and steelmaking processes implied that by-products could be considered CO_2 emission-free resources (FEhS - Institut für Baustoffforschung e.V, 2022).

Today, the Thyssenkrupp Steel Europe Mill in Duisburg, produces roughly 2,5 million tons of ironmaking slags annually, 1/5th of Germany's total slag output. Slag sand is utilised by local and regional cement makers, processed on-site, and partially exported to the Netherlands via the Rhine River (ST1). While lump slag was the leading segment until the 1990s, 90 % of blast furnace slags are now distributed in granulated form (FEhS - Institut für Baustoffforschung e.V, 2022). Slag sand, due to its virtually low-carbon materiality, has surpassed clinker in value (ST1).

While the demand for greener construction materials is growing, some obstacles remain, particularly in the institutional context, where restrictive tenders for construction still favour primary resource use in some cases (RS2, RS3).

In this third period, changing institutional contexts influenced the valuation process of slag sand, which is now seen as a valuable secondary resource. In the relational dimension of market construction, primary resources were devalued due to their negative material qualities (CO_2 emissions) while secondary resources emerged as valuable alternatives. The supposedly carbon-neutral materiality of slag sand proved highly relevant in the conventional dimension of market value construction due to an institutional setting that fostered low-carbon solutions. This also lead to changes in the transactional dimension as secondary resource use allows the mitigation of the costs for CO_2 emission allowances.

Currently, slag sand accounts for 18.7 % of the alternative resources used in cement making in Germany (Verein Deutscher Zementwerke e. V., 2022), making it the quantitatively most important alternative resource. The steel and cement industries work symbiotically together to find solutions to utilise future slags (RS3, CC2). This venture encompasses research on steelmaking slags from electric arc furnaces, which will play a vital role after the subsequent phase-out of current blast furnaces due to the decarbonisation efforts of the German primary steel industry, which aims to shift from coal-based ironmaking to hydrogen-based direct reduction (RS1, ST5, ST1).

6.2. Fly ash: from residue to binder in concrete-making

Coal-fired power plants emit non-combustible residues, leading to pollution in highly industrialised areas. To address this issue, regulatory bodies in Germany implemented policies requiring exhaust emission purification. Consequently, exhaust outputs must be filtered and captured ash must be discarded. As non-ignitable substances constitute up to 10 % of the hard coal used in energy making, large amounts of ash are produced in fossil energy generation. Power plants manage large quantities of these so-called fly ashes by selling them within about 200 km to cement and concrete makers (CC4).

In the following, I elaborate on how fly ash developed into a regional resource used as a binder in contemporary concrete-making. The analysis focuses on the Ruhr, with particular attention to the Gelsenkirchen Scholven hard coal powerplant, Germany's biggest of its kind.

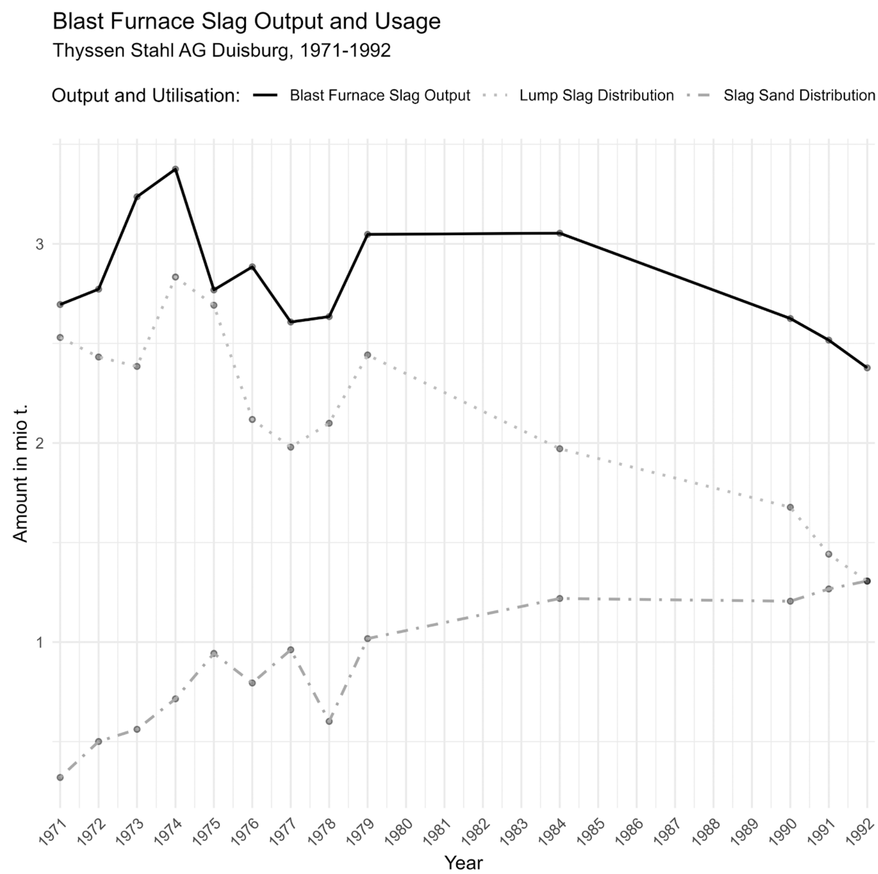

Fig. 2. Blast Furnace Slag Output and Utilisation at the Thyssen Stahl AG Plant in Duisburg, (own calculation based on TkA Data; missing values extrapolated[1]).

6.2.1. *Disposing of industrial waste*

Initially, fly ash, a by-product of coal-fired power plants, posed minimal challenges as it could be dumped in clay pits or was repurposed to mining mortar to stabilise colliery shafts (FA2). The first steps to utilise it for cement and concrete making occurred in the 1960s. By 1972, a firm in Marl in the Ruhr received building authority approval to distribute fly ash as a concrete additive. This approval legitimised and facilitated the use of fly ash in concrete making, overcoming initial resistance from cement makers who viewed it as waste:

> “So 1972 was […] the starting point for the industrial utilisation of by-products from coal-fired power plants. So everything that was already included in this technical approval back then is still valid today, although research and development over the years has of course added a great deal of knowledge and the positive properties of fly ash in concrete have become even, I would say even greater” (FA2, own Translation).

In this first period, waste mitigation was the driving mechanism. While the intrinsic material properties of fly ash posed challenges for powerplants, its latent hydraulic properties enabled its use as a binder in concrete, which was highlighted by successful industry projects. Conventional construction of market value in the form of a first building authority approval played a key role to enable by-product utilisation.

6.2.2. *Commodification of by-products*

During the 1970s and 1980s, the increased capacity of coal-fired energy generation in the Ruhr led to challenges in disposing of fly ash, especially for large powerplants like that in Gelsenkirchen, with an annual fly ash output of 800,000 tons (FA2). Economic and ecological considerations advanced its use as a binder in concrete, especially due to stricter regulations for deposition and growing societal environmental concerns:

> “From the 1970s onwards, we were first banned from landfilling. That was the reason why the […] coal-fired power plants were under a lot of pressure to do something positive with the residues: Because landfilling was simply not an option, the quantities were too large for that. And then of course you go into research and development and look at [its properties]: bulk good, constant composition” (FA3, own translation).

While by-product distribution in the Ruhr was initially managed by small enterprises, large energy companies and their subsidiaries took on the task and organised storage and distribution on a large scale in order to comply with environmental legislation (FA1). Investments in local fly ash silos and logistics at the Scholven Powerplant allowed to reduce dependency on the power plants’ seasonal running hours and, thus, volatility of supply (FA2).

In 1976, the coal-powered energy generation industry established a marketing association to promote the utilisation of its different by-products. The "Bundesverband Kraftwerksnebenprodukte e.V." (later WIN e.V.) represented the interests of by-product distributors and promoted by-product utilisation and the development of standards:

> "And then, of course, it’s about bringing the milestones [in development] into the standards bit by bit […]. That’s the essential thing, because the standard is the easiest way into the market, across the board, the same rules for everyone and not approvals only relevant for one company" (FA3, own translation).

Fly ash availability and demand grew through the 1970s and 1980s. By the mid-1990s, demand for fly ash outstripped supply, propelled by the German circular economy law and the introduction of fly ash as a standardised construction material in the European DIN EN 450 standard (FA3).

In this second period, changes in the regional economic system resulted in pressure to professionalise fly ash disposal and create infrastructures and markets. Fly ash was now a readily available secondary resource due to shifts in valuation in the relational and conventional dimension: Disposing actors founded an intermediary association that promoted fly-ash use, engaging in active relational construction of market value and institutional work, highlighting how its materiality was beneficial for construction projects in general as well as for very specific uses (e.g. acid resistant concrete). A sociomaterial context focused on environmental friendly solutions fostered its usage, and conventional construction of value was influenced by standards that enabled its widespread use.

6.2.3. *Increasing demand for secondary resources*

Today, 75 % of black coal fly ash is used in various concrete types, offering benefits like resistance to acidity, lower primary resource use and lower emissions (Lutze and vom Berg, 2008). The remainder is used in cement production, mining, or street construction. With the introduction of EU emission allowances and heightened societal awareness for CO_2 emissions, formerly disregarded solutions gain new attention. Methods like desiccating and processing already landfilled fly ash are now considered, reflecting an increased demand for fly ash as a binder:

> "I also see it in fly ash processing. You have to […] sieve, sift and dry the deposited ash, […] which is very energy-intensive. So we're working hard on this: how can we do this with other technologies? […] And we also see new approaches [in which] nobody was interested 15 years ago." (CC02, own translation)

The latest shift in valuation, from a by-product to a highly valued secondary resource, took place in a period of high demand for low-carbon resources. Already established markets gained further relevance in a changing institutional context. Here, international developments (e.g. EU emission allowances) influenced the valuation of regionally available by-products directly: From a relational value construction perspective, primary resources were devalued compared to secondary resources due to their materiality as a shifting sociomaterial context that promoted low-carbon solutions. Legislation promoting resource reuse played a key role from a conventional value construction perspective. Industry associations and researchers highlighted how utilising this readily available secondary resource is a contribution to a more resource-efficient and circular economy. Furthermore, the possibility to reduce costs for emission allowances influenced the transactional dimension. These developments lead to increased demand for fly ash as a regional secondary resource.

As Germany currently phases out coal-fired power plants, the availability of fly ash is steadily decreasing. The dissolution of WIN e.V. in 2023 reflects the challenge distributors face in sustaining costs (FA1). Despite the high demand for fly ash, long-term availability concerns require distributors to actively engage in relational market construction. Furthermore, concrete makers are exploring alternatives such as calcinated clay and other less CO_2-intensive pozzolans, recycled construction demolition waste, and carbon capture technologies to reduce emissions (FA1, FA2, CC2, CC6).

7. Discussion: (socio)materiality and spatiality in the dynamic social process of secondary resource valuation

Both waste-to-value processes were shaped by strategic firm decisions, institutional work by legitimising third parties (Jeannerat and Creviosier 2011), introduction of market devices, and, finally, driven by increased demand for low-carbon solutions. In this process, a variety of actors from suppliers and processors to third parties such as intermediaries engaged directly in standardisation, certification and demand creation processes or indirectly by reacting to key events or developments (e.g. energy scarcity) and, thus, influenced valuation practices.

Illustrating the key developments in both case studies along three key phases allows to answer which social mechanisms and regional dimensions influenced the evolution of residual materials into valuable resources (RQ1). In the first phase, producers play a central role, driven by the need to dispose of residues, due to factors like physical properties, quantity, and disposal challenges. The second phase involves intermediaries engaging in institutional work, fostering a conducive context where by-products become viable secondary resources. Sociomateriality, blending materiality with institutions and social processes (Leonardi, 2012) influences valuation practices. In the third phase, an institutional context emphasising resource efficiency and low-carbon solutions drives demand for secondary resources. Residues emerge as viable secondary resources due to different push and pull processes in changing institutional contexts. Valuation is based on different qualities directly connected to materiality (Table 3).

Today, secondary resources successfully compete with primary resources and are highly valued due to their positive material properties. Contrasting the by-product's properties with those of conventional resources that feature some inherently negative qualities (e.g., CO_2 emissions and energy consumption) qualifies their value. Consumers do not play an active role as co-developers in these innovations (Jeannerat

Table 3
Three phases of regional by-product valuation (own depiction).

Main Phase:	I. Initiation and pioneering	II. Market Creation for scaling	III. Increasing Demand
Driving Mechanisms	Process innovation for waste mitigation	Commodification, institutional work	Conducive environment for sustainable technologies
Key Actors	Disposers as Innovators & pioneers	Intermediaries advance certification & diffusion	Policymakers, consumers
Commercialisation	Contracts between the disposer and user	Commodification & regional markets	Commercialisation & cost reduction (EU ETS)
Quality of the Technology	Innovative disposal solution	Enhancing energy efficiency	Long-term sustainability: reducing environmental impact
Tensions	Non-conducive, incumbent-dominated environment	Incumbent resistance vs. material benefits	Institutional context as promoting and (partially) restricting
Sociomateriality	Approval of usage (standards & building authority approvals)	Market devices establish equivalency (specifications, certification)	Context of energy- and resource efficiency. Devaluation of primary resources due to their environmental impact
Materiality	Industrial residues: Intrinsic properties as a challenge (disposal) and solution (utilisation)	Viable by-products: Materiality ensures quality & equivalency.	Valuable secondary resources: Materiality of resources evaluated against future consequences
Central valuation Dimensions	Conventional & relational market construction	Relational & conventional market construction	Conventional & Transactional market construction
Spatial dimension	Local, small-scale reuse of residues	Regional commercialisation of by-products, radius restricted by materiality.	Regional markets in embedded in larger territorial context fostering sustainability

and Kebir, 2016) but advance demand for green products: Value cascades upstream from the final product (e.g. green buildings) along the chain of processors towards the initial material components and technologies used for processing these resources.

7.1. Materiality and spatiality interconnected: the case of secondary resource valuation

Materiality is an enabler and constraint within the three process phases, causing challenges for disposal, enabling utilisation or allowing certification and standardisation based on uniform material properties. Especially in the third phase, materiality can be best understood following Pentland and Singh's (2012) pragmatist perspective, which emphasises consequences in specific contexts rather than intrinsic physical properties. When actors determine the worth, dangers and potential of by-products (Hutter and Stark, 2015) materiality and spatiality are two highly influential aspects.

By-product valuation is highly influenced by spatiality. Slag sand and fly ash are inherently regional resources. They are not the main output of disposing industries; thus, their availability depends on global or national demand for the main products. Their economic feasibility originates from industrial processes already present in the region. Factors like transport and storage affect their valuation. In this context, fly ash and slag sand fit into the market logic of cement and concrete, which are regional products with a market radius of about 200 km (Dewald & Achternbosch, 2016). Even though the market radius of secondary resources extends in the context of a conductive institutional context that promotes energy- and resource efficiency, by-products are still additional output of processes aiming at the production of other goods (e.g. steel, energy), which circumvents upscaling their production.

While secondary resources in the construction sector follow (international) technical standards, they stand between customised and standardised products: The positive valuation of secondary resources is based on their material qualities in a specific institutional context (e.g. low carbon economies), and their territorially embedded symbolic meaning (e.g. sustainability as a specific quality of a good) (Binz and Truffer, 2017). Valuation is highly influenced by regional aspects, not because there is a direct coupling of producers and regions (as in some high status goods) but due to their regional availability as well as due to higher demand in certain territorial institutional contexts. The establishment of standards and other market devices enables national processing (as well as export or trading on international markets), which is why producers actively campaign for their introduction. While these standards create new opportunities for the distribution of by-products, their market range is still restricted by material properties (e.g. transportability, availability, seasonal volatility and long term supply security) that influence the relational dimension of market valuation (e.g. comparing it with other, more widely available resources).

7.2. Same dimensions, different mechanisms: specificities of secondary resource valuation

Jeannerat's (2013) relational, conventional, and transactional dimensions of market valuation help to analyse different aspects of the interplay between social and material factors in secondary resource utilisation. By-products are constantly re-evaluated based on their intrinsic properties, availability, seasonal volatility, transportability, and storability, which makes their use in certain contexts possible, impossible, or difficult (Leonardi, 2012). These factors, embedded in the sociomaterial context, influence the dynamics of by-product valuation.

In the relational dimension, referring to market devices and technical standards is pivotal to qualify alternative resources. Certificates, specifications, and building authorities' approvals legitimise and facilitate the use of alternative resources. Challenges occur in scaling up by-product output as production is optimised for main products and changes in demand for the main product (e.g. seasonality) restrict by-product availability. Producers adopt different strategies (e.g., investing in storage capacities or pooling sources) to counter this and engage actively in long-term relational construction of market value to alleviate supply security concerns.

Conventional market construction encompasses establishing or aligning equality principles within a market. Opposed to relational market construction, covering direct relations between market actors, it is connected to the institutional dimension that exists before and after individual transactions and is reinforced by those (Jeannerat, 2013). Initially met with resistance by some market actors, alternative resources gain legitimation through pioneering uses, standardisation and institutional work of intermediaries that enables the incorporation of secondary resources into existing commodity markets.

Transactional market construction for by-products differs significantly from that in conventional valuation processes. The compression of qualities of a market object into a price tag results in disembodiment from its physical representation, leading to practices of dissociation or externalisation of consequences (Bansal and Knox-Hayes, 2013; Ibert et al., 2019). By-products or secondary resources are, however, direct representations of consequences of production (e.g. waste). Their value derives not only from positive qualities but also from avoidance of consequences (e.g. waste deposition, emissions) and costs connected to these (Pentland and Singh, 2012). Besides monetary exchange, factors such as cost avoidance (e.g. CO_2 emission allowances, waste fees, fuel costs) play a major role. Sustainability-focused policies elevate their value, altering transactional dynamics (e.g. from disposer pays to recipient pays).

Overall, boundaries between disposer, producer, intermediary, receiver, and consumer relations are less clear-cut throughout valuation processes connected to circular production or resource reuse. Buyer-seller relations are dynamic, shifting between service provision (disposal) and commodity purchases (secondary resource processing).

All three dimensions of market valuation play a role throughout valuation processes and practices. Analysing the market entry of new (green) market objects or the re-evaluation of former by-products, however, shows that dimensions are of different importance in each of the three phases identified above: The conventional dimension is especially relevant for the establishment of new markets and their scaling, while relational market construction plays a role in addressing opposition by incumbent actors. In the context of territorial economies shifting towards more sustainable ways of production, changes in institutional context may also lead to shifts in the transactional dimension, so the establishment of equivalency between a resource and the exchange for it. Secondary resources are at some point valued more positively than conventional primary resources due to their environmentally beneficial qualities, surpassing conventional resources in value as the use of primary resources may lead to additional costs, for example for emission allowances.

7.3. Promising paths for future research

The two case studies offer initial insights into how materiality can expand the valuation perspective when it comes to understanding processes of decarbonisation and circularity (RQ2). In contrast to the much broader term of 'transformation', the notions of decarbonisation and defossilisation are inherently linked to materiality (e.g., fossil fuels or carbon). I propose for economic geography to follow this trend when it comes to assessing economic activity in the light of different planetary boundaries. Markets and especially processes of valuation, offer one promising focal point for future research, especially when we aim to better understand the spatiality of circular economy solutions (Davies et al., 2024).

Integrating concepts from the materiality discourse enriches the valuation perspective in the context of green innovation, socioeconomic market construction, and regional resource use. Moving beyond a mere focus on innovation, production and high-quality status goods allows to bring together research on valuation practices and market dynamics with research on decarbonisation and may, thus, enable EEG to engage with the often omitted aspects of market creation and demand (Martin et al., 2019; MacKinnon et al., 2019). This allows to connect economic geography research with the broader sustainability discourse, for example when it comes to the valuation of local ecosystem services. Furthermore, this approach allows to counter the dissociation of valuation and innovation processes from their consequences that may manifest on other scales, such as production processes causing globally relevant emissions (Jeannerat, 2024).

Looking at evolutionary economic geography in general, sharpening the understanding of how the valuation of certain innovations, technologies and resources in some regions may influence others, for example offsetting production emissions in Europe by investing in reforestation in Southern America or importing green energy carriers such as hydrogen. Sensitivity to materiality allows to engage with green as well as brown industries (Njøs et al., 2024). Finally and from a broader perspective, (re)integrating materiality may open up new avenues for research, for example on where materiality manifesting in the form of certain assets or infrastructures may influence inter-path dynamics (Frangenheim et al., 2020; Hassink et al., 2019).

8. Conclusion & outlook

The analysis reveals how a valuation perspective that incorporates the notion of materiality complements eco-innovation and green industrial development research by facilitating an understanding of processes such as valuation practices that influence market making, demand nurturing, and are directly connected to conducive institutional contexts for green innovation diffusion.

The two case studies illustrate how valuation processes of by-products can change over time, allowing the identification of key process mechanisms. In both cases, the shifts in the dynamic social process of valuation unfold in three phases, connected to one or more key events such as changes in policy, society or technology: initiation through waste mitigation, sustaining steady demand through market creation, and underpinning the growing demand through an environmentally sensitive institutional context.

These phases broadly suggest three distinct but converging approaches to organising regional circular economy solutions: a) bilateral contracts for reuse and recycling, b) commodification of regionally clustered surpluses, and c) market-based solutions in a policy environment that promotes resource-efficient solutions. While the first approach focuses on disposal, the second depicts secondary resources as regional solutions for enhanced energy and resource efficiency. The third approach nurtures the utilisation of sustainable solutions in general, which may lead to the emergence or strengthening of (regional or national) solutions. This results in different implications for policymakers: Reuse and recycling require standards and approval of use, commodification can be fostered by establishing equivalency with other solutions, while a conducive context less focused on the materiality of specific resources but on the long-term consequences of materiality may nurture existing markets.

While standardised goods are traded globally, by-products are regionally significant due to specific factors such as the regional industrial base, infrastructures, availability, transportability and a conducive sociomaterial context. Policies for resource efficiency and reduced landfilling, limiting or open tenders and strong incumbents, can either support or hinder by-product utilisation. Understanding regional dimensions is crucial to successfully scale innovations based on the recovery and use of materials in high-density, high-demand regions (e.g. recycling of construction-demolition-waste or urban mining). It is, however, equally important to note that developments on other scales (e.g. the international level) also have an important impact on these valuation practices (e.g. standardisation of certain solutions or CO_2 emission allowances)

The decarbonisation of energy and steel production brings challenges to existing by-product markets due to technological change. Nevertheless, findings on materiality and regionality may inform future research on evolving markets for sustainable solutions like bioeconomy, circular construction, and carbon capture and utilisation (CCUS). Here, a spatial perspective enriches debates on circularity and decarbonisation, revealing how the materiality and spatiality of solutions may affect neighbouring industries or offer vantage points for regional development strategies.

Further research in other industries, including the bioeconomy and agriculture, is needed due to the limited scope of this analysis. Investigating by-product and secondary resource utilisation beyond Europe, particularly in regions where informal networks play a key role and policy is less conducive to sustainable solutions, could further broaden the scope of understanding.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Deepl and ChatGPT in order to correct and improve the language of the paper. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Marius Angstmann: Writing – review & editing, Writing – original draft, Visualization, Project administration, Funding acquisition, Data curation, Conceptualization.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.peg.2024.100034.

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