How to build (in) a sustainable future? A multi-scalar perspective on the socio-technical transition toward a bio-based construction sector

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Abstract

The anthropogenic climate crisis is one of the most pressing challenges of our time. To limit negative consequences, reductions in CO_2 emissions must be rapid, and sustained, alongside large-scale adaptation and societal transformation. The construction sector is responsible for a significant share of these emissions and thus provides substantial opportunities for mitigation. Bio-based materials, such as cross-laminated timber and engineered bamboo, have the potential to transform buildings into carbon sinks. The socio-technical transition toward the widespread use of bio-based materials in the construction sector is still in its early stages and requires extensive societal changes, including the legitimacy of new construction materials.

In this dissertation, I examine the ongoing transition from a multi-scalar perspective, considering relations and interactions across multiple geographical scales. I analyze and compare the sustainability transitions in China, India, Germany, and Italy on a national level. The focus is particularly on India because its construction sector is expected to grow the most in the future and thus has high mitigation potential. Simultaneously, India is an intriguing case since it has several regions at the forefront of experimentation with bio-based materials and first large-scale demonstration projects. I analyze one of these regions, the greater Chennai area, which has a long tradition of using bio-based materials. Despite the potential of bio-based materials to transform the construction sector, their adoption depends on phasing out mineral-based construction materials such as cement and steel, as well as the socio-technical systems in which they are embedded. These systems are often reluctant to change. In this dissertation, I take the contestation that often shapes ongoing socio-technical transitions as my starting point, adopting an economic geography of sustainability transitions perspective.

I investigate how the future of the bio-based construction sector is envisioned across different countries and reveal various visions of contested directions a transition could take. To understand what constitutes a dominant vision, I conceptualize the legitimacy of visions as a key condition for them to be adopted and collectivized. Struggles over legitimacy emerge in transitions in-the-making, where transformative and incumbent configurations both compete. The contestation over institutional elements, leads to relations and interactions between emerging socio-technical configurations that shape the directionality of transitions. I explore this empirically for the field of sustainable construction materials and conceptualize interactions between emerging configurations. Based on a focused regional case study, I develop a framework that provides a multi-scalar perspective on the (de-)legitimation of bio-based construction materials in Chennai. The results in this dissertation reveal that although bio-based materials demonstrate transformative potential across countries, incumbents have thus far successfully constrained this transition by resisting changes to building codes and other established rules of the game.

Keywords: Geography of sustainability transitions, socio-technical configurations, legitimacy, visions, construction sector, bio-based materials

Zusammenfassung

Die anthropogene Klimakrise ist eine der drängendsten Herausforderungen unserer Zeit. Um die negativen Folgen einzudämmen, braucht es eine schnelle, dauerhafte Senkung der CO_2-Emissionen und einen tiefgreifenden gesellschaftlichen Wandel. Der Bausektor ist für einen erheblichen Anteil dieser Emissionen verantwortlich und bietet demnach großes Potential zur Einsparung von Emissionen. Bio-basierte Materialien wie Holz und Bambus können zu dieser Transformation beitragen und Gebäude langfristig zu Kohlenstoffsenken transformieren. Der sozio-technische Wandel hin zu einer breiten Nutzung bio-basierter Materialien im Bausektor steht jedoch noch am Anfang und erfordert weitreichende gesellschaftliche Veränderungen, wie die Legitimierung neuer Baustoffe.

In dieser Dissertation untersuche ich die Nachhaltigkeitstransition aus einer multi-skalaren Perspektive, um die Beziehungen und Wechselwirkungen zwischen unterschiedlichen geografischen Ebenen systematisch zu erfassen. Empirisch analysiere und vergleiche ich Transformationsprozesse auf nationaler Ebene in China, Indien, Deutschland und Italien. Ein besonderer Fokus liegt auf Indien, da dort künftig ein starkes Wachstum im Bausektor erwartet wird und folglich ein erhebliches Potenzial zur Emissionsminderung besteht. Zudem bietet Indien einen besonders relevanten Analysekontext, da verschiedene Regionen eine Vorreiterrolle bei der Erprobung bio-basierter Materialien einnehmen und erste Demonstrationsprojekte im großen Maßstab realisiert wurden. Eine dieser Regionen, der Großraum Chennai, wird in der Dissertation vertieft untersucht, da dort eine lange Tradition in der Verwendung bio-basierter Baustoffe besteht. Trotz ihres erheblichen Potenzials ist die breitere Diffusion bio-basierter Materialien jedoch davon abhängig, dass etablierte mineralische Baustoffe wie Zement und Stahl schrittweise substituiert werden. Das betrifft nicht nur die Materialien selbst, sondern auch die sozio-technischen Systeme, in denen sie verankert sind, die sich häufig sehr resistent gegenüber Veränderungen zeigen. Diese Herausforderungen dienen als Ausgangspunkt für die Analyse von Nachhaltigkeitstransitionen aus wirtschaftsgeografischer Perspektive in der vorliegenden Dissertation.

Dazu untersuche ich zunächst, wie sich Akteure in verschiedenen Ländern die Zukunft eines bio-basierten Bausektors vorstellen. Dabei zeigt sich, dass unterschiedliche, teils konkurrierende Zukunftsvorstellungen existieren, die verschiedene Transformationspfade bedingen können. Um zu verstehen, was eine dominante Zukunftsvision auszeichnet, konzeptualisiere ich die Legitimität von Visionen als eine zentrale Voraussetzung dafür, dass sie im Diskurs aufgegriffen und kollektiviert werden. Diese Aushandlungsprozesse von Legitimität vollziehen sich bereits in gegenwärtigen Transformationsprozessen, in denen transformative und etablierte Konfigurationen konkurrieren. Die Auseinandersetzung mit institutionellen Regeln und Normen führt zu Beziehungen und Interaktionen zwischen entstehenden sozio-technischen Konfigurationen, die maßgeblich die Richtung von Transformationen bestimmen. Diesen Aspekt untersuche ich empirisch im Feld nachhaltiger Baumaterialien und entwickle ein Konzept, das die Interaktionen zwischen neu entstehenden Konfigurationen sowie deren Wirkungen systematisch erfasst. Auf Basis einer regionalen Fallstudie wird zudem ein Rahmenkonzept erarbeitet, das eine multi-skalare Perspektive auf die (De-)Legitimation bio-basierter Baumaterialien im Großraum Chennai ermöglicht. Die Ergebnisse der Dissertation verdeutlichen, dass bio-basierte Materialien zwar länderübergreifend transformatives Potenzial aufweisen, ein erfolgreicher Wandel bislang jedoch von etablierten Akteuren begrenzt wird, insbesondere durch Widerstand gegen die Anpassungen von Bauvorschriften und anderen etablierten ‚Spielregeln'.

Schlagworte: Geographie der Nachhaltigkeitstransition, sozio-technische Konfigurationen, Legitimität, Visionen, Bausektor, bio-basierte Materialien

Acknowledgements

"The built environment is the elephant in the climate room, as it's responsible for 40% of global GHG emissions"
Hans Joachim Schellnhuber (FAO, 2021)

Während über die Klimakrise und ihre Auswirkungen viel diskutiert wird, spielt die gebaute Umwelt meist nur eine untergeordnete Rolle, obwohl sie eigentlich Elefant im Raum ist. Ich bin daher sehr dankbar, dass ich mich in den vergangenen drei Jahren im Kontext des Bausektors detailliert mit potenziellen Lösungswegen auseinandersetzen durfte. Die Möglichkeit, die Nachhaltigkeitstransformation hin zu einem bio-basierten Bausektor wissenschaftlich zu untersuchen und dazu in kleinem Rahmen beizutragen, hat mir große Freude bereitet. Die Forschungsarbeit war für mich nicht nur fachlich spannend, sondern hat mich auch persönlich sehr bereichert.

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Chapter One

1 Overview

1.1 Motivation

Human activities, particularly changes in land use and the burning of fossil fuels, caused the warming of the atmosphere and pushed the earth system into a period of rapid and widespread change. This warming is intensifying extreme heat, heavy rainfall, droughts and rising sea levels, and disrupting ecosystems worldwide. The risks are increasing sharply with every additional temperature increase (IPCC, 2022). Limiting these negative consequences requires rapid, deep and sustained reductions in emissions, alongside large-scale adaptation and societal transformation. This dissertation takes a multi-scalar perspective on the required socio-technical change in one of the most polluting sectors: the construction sector. Buildings account for at least 37% of global emissions, a considerable proportion of which is related to the embodied emissions of the materials used. Concrete and steel are responsible for 11% of global carbon emissions (UNEP, 2023; Zhong et al., 2021). To mitigate this impact on the ongoing climate crisis, the construction sector must inevitably reduce its reliance on mineral-based materials (Cabeza et al., 2022).

The most promising materials in this regard are bio-based, such as timber or bamboo, which could transform buildings into carbon sinks. This would mitigate the emissions of construction by avoiding production emissions from mineral-based materials and storing biogenic carbon in long-lasting building structures (Churkina et al., 2020). Careful planning and governance could make large-scale use of bio-based materials in the construction sector feasible, even without deforestation and biodiversity loss (Mishra et al., 2022). The success of bio-based materials, however, is intertwined with the phasing out of cement and steel in the sector (Jayaweera et al., 2023). In addition to these bio-based solutions, there are a variety of approaches that aim to continue relying on mineral-based materials while reducing or altering the energy used, using alternative binders, and incorporating recycled materials to some extent. While these approaches would mitigate emissions through adapted production processes and modified technologies, they imply less decarbonization than bio-based materials and only incremental socio-technical changes in the construction sector (Dewald and Achternbosch, 2016; Gibbs and O'Neill, 2015). Furthermore, introducing solutions that aim for incremental rather than transformative change can influence the direction of the transition by shaping which pathways attract investment, policy support and legitimacy (Smith and

Raven, 2012). Rather than assuming a single 'ideal' pathway, this dissertation explores low-carbon construction materials as a field of contested and partly overlapping directionalities, whose futures are actively negotiated (Stirling, 2011).

The literature on sustainability transitions explores how such a socio-technical transition happens or could happen in the future. It emphasizes that not only technologies need to be adapted but the entire institutional context and actor networks as well (Geels, 2004; Rip and Kemp, 1998). In this context the destabilization and phasing-out of conventional technologies need to be considered as well (Rinscheid et al., 2021). These processes have been incorporated by transition scholars into established conceptual frameworks that capture the complexity of transitions toward socio-technical change (Markard et al., 2012). Such a systems perspective is particularly relevant to studying the construction sector, where safety expectations, standards, public procurement, liability concerns, and fragmented value chains can stabilize incumbents and prevent innovation, despite the existence of better technical alternatives (Butzin and Rehfeld, 2013; Geels and Deuten, 2006).

In this dissertation, I rely on, refer to and ultimately aim to contribute to the intersection of the fields of economic geography and transition studies, which was recently laid out by Binz et al. (2025). Inspired by the work of Benner (2024) and Gong (2024), who both advocate for a forward-looking approach to economic geography, I adopt an economic geography perspective on sustainability transitions and their futures. This perspective is beneficial because it considers socio-technical transitions to be both geographically uneven and multi-scalar. What constitutes a viable or 'sustainable' solution in a transition, which actors can mobilize resources, and which visions dominate the discourse are all shaped by the geographical context, while being influenced by developments across geographical scales (Coenen et al., 2012; Hansen and Coenen, 2015). This theoretical perspective underpins the central premise of this dissertation: building *'(in) a sustainable future'* is not simply a matter of selecting the best technologies. Rather, it is a multi-scalar process of socio-technical change in which actors articulate contested visions of desirable futures, seek to legitimize those futures, and build or impede socio-technical configurations in the present. In line with transition studies' understanding of socio-technical configurations as coherent alignments of actors, institutions, and technologies (Miorner et al., 2026), I explore what constitutes 'configurations that work' in particular geographical contexts, while others remain fragile or contested.

India and China are among the most interesting cases for studying the socio-technical transition in the construction sector as they are expected to be the main emitters of future greenhouse gas emissions related to construction materials (Zhong et al., 2021). Thus, struggles over what constitutes an 'appropriate' construction material and what is financed, standardized and publicly supported have particularly far-reaching implications for the future of the sector and its climate impact. Thus, it also affects potential emissions that could be avoided in the future. At the same time, India and China are expected not only to generate the most emissions related to mineral-based construction materials, but also to demonstrate significant potential for transformative change in the sector. Bio-based construction materials, such as bamboo, are increasingly used and proven also in larger-scale demonstration projects (Liu et al., 2022; Manjunath, 2025; Yadav and Mathur, 2021). Whether such emerging configurations around bio-based materials can become 'configurations that work' depends not only on the technical performance of the materials, but also on how actors articulate desirable futures and build legitimacy across geographical scales. To broaden the geographical context, I analyze these aspects across countries, incorporating Germany and Italy alongside India and China. This enables me to capture the different contexts of the socio-economic, institutional and built environments. As taking a geographical perspective goes beyond comparing different countries, I further focus on a regional sustainability transition case in Chennai, India which exemplarily demonstrates the transformative potential of bio-based materials. The greater Chennai area hosts a diversity of bio-based materials and innovative approaches and technologies to assemble them (Kulshreshtha et al., 2020). At the same time, the region faces high urbanization pressure with a quickly growing built environment and a strong reliance on cement and steel (Kennedy, 2025). Thus, Chennai provides an interesting case to study the socio-technical transition toward bio-based materials incorporating both; a lot of potential and still strong resistance to change and development pressures.

Taken together, I aim to contribute to the economic geography of sustainability transitions and their futures by conceptualizing and empirically examining how visions, struggles over legitimacy and relations between co-existing configurations jointly shape the transition toward a bio-based construction sector. By comparing multiple national contexts and focusing on a regional transition case, I aim to provide grounded insights into how transformative configurations can gain or lose traction under uneven geographical conditions. Ultimately, I seek to advance our understanding of how sustainable construction futures are imagined, validated and enacted, and how these futures can be realized to reduce the construction sector's adverse impact on climate change.

This dissertation proceeds as follows. The theoretical background starts with elaborating what makes socio-technical configurations 'work' and by introducing the economic geography of sustainability transitions as the central lens for analyzing socio-technical transitions in this dissertation. Next, I will outline how struggles over legitimacy can form the conceptual hinge for understanding how socio-technical configurations evolve in the present and how transitions are envisioned to take place in the future. This is followed by developing the current state of research on such futures in sustainability transitions. Based on this body of research, I identify and describe the research objectives. In the next section on the methodology, I will briefly depict the empirical case of this dissertation, provide some context for the data used, and show how the methods are used to address the research objectives. Next, I will outline the research articles as well as their main findings. This overview of my dissertation will be concluded by the theoretical contributions, policy implications, limitations and potential for further research. The following chapters consist of four research articles that constitute the core of my dissertation. The articles each address different research objectives in non-chronological order. The order of these articles will be explained in section 1.3.

1.2 Theoretical background and research objectives

1.2.1 Socio-technical configurations that 'work'

In the context of global crises, central societal functions such as housing, mobility, energy, and water are under increasing pressure to adapt to changing conditions. The literature on sustainability transitions provides a perspective for understanding how "*established socio-technical systems shift to more sustainable modes of production and consumption*" (Markard et al., 2012, p. 956). Early on, these theories developed this as a 'problem of technological regime shifts' (Kemp, 1994), based on the niche-regime typology (Kemp et al., 1998; Rip and Kemp, 1998). Geels (2002, 2004, 2011) combined and advanced these frameworks to develop a multi-level perspective that views sustainability transitions as the reconfiguration of socio-technical systems consisting of three levels: niche, regime, and landscape. This still-prevalent dichotomy of a niche that emerges and, ideally, at a certain point, disrupts the socio-technical regime neglects the more complex dynamics at play when analyzing socio-technical change in a sector (Miorner et al., 2026; Runhaar et al., 2020).

A useful entry point is the concept of socio-technical configurations, i.e. coherent sets of actors, institutions and technologies. More specifically, the concept captures patterned alignments in which actor relations, institutional structures, and technological solutions are assembled, which addresses the internal alignment of configurations (Heiberg, 2022; Miorner et al., 2026). Importantly, configurations are not merely 'systems' in an abstract sense; they are historically built and maintained accomplishments that require ongoing coordination. A configuration 'works' when it delivers a societal function and can evolve over time (Rip and Kemp, 1998). This approach shifts the focus from novelty to viability: configurations work because their components are sufficiently aligned (Heiberg et al., 2022; Heiberg and Truffer, 2022a). In this sense, 'working' is not just a property of technology, but the result of ongoing alignment across three components that are mutually constitutive: *actors*, *institutions*, and *technologies* (Fuenfschilling and Truffer, 2016; Miorner et al., 2026).

Firstly, configurations rely on a variety of *actors*, including firms, industry bodies, public agencies, municipalities, intermediaries, researchers, financiers, civil society and users (Kivimaa et al., 2019; Rip and Kemp, 1998). Whether they align in configurations depends on coalition-building, resource mobilization and cross-organizational coordination rather than on isolated innovators (Heiberg and Truffer, 2022a). Actor constellations also hold competing ideas about desirable futures, which can guide investment and legitimation strategies (Hawxwell et al., 2024).

Second, *institutions* provide relatively stable ‘rules of the game’ that structure action and reduce uncertainty. Following Scott (2014) there are three pillars of institutions: regulatory, normative and cognitive. Formally codified and enforceable arrangements, such as laws, permitting procedures, and liability rules, define what is allowed and required (*regulatory*). Shared values and obligations, such as professional norms and expectations regarding appropriate outcomes and acceptable risk, shape what is considered legitimate or responsible behavior (*normative*). Taken-for-granted framings influence how actors define problems, recognize solutions and judge what counts as credible evidence (*cognitive*) (North, 2009; Scott, 2014). At the same time, these institutional structures are continuously reproduced, interpreted, and contested, making legitimation and institutional work central to why certain configurations evolve while others remain marginal (Fuenfschilling and Truffer, 2016; Lawrence and Suddaby, 2006).

Lastly, *technologies* entail “*all tools, machines, utensils, (...) and the skills by which we produce and use them*” (Bain, 1937, p. 860). In socio-technical configurations, this includes artefacts and infrastructures as well as designs and codified knowledge elements that are mobilized to provide a societal function. Technologies are not neutral carriers of functionality: they often embody specific types of knowledge and problem framings and can consolidate values and beliefs in a tangible form (Dosi, 1982; Nelson and Winter, 1985).

The socio-technical configuration lens also helps avoid overly clean and simple pictures of sectors. Several configurations within a given sector co-evolve and co-exist, as they compete with each other to grow and to provide the dominant solution for a certain need (housing, energy, water etc.) (Miorner et al., 2026). The degree to which the provided solution aims at a transformative change of the sector varies highly. Some socio-technical configurations pursue ‘stretch and transform’ a socio-technical system, while other configurations only aim for incremental changes of the status quo following ‘fit and conform’ (Smith and Raven, 2012). Thus, sectors often host diverse ways of delivering the same function, but with different approaches and degrees of how transformative and sustainable the solution would be (Bulah et al., 2024; Weber and Rohracher, 2012). While several (potential) directions exist in a sector, transitions unfold through changing relations among the co-existing configurations (Andersson et al., 2021; Stirling, 2011). This diversity can generate complementarities, for instance, when different configurations occupy distinct segments of a value chain, share infrastructure, or jointly contribute to broader system building (Mäkitie et al., 2022; Markard and Hoffmann, 2016). At the same time, diversity produces contestation: configurations compete over policy support, standards, legitimacy, skilled labor, and investment (Heiberg and Truffer, 2022a; Miörner et al., 2022a). Such contestation is not restricted to niche-regime interactions as often implied in the literature (Smith and Fressoli, 2024); it can also occur among multiple emerging configurations that disagree about desirable futures, acceptable governance models, or required degrees of transformation (Hawxwell et al., 2024; Madsen et al., 2022). Thus, technologies interact with each other which affects their evolution. Some technologies might benefit from such interactions while others are inhibited in their evolution (Havinga et al., 2024; Pistorius and Utterback, 1997; Sandén and Hillman, 2011).

In some contexts, it has been proven be helpful to treat a sector, or an emerging part thereof, as a strategic action field in which configurations are stabilized or destabilized through struggles over rules, positions and resources (Fligstein, 2001; Fligstein and McAdam, 2011). This lens redirects the focus from configurations as competing entities to the arena in which they are made comparable and governable. This includes considerations such as who is recognized as an influential actor, what constitutes legitimate proof of performance, and which decision-making procedures are considered binding (Kungl and Hess, 2021). This is particularly helpful when configurations partially overlap with regard to actors or institutions, as this associates them with the same field-level rule environment, rather than allowing them to develop independently (Chlebna and Mattes, 2024; Heiberg et al., 2022). In such fields, directionality is an emergent outcome of these patterned relations (Heiberg and Truffer, 2022a). Chapter four adds to this debate by looking at specific interactions between socio-technical configurations and their effects on the evolution of the more transformative configuration and on directionality in the entire technological field.

Whether socio-technical configurations 'work' is also geographically contingent. The geography of transitions scholarship argues that socio-technical change is shaped by place-specific institutional contexts, localized capabilities, and spatial relations, connecting regions, nations, and transnational arenas (Coenen et al., 2012; Hansen and Coenen, 2015; Truffer and Coenen, 2012). This has some implications for the analysis of socio-technical configurations in particular: territorial embeddedness plays a crucial role as regulations, planning cultures, procurement practices, and industrial capabilities differ across countries and regions. A configuration might work in one place due to supportive governance routines and complementary resources, but not in another place where institutions do not align (Coenen et al., 2021; Jayaweera et al., 2025). It may nevertheless be able to mobilize such system resources (i.e. knowledge, investment, market formation and legitimacy) across scales to build on it (Binz et al., 2016b; Binz and Truffer, 2017). Accordingly, when studying socio-technical configurations, there are relational interdependences across places (Crevoisier and Jeannerat, 2009). Thus, configurations unfold in a multi-scalar manner (Miörner and Binz, 2021) and are often assembled through trans-local diffusion (Butzin and Widmaier, 2016; Loorbach et al., 2020), whereby supply chains or professional communities link multiple regions. This diffusion process involves translation and adaptation rather than replication (Miörner et al., 2025). Recent agenda work at the intersection of sustainability transitions and economic geography further emphasizes that transition pathways are shaped by uneven opportunity spaces across scales, which are produced through the co-evolution of industries, institutions and knowledge bases (Binz et al., 2025). Configurations 'work,' in this sense, not only because they fit a local context, but because they connect effectively to extra-local resources and rule systems, across geographical scales (Heiberg, 2022). This conceptualization supports a nuanced analysis of diversity (Stirling, 2011), i.e. how multiple configurations co-exist, compete, and complement one another, and how their viability and trajectories vary across places and scales. Chapters four and five contribute to these debates.

1.2.2 Legitimation of socio-technical configurations and visions

Socio-technical change is not only a matter of inventing better technologies. It is also a matter of making novel objects part of the social reality, that is, making them intelligible, appropriate and worthy of support, in contexts that are already organized around established routines, value hierarchies and taken-for-granted ways of doing things and 'ways of knowing'. In social constructivist terms, what is considered normal, necessary or rational is continuously produced and reproduced through interaction and shared meaning, while simultaneously becoming experienced as an objective order (Berger and Luckmann, 1966; Weber, 1968).

This is why the evolution of socially constructed objects such as an emerging vision, technology, or a broader socio-technical configuration depends on whether it is perceived as legitimate within the prevailing social order (Johnson et al., 2006). That order is itself institutionalized, historically consolidated, and unevenly distributed across places (Powell and DiMaggio, 1991). When the perceived 'fit' is low, proponents encounter liabilities of newness and incongruence: not only skepticism about performance, but also doubts about relevance, propriety, and broader desirability (DiMaggio, 1997). The resulting struggles over legitimacy are not insignificant considerations. Rather, they are constitutive to how socio-technical systems stabilize and transform (Schnell and Mattes, 2026). Suchman (1995) defines legitimacy as "*a generalized perception or assumption that the actions of an entity are desirable, proper, or appropriate within some socially constructed system of norms, values, beliefs, and definitions.*" (p. 574).

In this dissertation, I adopt Alsheimer et al.'s (2025) dimensions of legitimacy, which treat legitimation as a generalized, intersubjective evaluation linking an *object* (what is to be legitimized), an *evaluator* (who confers or withholds legitimacy) and a *socially constructed system*, which provides the institutionalized background against which evaluations become meaningful. This is helpful because it prevents legitimacy from being narrowly interpreted as public support or collective acceptance, and instead directs the focus toward the various evaluators that are important in sustainability transitions, such as regulators and administrators, investors and incumbents, experts and advocacy groups, users and affected communities (Schnell, 2025; Schnell and Mattes, 2026).

It is also important to distinguish legitimacy from related concepts such as social acceptance. While acceptance research often focuses on favorable responses and behaviors by specific social units, legitimacy refers to more generalized perceptions rooted in institutionalized expectations and shared understandings of what is appropriate (Alsheimer et al., 2025; Suddaby et al., 2017). There are, however, different approaches in the broader fields of sustainability transitions and innovation studies in the conceptual understanding: legitimacy as a system resource that actors can leverage (e.g. Binz et al., 2016b; Binz and Truffer, 2017; Mazzoni et al., 2025), legitimation as a process of social construction and contestation (e.g. Binz et al., 2016a; Markard et al., 2016; Schneider and Rinscheid, 2024), and the focus on legitimacy as grounded in rather micro-level propriety that eventually aggregates into field-level validity (e.g. Bitektine and Haack, 2015; Schnell, 2025). A further refinement comes from distinguishing dimensions of legitimacy. The widely used typology by Suchman (1995) (see e.g. Harris-Lovett et al., 2015; Rohe and Chlebna, 2021) differentiates between pragmatic evaluation (self-interested utility), moral evaluation (normative approval), and cognitive evaluation (comprehensibility and taken-for-grantedness). In the context of studying sustainability transitions, this typology is often slightly adjusted (see Markard et al., 2016; Schnell and Mattes, 2026) inspired by the institutional pillars by Scott (2014), which were introduced as part of section 1.2.1.

Within innovation and transition studies, legitimacy has become a key explanatory factor for why some technologies gain momentum while others stagnate. In technological innovation systems (TIS), legitimacy is treated as a core function (Hekkert et al., 2007; Markard and Truffer, 2008). This systemic perspective also highlights competition: emerging technological fields rarely develop in a vacuum, but face adversaries defending established systems and their institutional infrastructures (Bergek et al., 2008; Bergek et al., 2015). At the same time, transition-oriented policy debates add an additional layer: legitimacy is not only needed for novel technologies, but also for policy interventions that aim at transformative change. When policy objectives shift from incremental innovation toward sustainability-oriented transformation, new justificatory lines are required, especially when interventions target long-term system reconfiguration rather than short-term market corrections (Weber and Rohracher, 2012). In this sense, legitimation becomes relevant not only for technologies and markets, but also for governance rationales and the public framing of intervention itself (Geels and Verhees, 2011).

A critical advance in this literature is the shift from viewing legitimacy as an aggregate 'state variable' of system maturation, to analyzing how it is actively constructed. This process-based approach corresponds with the conceptualization of 'legitimation as a social process' (Johnson et al., 2006) involving local validation in protective spaces, diffusion into new contexts, and eventual general validation, whereby the innovation becomes culturally embedded and increasingly taken-for-granted (Binz et al., 2016a). Crucially, once general validation has been achieved, the focus changes from gaining legitimacy to maintaining it. This involves the continued reproduction of institutions, monitoring emerging challenges, and selectively repairing crises (Oliver, 1992; Suchman, 1995).

The institutional work perspective provides a conceptualization of how several configurations, co-evolve over time. It foregrounds the practices of creating, maintaining, and disrupting institutions, showing how agency is exercised within institutional constraints rather than outside them, and how transition dynamics hinge on the ongoing work that sustains or unsettles the reproduction of established incumbent configurations (Fuenfschilling and Truffer, 2014, 2016; Lawrence and Suddaby, 2006). In technology legitimation, institutional work directs attention to practices such as advocacy, theorizing, building normative networks, and shaping meanings through discourse, which are forms of embedded agency that simultaneously draw on and challenge existing structures (Binz et al., 2016a).

Recent consolidation efforts translate these insights into the transition work framework (Löhr et al., 2022) that emphasizes activities that accelerate, slow down, or halt transitions through creating, maintaining, and disrupting transition-related processes across institutions, actors, and materiality. This contribution is crucial for the focus of this dissertation because it allows treating the *object* of legitimacy not merely as a technology, but as a socio-technical configuration: a patterned combination of technologies, institutional arrangements, and actor constellations that must become aligned to 'work' and to persist (Fuenfschilling and Truffer, 2016; Heiberg, 2022). Chapter five contributes to these ongoing efforts to conceptualize how socio-technical configurations are objects of (de-)legitimation.

Sustainability transitions are not only about building legitimacy for emerging configurations. They also involve the phase-out of unsustainable trajectories (Markard et al., 2021; Rinscheid et al., 2021), i.e. the erosion of institutionalized practices, weakening of taken-for-granted organizational forms, and active contestation of incumbents (Maguire and Hardy, 2009). Research on deinstitutionalization conceptualizes this as erosion, discontinuity or rejection, triggered by political pressures (e.g. shifting power distributions and internal dissensus), functional pressures (e.g. withdrawal of rewards, performance crises and rising competition) and social pressures (e.g. normative fragmentation and disrupted historical continuity) (Davis et al., 1994; Oliver, 1992). In transition studies, these dynamics are visible in contestations over legitimacy in the phase-out of conventional technologies (Biddau et al., 2024). A discourse network analysis of coal phase-out debates shows how opposing coalitions mobilize competing storylines over time. One coalition systematically undermines the legitimacy of coal, while another attempts to re-legitimize it and preserve its position in the socio-technical system (Markard et al., 2021). Similar dynamics occur in regional discourses, where coal traditions and livelihoods are used to stabilize the current situation, while renewable energy can simultaneously be de-legitimized through framing that undermines alternative configurations (Biddau et al., 2024). Incumbents do not passively resist; they can actively protect established evaluation criteria, stabilize existing categories of what is considered appropriate, and selectively repair legitimacy when it is challenged (Lehmann et al., 2022; Maguire and Hardy, 2009).

Such conflicts highlight an important implication of analyzing socio-technical configurations: the processes of legitimizing an emerging configuration and de-legitimizing an established one are not independent (Schnell and Mattes, 2026). They interact through shared arenas, overlapping evaluators and mutually influencing narratives. Notably, the legitimacy of incumbents can hinder the development of new solutions by portraying alternatives as 'unthinkable' (Geels, 2014; Schneider and Rinscheid, 2024). Against this background, there is an emerging debate on transformative knowledge which aims at addressing knowledge as central to understanding whether transformative innovation might be successful to challenge established technologies. Jeannerat et al. (2025) propose to explore "*knowledge for, by, and as action [as it] allows (…) to better grasp how knowledge not only informs solutions (for), but also emerges through experimentation and action (by) and is dynamically enacted in practices and routines (as).*" (p.12). Scholars often refer to transformative knowledge and similar concepts such as grassroots innovations as a key approach to drive transformative change (Hermans et al., 2016; Urmetzer et al., 2020). There is often, however, an uncertainty whether related initiatives or projects are able to scale in order to actually achieve transformative change (Seyfang, 2010). Chapter five in this dissertation examines a case of a transformative knowledge region and bridges it with a legitimation perspective to analyze a crucial condition for its diffusion. It further aims to advance the understanding of the two-sided coin of legitimation and de-legitimation of emerging configurations aiming for transformative change.

Legitimacy is also central to understanding transitions as contested futures in the making (see Section 1.2.3), given that visions themselves can be objects of legitimation (Rohde and Santarius, 2023). This is crucial because visions rarely stabilize through persuasion alone; they are only embraced by others when they are repeatedly validated as appropriate and credible across spaces (Berkhout, 2006; Späth and Rohracher, 2010). Visions do not merely 'influence' technological development; they can become institutionally stabilized as interpretive schemas that determine what is relevant, urgent and desirable, and can eventually contribute to collectively shared imaginaries (Altstaedt, 2024). This stabilization does not happen automatically. Instead, it is achieved through overlapping processes of legitimation, performance and materialization. Visions are enacted through representations and demonstrations, and are inscribed into artefacts and infrastructures. These then feed back into what appears feasible and appropriate (Rohde and Santarius, 2023; Rudek, 2022). This reasoning sheds light on how visions appear appropriate and how they might become collectivized (Kuchler and Stigson, 2024). With the conceptual focus of chapter three I aim to contribute to this ongoing debate.

Legitimation also has an explicit geographical dimension. The same technology or configuration may be considered legitimate in one region but contested in another, due to differences in evaluators, institutional contexts and material experiences. Place-specific analyses demonstrate that pragmatic and moral legitimacy are particularly influenced by regional characteristics, such as local value creation, trust in procedures, and the perceived fairness of planning and site selection (Rohe and Chlebna, 2021). Beyond regional variation, legitimation in transitions is inherently multi-scalar (Alsheimer et al., 2026). Emerging configurations may need to mobilize legitimacy from nonlocal sources by attracting external actors and absorbing legitimacy generated elsewhere (Heiberg et al., 2020). Recent work also suggests that legitimacy creation can itself scale: legitimacy may be established first at regional levels and then shift toward national and global scales as markets, networks, and materialization processes evolve (Ayrapetyan et al., 2025). In recent contributions applying the global innovation systems (GIS) framework (Binz and Truffer, 2017), these dynamics across spatial scales are conceptualized for legitimacy as one of the system resources (Mazzoni et al., 2025; Mazzoni and Losacker, 2024; Snijders and van der Loos, 2025). In chapter five, these multi-scalar dynamics are refined zooming in on only one system resource, i.e., legitimation.

1.2.3 Futures in sustainability transitions

Traditionally, much transition research has taken an ex-post perspective, explaining how and why socio-technical change happened (or failed to happen), and how incumbent configurations remained stable. In recent years, this has been complemented by a growing interest in futures: how actors make possible future socio-technical configurations visible, how these futures influence action and decision-making in the present, and how they might affect the direction of transitions (Friedrich and Hendriks, 2024; Gong, 2024).

As such, desirable future states in sustainability transitions (i.e. imagined future socio-technical configurations), are made visible by how the future is imagined and articulated e.g. in visions or imaginaries (Benner, 2025; Friedrich and Hendriks, 2024). Taking such a forward-looking perspective uncovers potential future directions (Gong, 2024) and unveils the process of ideation, i.e. the formation of these ideas on the future (Benner, 2024) which are emerging debates in both sustainability transitions and economic geography. Viewing these potential future directions a sustainability transition could take, opens up inroads for scholars as they are able to address upcoming tensions or trade-offs and to study further implications for the socio-technical transition (Sovacool et al., 2019). In this sense, futures are not distinct from sustainability transitions; rather, they form part of the process by which transitions become thinkable, actionable and governable in the present (Christley et al., 2024; Friedrich and Hendriks, 2024).

Various desirable futures in the same socio-technical system are often contested and compete over one another to eventually become the dominant idea on how a (sustainable) future could ideally look like (Berkhout, 2006; Späth and Rohracher, 2010). Thus, envisioned futures depict which technologies and institutional arrangements come to be seen as desirable shaped by the actors in a given sector. Put differently, transitions are also struggles over directionality (Weber and Rohracher, 2012): over which futures are considered desirable and achievable, and whose visions are prioritized (Friedrich and Hendriks, 2024). A key reason why these ideas matter lies in their performativity. Anticipatory representations, whether framed as expectations, visions or imaginaries, are capable of far more than simply describing possible futures. They can also influence present-day decisions, coordinate actors, and facilitate the formation of coalitions around specific trajectories (Borup et al., 2006; Friedrich and Hendriks, 2024; Oomen et al., 2022). From an empirical perspective, plural and conflicting futures are typical in sustainability transitions (e.g. Bauer, 2018; Mast, 2022; Wiarda et al., 2023). In debates on the energy and mobility transitions, for example, experts articulate utopian and dystopian visions that coexist and contradict each other. Such tensions can be strategic, for example as a way to strengthen promises, but they can also highlight practical risks and distributional consequences that more optimistic visions tend to overlook (Sovacool et al., 2019). This indicates that transition research is increasingly studying how futures are constructed, negotiated and stabilized, and how this may ultimately shape pathways and outcomes (Benner, 2025; Friedrich and Hendriks, 2024).

While Benner (2024, 2025) expects an 'ideational turn' in sustainability transitions and economic geography, the growing attention has also produced a crowded conceptual field. Work across the social sciences refers to and studies expectations, visions, imaginaries, narratives, imagined futures and related constructs, often without a stable definitional consensus (Benner, 2024). This lack of conceptual clarity can be problematic when different concepts are treated as equivalent implicitly, despite them referring to different forms of future-oriented knowledge, degrees of normativity and levels of collectivization and institutionalization (Rudek, 2022). As elaborated in the remainder of this section and used in the remainder of this dissertation, I understand ideational concepts within sustainability transitions along the level of abstraction and normativity, as well as their level of collectivization and stabilization. In this sense, *expectations* are often the most diffused and pervasive ideational form as developed in the 'sociology of expectations', as "*real-time representations of future technological situations and capabilities*" (Borup et al., 2006, p. 286) that make futures present and guide action. Expectations surrounding technological development help to coordinate investment, research agendas and commitments from various stakeholders. These expectations can be optimistic or cautionary, and may remain implicit or be articulated in the form of promises, forecasts or projected performance trajectories (Beckert, 2016; van Lente, 2012).

Visions in sustainability transitions tend to be more concrete and explicitly normative (Berkhout, 2006). They express desirable future states and often implicitly or explicitly propose a pathway or orientation for action (Friedrich and Hendriks, 2024). Visions can be held privately by individuals or organizations, but they can also be shared and negotiated among multiple stakeholders. Furthermore, they function as 'bids' in the ongoing processes of coalition building and agenda setting (Berkhout, 2006). Visions therefore, represent not only preferred endpoints but also instruments for mobilization: they attract allies, define roles, and help establish obligations and responsibilities (Späth and Rohracher, 2010). Thus, they invite contestation over which values, interests and distributional outcomes are embedded in the proposed direction of the transition (Friedrich and Hendriks, 2024; Longhurst and Chilvers, 2019).

When such visions are collectively held, institutionally stabilised and publicly performed, the concept of *socio-technical imaginaries* (Jasanoff and Kim, 2009, 2013, 2015) is useful for capturing the reproduction of visions with broader understandings of social order and the public good (Longhurst and Chilvers, 2019; Rohde and Santarius, 2023). Nevertheless, a conceptual gap remains: while scholarship has extensively used imaginaries to interpret existing transition pathways, especially in energy transitions, comparatively little attention has been paid to the phase of uncertainty in which visions are still forming and being negotiated, and are only partially shared (Benner, 2025; Hendriks et al., 2025; Rudek, 2022). This stage, described as 'imaginaries in the making' by Braun and Kropp (2023), matters because it is where directionality is contested before it becomes institutionalized. Multiple competing visions can coexist (Longhurst and Chilvers, 2019). Each vision promises to fulfil a crucial societal function, but prioritises different aspects (e.g. productivity, integration or sustainability), thereby opening up certain possibilities while excluding others (Friedrich and Hendriks, 2024; Jasanoff and Simmet, 2021; Muehlberger et al., 2024). Therefore, those involved in sustainability transitions often compete for either an incumbent or a transformative future (Hawxwell et al., 2024). These dynamics suggest that a plurality of visions is not only indicative of diversity (Friedrich and Hendriks, 2024; Longhurst and Chilvers, 2019), but also a struggle over dominance, in which some futures are given greater attention while others are overlooked (Polzin, 2024; Rudek, 2022). Furthermore, contestation over desired futures can result in complementary or contradictory visions of the future (Trencher and van der Heijden, 2019). Chapters two and three pick up on the described issues by identifying how ideations differ in their priorities and logics, and how processes of contestation, alignment, and legitimation shape which desirable futures gain traction.

These contested dynamics bring conceptual attention to another gap: how exactly visions become collectivized and why some futures become dominant while others remain marginal. In a literature review Kuchler and Stigson (2024) have revealed that 'what is collectivized' in desirable futures often remains unclear. Many studies mobilize socio-technical imaginaries without clearly specifying what constitutes 'the collective' which is supposedly holding a socio-technical imaginary. It remains unclear how individual agency and less powerful actors enter into the shaping and reshaping of collective futures (Hendriks et al., 2025). In other words, imaginaries are often identified in hindsight, while the crucial processes through which private visions become shared, namely, justification, legitimation and coalition building, remain under-specified (Rohde and Santarius, 2023; Rudek, 2022). Similarly, Kuchler and Stigson (2024) argue that the 'collective' should be treated as an empirical accomplishment rather than an assumed scale. This raises questions about which visions are aggregated, translated or excluded when the future is held collectively. This implies that studying socio-technical imaginaries in the making (Braun and Kropp, 2023) requires conceptualizing the intermediate steps between expectations, private visions, and more stabilized shared orientations, i.e., what exactly gets aligned and reaffirmed until it is collectively embraced. Chapter three takes up this concern by staying close to the formation phase (imaginaries in the making) and examining how visions become collectivized, as they are negotiated, justified, and gradually stabilized across actor constellations.

The formation of such desirable futures is arguably also influenced by the geographical context in which they evolve or are embedded in (Lambert, 2022). It is crucial because the desirability and feasibility of socio-technical futures are interpreted through place-specific industrial structures, infrastructures, cultural repertoires, and political economies (Benner, 2025; Feola et al., 2023). As a result, what counts as a credible 'sustainable' direction[1] in a future transition can differ substantially across countries, regions, or sectoral communities, even when actors invoke the same overarching goals (e.g., decarbonization of a sector) (Chateau et al., 2021; Eaton et al., 2014).

In this context spatial imaginaries take different forms (e.g., imaginaries of places, idealized spaces, or spatial transformations) and a performative view helps to link these ideas to material practices and outcomes (Benner, 2025; Watkins, 2015). Chateau et al. (2021) adopt this notion for energy transitions, arguing that socio-technical imaginaries are co-produced with spatial imaginaries. Similarly, transition research on regional discourses demonstrates that place-based 'guiding visions' can become transformative when institutionalized and translated strategically across governance levels (Späth and Rohracher, 2010). Benner's (2025) more recent attempt to conceptualize imaginaries as time/geography configurations crystallizes the implication: to use imaginaries productively, scholars should be explicit about which temporal and spatial dimensions they analyze. Chapters two and three in this thesis consider the spatial embeddedness of desirable futures and discover how geographically situated visions shape, and are shaped by, processes of alignment and contestation

Taken together, the three key literature strands introduced above form the conceptual foundation of my dissertation. Sustainability transitions are approached as contested processes in which actors advance and negotiate futures, seek legitimacy for those futures and for the socio-technical configurations that they are incorporated in. Ultimately in the attempt to assemble alignments that are robust enough to provide societal functions in practice that are more sustainable than what is established. The dissertation uses the construction sector as the empirical case to identify these dynamics across different geographical contexts and scales, showing how place-specific institutions and trans-local relations shape which futures gain traction, which configurations evolve, and how directionality is produced through interaction rather than through isolated innovation.

[1] What is considered 'sustainable' is contested within the sustainability transitions community. For instance, transition scholars take quite different positions regarding desired mobility futures (Hawxwell et al., 2024). While some refer to incremental changes to the current socio-technical system (incumbent futures), others pursue transformative futures. Following the commonly used definition in the field by Markard et al. (2012), in this dissertation, I understand the shift "towards more sustainable modes of production and consumption" (p. 955) as a fundamental and transformative change of the current socio-technical system.

1.2.4 Research objectives

This dissertation aims to contribute to several key aspects of the research fields introduced in previous sections, namely the economic geography of sustainability transitions and their futures, in line with calls for further research in the scholarship. This dissertation outlines research objectives that address these calls for a better understanding of ideational dynamics and future-oriented perspectives in economic geography (Benner, 2024; Gong, 2024). It also aims to advance the conceptualization of contested transitions embedded in multi-scalar socio-technical structures (Binz et al., 2025). In this dissertation, I examine how sustainability transitions are shaped by the interplay of *contested visions of the future* (articles 1 and 2), *struggles over legitimacy* (articles 2 and 4), and *the relation and interaction of socio-technical configurations in the present* (articles 3 and 4). I explore how the direction of sustainability transitions is not simply determined by the adoption of new technologies, but emerges from geographically embedded processes in which actors articulate and seek validation for their visions of the future, and build or impede configurations through institutional work and resource mobilization. This dissertation aims to examine how legitimacy is built and contested across scales, which desirable futures become collectively held, and the extent to which transformative knowledge can initiate transformative change. To explore these aspects, I compare multiple national contexts and zoom into a regional sustainability transition case. Therefore, I aim to contribute to the empirical understanding of how a sustainability transition in the construction sector is currently being imagined, validated, and (partly) enacted across places and scales.

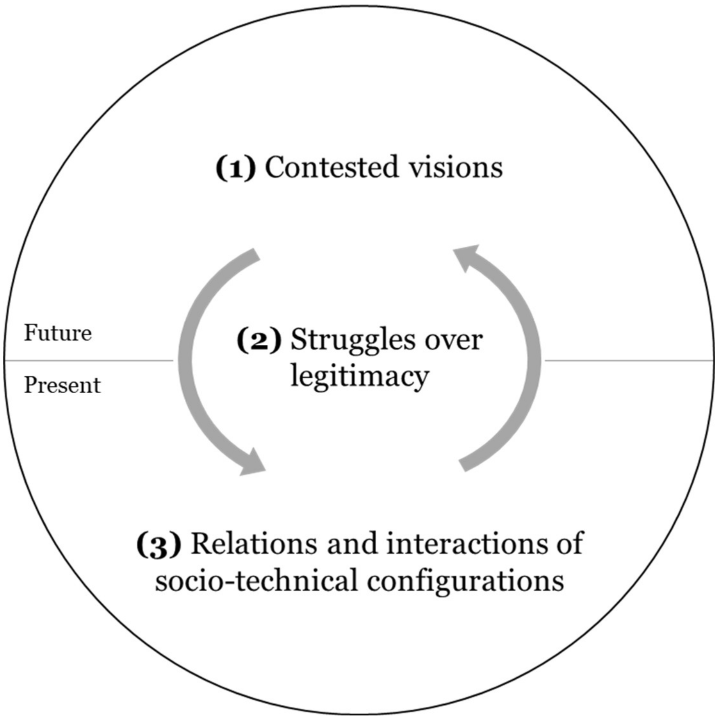

Figure 1: Structure and relation of the research objectives in this dissertation

Overall, the articles in this dissertation first identify where a transition might lead to (in the future), then aim to understand what is perceived as legitimate and why and lastly, address how different configurations affect each other in the present and how they interact. Legitimacy acts as a bridge between the present and the future, influencing both as it is negotiated between them (Figure 1). Ultimately through three research objectives, I aim to draw inroads to approach the title question of this dissertation: *how to build (in) a sustainable future?*

Research objective 1: To conceptualize how diverse and contested visions of the future evolve in sustainability transitions in different national contexts (articles 1 & 2).

While the sustainability transitions literature increasingly addresses desirable futures (e.g. through articulating visions), it often underestimates the inherent diversity of possible outcomes (Friedrich and Hendriks, 2024). Additionally, it lacks conceptualization of future ideations in transitions (Benner, 2024, 2025), and of how the competition to become the dominant desirable future unfolds (Rudek, 2022). Conceptualizing these aspects will enable us to analyze how actors articulate different desirable futures for sustainability transitions, how these desirable futures embed distinct socio-technical logics regarding what a future sector might look like, and how specific visions of the future can be simultaneously complementary and conflicting. In this context, recent work has often ignored the different implications various visions have for different countries: How the transition toward a sustainable construction sector is imagined in Germany can be expected to contrast with how it is imagined in India or China. Further, the potential for decarbonizing the sector in India and China is overlooked in the mostly European-centric field of studying futures in transitions (Friedrich and Hendriks, 2024). It is also crucial to address the conceptual fuzziness of different ideations, such as expectations, visions, or imaginaries. Therefore, a framework on the formation of collectivized visions will enable approaching this gap. It further addresses the issue that, when studying collectivized desirable futures, it often remains unclear what is meant by 'the collective' (Kuchler and Stigson, 2024). Scholars often mentioned that visions need trust, justification, or that they need to appear legitimate (Koole, 2022; Rohde and Santarius, 2023), which is, however, rarely conceptualized. Exploring the legitimacy of visions can therefore be a fruitful inroad to address the conceptual fuzziness in how ideations of the future collectivize.

In this way, contested futures are a crucial starting point for gaining insights into how the directionality of entire socio-technical systems or fields might emerge, especially under geographically uneven conditions. In the next step, it is worthwhile exploring both sides of legitimation more specifically: visions require legitimacy, while at the same time they contribute to building legitimacy to justify a (sustainable) technology. Accordingly, this can be an inroad to understanding the determinants of successfully advocated desirable futures.

Research Objective 2: To conceptualize how struggles over legitimacy unfold in sustainability transitions (articles 2 & 4).

This research objective positions legitimacy as the conceptual hinge between desirable futures and socio-technical reconfiguration in the present. Even compelling visions do not become drivers of transitions by virtue of articulation alone: they must be validated, rendered appropriate, and made actionable through evaluation (Rohde and Santarius, 2023). Accordingly, a framework that captures the legitimacy of visions will enable transition scholars to comprehend one condition for the collectivization of desirable futures. At the same time, socio-technical configurations that could enact those visions in the present must be legitimized to mobilize resources, stabilize coalitions, and reproduce practices. That amplifies legitimacy as a central bridge between futures that are desirable and 'socio-technical configurations that work' in the present.

The coexistence of different ideas about what constitutes a desirable future indicates that there are several possible pathways for a transition, all of which compete for legitimacy. These struggles over legitimacy in the present are increasingly addressed in recent contributions, acknowledging that legitimation goes beyond the issue of legitimizing single technologies or socio-technical configurations, but is also affected by the de-legitimation of incumbents (Schneider and Rinscheid, 2024; Schnell and Mattes, 2026). So far, transition scholars developed helpful conceptual frameworks for both the legitimation of technologies (Binz et al., 2016a; Markard et al., 2016) and on how technologies are de-legitimized, often in the phase-out of conventional technologies (Markard et al., 2021). Both perspectives largely disregard that both processes are mutually interdependent, as legitimation of an emerging configuration is affected by incumbent configurations legitimizing themselves, aiming to defend their practices and vice versa. Thus, a conceptualization of how emerging configurations aim to legitimize themselves and how this is affected by the de-legitimation of incumbents, enables the examination of a broader picture of struggles over legitimacy in sustainability transitions. Achieving this research objective entails developing a multi-scalar view of legitimacy in which judgments of appropriateness are produced across locations, rather than residing locally or nationally in isolation.

Research Objective 3: To conceptualize how relations and interactions among co-existing socio-technical configurations are structured (articles 3 & 4).

Lastly, the contestation between co-existing socio-technical configurations will be examined. This is of crucial importance, especially in sectors with diverse potential directions that the transition could take, since sustainability transitions unfold through the co-existence of multiple configurations (Miorner et al., 2026). Whether transformative alternatives gain traction depends not only on their internal performance, but on their patterned relations with other configurations, i.e. relations that can generate synergies, dependencies or competition. Seminal contributions have developed frameworks for the interaction of technologies and how that affects the development of such technologies (Pistorius and Utterback, 1997; Sandén and Hillman, 2011). I argue, however, that the way in which several configurations interact is not only influenced by the technologies involved, but also by how they interact at the interface of institutions that are associated with several configurations. The broader transition and innovation studies scholarship might benefit from conceptualizing these more specific interactions between socio-technical configurations, to ultimately identify how interaction affects the evolution of socio-technical configurations. To achieve this, this dissertation will theorize interaction modes among configurations, to approach how configurations may benefit or be harmed from co-existence, by examining how they draw on the same system resources, i.e. knowledge, legitimation, market formation and investment (Binz et al., 2016b). It is further important to understand, how configurations specifically contest for mobilizing these system resources. Therefore, a framework on how socio-technical configurations affect each other through (de-)legitimation needs to be developed to provide a perspective on the mobilization of one of the system resources. This framework will take a multi-scalar perspective on the relation of configurations, to provide some understanding of why some relations widen the space for transformative change, whereas others reproduce lock-in through antagonism, and standards that privilege incumbent configurations.

In the context of research objective three, transition studies scholarship may also benefit from new methodological approaches beyond classical qualitative methods by combining them with semi-quantitative approaches (Heiberg et al., 2022; Truffer et al., 2025). This accounts in particular for interactions which are conceptualized in various forms in transition studies (e.g. niche-regime interactions or multi-system interactions (Andersen and Geels, 2023; Smith and Fressoli, 2024)), but lack optimized methods to be operationalized.

1.3 Methodology

The research objectives in this dissertation require advancing both the use of qualitative and semi-qualitative methods at the intersection of economic geography and sustainability transitions: discourse analysis might enhance the study of futures in economic geography, as put forward by Gong (2024) and using socio-technical configuration analysis (STCA) to assess the relations between socio-technical configurations, could also be leveraged by economic geography scholars more broadly, as suggested by Truffer et al. (2025). The articles in chapters two to five as well as the elaboration on the methods in this section, are presented in the order in which they were written, according to their geographical focus. First, we identify visions of bio-based construction futures across countries. We then narrow the focus to a comparison of transition cases in two countries. Finally, we analyze a regional transition case and consider multi-scalar influences. Before I elaborate on the methodology and the specific (semi-) qualitative approaches used, I will provide some background on the empirical case and the data used, which were developed as part of the larger TRABBI research project[2].

1.3.1 Empirical case

The construction sector provides a very interesting empirical case for studying socio-technical transitions because its decarbonization is not a matter of substituting a technology, but of altering highly stabilized material-institutional structures. Cement and steel are reproduced through taken-for-granted benchmarks and routines for design, procurement and regulation (Geels and Deuten, 2006; Gibbs and O'Neill, 2015; Jayaweera et al., 2023). As a result, alternative (not mineral-based) material pathways are not only evaluated on technical performance, but on whether they can be rendered legitimate within existing approval systems, standards, and valuation practices. This makes the transition toward a bio-based construction sector an ongoing, geographically uneven process in which multiple socio-technical configurations co-exist and compete over what counts as an appropriate and affordable building (Mast, 2022; van Veelen and Knuth, 2024; Wiarda et al., 2023).

Against this background, the dissertation focuses on the socio-technical transition toward bio-based materials (cross-laminated timber, glulam, bamboo, straw, hemp, …) as a multi-directional transition rather than focusing on one pathway. Bio-based solutions are diverse and therefore generate competing expectations about durability, fire safety, moisture, aesthetics, cost, and scalability. These expectations are stabilized, or challenged, through standards, certification systems, procurement routines, and professional judgments (Jayaweera et al., 2025; Seyfang, 2010). Thus, the empirical case can illustrate how directionality is produced through geographically embedded evaluation processes. Actors articulate visions of the future, seek validation for them, and attempt to build socio-technical configurations that evolve and challenge the status quo, while incumbent configurations remain highly resistant to change.

This dissertation takes a comparative approach, building on four national contexts: Germany, Italy, China, and India. These countries offer variation in terms of the predominant bio-based materials and other contextual factors to consider, such as socio-economic differences and

[2] The project titled 'Socio-technical transformation processes for a sustainable construction sector in the bioeconomy: Regional lead markets and global innovation systems' is funded by the German Federal Ministry of Research, Technology and Space (grant number 031B1281; https://www.trabbi-bioeconomy.de/en)

existing built environments[3]. Germany and Italy provide contexts in which timber-based construction is regionally established, yet embedded in different industry structures, professional cultures, and institutional environments (EOS, 2023; UNECE, 2023). China and India provide contexts in which bamboo-based construction is visible as a potential pathway, while also illustrating divergent styles of standardization, scaling, and coordination between state and industry (Fuqaha et al., 2025; Yadav and Mathur, 2021). In particular, India combines rapid growth in the construction sector and stable incumbency with emerging experimentation with bio-based materials. This makes it an ideal case study for examining how legitimacy is established and contested amid intense development pressures. Chennai was selected within India to provide a regional perspective that makes multi-scalar dynamics empirically observable. Chennai can be characterized as a dense area with high urbanization pressure and a largely growing built environment where actors experiment with bio-based construction while they are confronted with the everyday dominance of mineral-based buildings (Kennedy, 2025; Kulshreshtha et al., 2020). This enables a suitable case to study how legitimacy for bio-based materials is mobilized across scales (e.g. through established standards, demonstration projects and expert networks), while also examining how it is simultaneously undermined by regional doubts over feasibility

This case directly supports the three research objectives of the dissertation. Firstly, the bio-based transition is characterized by competing visions of the future that incorporate different socio-technical logics, ranging from industrialized, standardized approaches to more frugal alternatives. This allows us to conceptualize how such visions evolve and compete across national contexts. Secondly, the sector's high sensitivity to risks gives rise to struggles over legitimacy: visions require legitimacy in order to be adopted collectively, and socio-technical configurations require legitimacy in order to mobilize resources and stabilize their practices. At the same time, incumbents defend their own legitimacy and undermine alternatives. Third, the co-existence of multiple potential pathways leads to interaction among emerging configurations: they overlap by relating to and building on e.g. the same norms, values or goals. Studying Germany, Italy, China, and especially India by zooming into the regional transition in Chennai, therefore enables examining how contestation over visions and legitimacy, and between configurations are produced across places and scales in a hard-to-decarbonize sector.

[3] For a more detailed case description of the construction sector, see section 3.4.

1.3.2 Data

In the dissertation, the central empirical foundation consists of semi-structured expert interviews conducted between 2023 and 2024 as part of the TRABBI project. A total of 90 interviews were conducted across countries in the first round of online interviews. I conducted the expert interviews in India; Tim Becker and Yongmin Shang conducted those in China; Moritz Schütz in Germany; and Francesca Mazzoni in Italy. In the second round, I conducted fieldwork in Chennai, where I carried out 18 in-person interviews and gained first-hand insights into the local construction sector, including a few transformative experiments with bio-based construction materials. To explore incumbents as well, I visited a concrete trade fair in Mumbai, where I conducted nine short interviews with large companies from the Indian concrete industry. Our focus was on the upstream and core actors in the construction sector's supply chain, primarily start-ups and suppliers (upstream), as well as architects, engineers and planners (core). These were supplemented by further interviews with researchers, intermediaries, other relevant associations, and government-related organizations. Specific roles and further details on the interviewees can be found in the dedicated tables in each chapter, as the subsets used differ depending on the empirical focus of each article (see tables 6, 9 and 13). The interviews were conducted in different languages[4] and all were transcribed and translated into English to allow consistent cross-case analysis. This approach has, of course, its limitations, as different languages can complicate interpretation, with certain meanings or contexts potentially being understood differently in different languages. The coding process was conducted collaboratively with colleagues in the research project to enable triangulation, and was complemented by procedures aimed at consistency and interpretive robustness, such as intercoder reliability testing (Flick, 2004; O'Connor and Joffe, 2020).

The specific subsets of interview data used for each article will be explained in each chapter, and the numbers will vary since further interviews were conducted throughout the writing process of the articles. The method sections of chapters two to five provide a more detailed description of the data, including how interviewees were identified, how the interview guidelines were structured, the coding procedures, and how the different conceptual frameworks were operationalized using inductive, deductive, and abductive approaches. As these aspects differ for each article in this dissertation, the dedicated method sections describe which parts of the data were used in each context and provide further information.

[4] The interviews conducted in Germany were mostly conducted in German (including one in English), while those carried out in Italy were conducted in Italian, in India in English and in China in Chinese, English and German.

1.3.3 Methods

Based on this data, and in collaboration with co-authors, we employed various subsets and methods tailored to address the research objectives outlined in section 1.2.4 (Figure 2). The first two articles in chapters two and three address research objective one by exploring the desirable futures envisioned in the construction sector across countries, using a deductive approach and, to some extent, an inductive one. This first enables the identification of the possible future directions of the socio-technical transition, before analyzing specific transition dynamics in the present. To examine desirable futures, discourse analysis has proven beneficial in exploring what Oomen et al. (2022) refer to as 'techniques of futuring'. This is because desirable futures become most visible when storylines that inform us about the future are identified (Hajer, 2010). These storylines and discourse coalitions also help to address the second research objective by examining the extent to which the previously identified visions are validated locally and generally, and ultimately assessing the extent to which the visions are perceived as legitimate (Johnson et al., 2006). Both articles on the futures of bio-based construction compare the four countries in order to assess the differences in the socio-technical logics of visions, as well as their legitimacy across countries. This comparative design (Yin, 2009) allows for the identification of how visions vary across institutional and geographical contexts.

To operationalize the activities and processes currently taking place in relation to the socio-technical transition in the construction sector, STCA (Heiberg et al., 2022; Truffer et al., 2025) and well-established qualitative content analysis have previously been used in the literature to achieve research objectives two and three. Qualitative content analysis provides a helpful approach for analyzing struggles over legitimacy in present sustainability transitions (research objective two) (Alsheimer et al., 2026; Schnell and Mattes, 2026). The STCA was developed in previous years to identify socio-technical configurations and their relations (research objective three) (Heiberg et al., 2022; Truffer et al., 2025). To complement the study of four different countries in chapters two and three, chapter four narrows its geographical focus to analyze present socio-technical transitions in two contrasting geographical contexts: India and China. The aim is to compare the different stages of maturation of bio-based construction materials. The logic behind this choice is explained in more detail in sections 4.3 and 4.4.1.

Chapter	Research objectives	Geographical focus	Temporal dimension	Methods
II	Contested visions	Germany Italy India China	Future	Discourse analysis
III	Contested visions; Struggles over legitimacy		Future	Discourse analysis
IV	Struggles over legitimacy; Relations and interactions of socio-technical configurations	Germany India	Present	Socio-technical configuration analysis & qualitative content analysis
V	Relations and interactions of socio-technical configurations	Chennai	Present	Qualitative content analysis

Figure 2: Details on methods and geographical focus of the different articles

To address the core of research objective three, the alignment of technologies, institutions and actors within several socio-technical configurations was identified using STCA based on a stratified subset of the interview data (Robinson, 2014). STCA is a semi-quantitative method that reconstructs how technologies, institutions and actors become aligned into 'configurations that work' within a given socio-technical field or system (Heiberg et al., 2022). It originated in sustainability transitions research as a response to the limits of single case narratives toward more diversity, and it adapts insights from discourse network approaches (Leifeld, 2017) to capture how actor positions, institutional elements, and technological options are assembled and contested across contexts. STCA starts from the epistemological assumption that actors' reported statements and practices reveal deeper structures, i.e., coherent packages of technological and institutional elements that tend to cluster into recognizable configurations (Heiberg et al., 2022; Truffer et al., 2025). To proceed, the method requires coding textual data (e.g., interview transcripts, newspapers, reports) by linking certain actors to concepts (technologies, rules, norms, values, policy instruments, practices). Speaking of the construction sector, if an architect talks positively about timber and its benefits from prefabrication, then it might be coded with the actor code 'architect' and the concept codes 'timber' and 'prefabrication'. These co-mentions of actor and concept codes are then translated into two-mode actor or concept networks and projected into network maps using similarity measures (mostly based on the Jaccard-value), which visualize patterns of relatedness between elements (see Miörner et al., 2022b). The coding process occurs in an abductive approach (Vila-Henninger et al., 2024) including triangulation with colleagues and testing. Clusters that are visible in the networks can be interpreted as contested or complementary configurations, while shifts in centrality and clustering indicate changing degrees of institutionalization and emerging trajectories. In this way, STCA bridges qualitative content analysis with tools from social network analysis to map the building of configurations, contestation, and field or system structuration in a transparent and comparable manner (Heiberg et al., 2022; Truffer et al., 2025).

The method is increasingly used in transition studies (Lesch et al., 2023; Miörner et al., 2022a; Yap et al., 2023), but is still before broad adoption in the field. In the effort to advance the interpretation of STCA, we extended the classical STCA by analyzing the specific interactions between configurations in detail (chapter four) using qualitative content analysis (Kuckartz, 2019). This overcomes the so far mostly descriptive nature of links in STCA networks. Although the strength of links could be assessed using Jaccard values, it remained unclear what this strength indicates about the relationship between two elements in a network. The proposed extension allows the connotation of a link to be interpreted, as it may have a positive, neutral, or negative association between two elements in a network. Once the links' connotation is identified, the interaction mode between the two configurations can be assessed. This modifies Sandén and Hillman's (2011) framework for assessing how technologies interact, extending it to encompass entire socio-technical configurations and their interactions. Section 4.3 describes the extension and underlying principles of STCA in more detail.

Lastly, research objectives two and three are jointly addressed in chapter five, where the relations between configurations are examined by conceptualizing struggles over legitimacy. To assess how and which system resources are mobilized by which configurations, qualitative content analysis is suitable (Heiberg and Truffer, 2022b; Mazzoni et al., 2025). We applied this to one system resource (i.e. legitimation) and aimed to explore how the relationship between socio-technical configurations is shaped by legitimation and de-legitimation. This article's conceptual framework is based on transition and defensive work, which can be examined using qualitative content analysis (Löhr et al., 2022). We used a deductive coding approach to identify (de-)legitimation, which is described in more detail in section 5.3. In this context, we examined a sustainability transition case in Chennai in order to analyze a particular regional case. To assess the multi-scalarity inherent in legitimation, including de-legitimation derived from other geographical scales, we employed qualitative content analysis. Unlike chapters two and three, where the object of legitimacy was the respective visions, chapter five focuses on the emerging socio-technical configuration in Chennai that pursues bio-based materials. This allows us to analyze whether a coherent set of interrelated technologies, institutions and actors is considered legitimate. Similar to the approach of Schnell and Mattes (2026), this approach broadens the scope of previous operationalizations of technological legitimacy (Binz et al., 2016a; Markard et al., 2016) by addressing the complexity of socio-technical transitions beyond the mere functioning and legitimacy of a technology.

1.4 Overview of research articles and main findings

This dissertation comprises four research articles that address the three research objectives. All of the articles have been either published or are under peer review in international academic journals. Table 1 lists details on the publication status, title, authors and objective of each article, as well as the chapter in which it is displayed in this dissertation. In addition to these articles, I initially started exploring bio-based technologies in the chemical and pharmaceutical sectors. Together with Sebastian Losacker and Sven Wydra, I analyzed national specialization and diversification in bio-based technologies (Fischer et al., 2024), which sparked my excitement about the potential of bio-based solutions.

All of the articles draw on the interview data described in section 1.3.2, and each one contributes to achieving some of the research objectives. A detailed discussion of the results of each article can be found in its respective section of this dissertation. Sebastian Losacker co-authored the first two articles and supported the conceptualization and writing of minor parts of both. These articles examine how the future of a bio-based construction sector might look in order to address the first research objective. Chapter two identifies six imaginaries in the making of a bio-based construction sector in four countries. The most developed imaginary is the selective use of bio-based materials alongside conventional materials. We find that actors in India and China predominantly envision using bamboo in the sector's future. While this seems promising at first, conflicts arise from the intended use of the material. Some envision an engineered use of bamboo to produce higher-quality, albeit more expensive, construction materials, while others imagine a frugal use of bamboo to produce affordable, sustainable, and simple buildings. Similar differences exist in the socio-technical logic of how materials are envisioned to be used in Germany and Italy. Some actors advocate using timber in multi-storey housing, while others pursue an ecologically balanced use of timber to ensure the sustainable use of locally sourced wood. We reveal central tensions and complementarities among different socio-technical logics. In principle, the market segments addressed by visions of more sustainable uses of bio-based materials are complementary to those involving highly processed bio-based materials. However, the underlying values of these logics lead to significant conflicts, as observed in the expert interviews. These conflicts arise from each actor presenting their own vision as the only appropriate logic while denying the validity of alternative logics for using the construction material. These conflicting ideas about the future of bio-based construction could hinder the sector's sustainability transition.

Table 1: Details of research articles in this dissertation

Chapter	Title and authors	Objective	Publication status
II	Competing or complementary?: Socio-technical imaginaries of a bio-based construction sector - *Fischer & Losacker*	Identifying imaginaries in the making of a future bio-based construction sector	Published in the *Journal for Technology Assessment in Theory and Practice*
III	How to build (in) the future? Legitimacy of socio-technical visions in a bio-based construction sector - *Fischer & Losacker*	Conceptualizing how socio-technical visions become collectivized by analyzing a crucial condition: their legitimacy	Published in *Environmental Innovation and Societal Transitions*
IV	Partners, foes or parasites? How interacting socio-technical configurations shape the directionality of technological fields - *Fischer, Losacker & Truffer*	Developing a conceptual framework and extension of the STCA to study the interaction of emerging socio-technical configurations	Submitted to *Research Policy* in November 2025 Under review as of February 2026
V	Why does transformative knowledge fail to transform? A multi-scalar (de-)legitimation perspective on the construction sector in Chennai, India - *Fischer & Losacker*	Conceptualizing multi-scalar (de-)legitimation of an emerging socio-technical configuration	Submitted to *Regional Studies* in December 2025 Under review as of February 2026

The next article discusses a key condition for visions to become collectivized: legitimacy (chapter three). By bridging the work on socio-technical visions and the literature on legitimacy, we address research objectives one and two by conceptualizing the collectivization of visions. The developed framework reveals how individual visions become collectively embraced and potentially evolve into socio-technical imaginaries. We argue that visions are validated locally and, depending on their perceived legitimacy within a sector, they may become dominant. This depends on general validation; that is, if a vision shows high legitimacy across all dimensions (pragmatic, moral, and cognitive) and thus constitutes the dominant vision within a sector. The framework enables transition scholars to explain why some visions become dominant while others remain alternatives. A central barrier to legitimizing visions of a bio-based construction sector is aligning them with established customs and beliefs (cognitive legitimacy). We find that prior validation of the pragmatic and moral dimensions is required for the cognitive dimension, in order to demonstrate the tangible benefits of adopting the vision and ensure consistency with the sector's prevailing norms and values. Otherwise, actors struggle to make their vision comprehensible, especially to other key actors in the sector. The only vision that is somewhat taken for granted is engineered bamboo in China, mainly due to prior demonstration projects.

The remaining two articles use these potential future directions of the transition as premises to analyze what shapes the evolution of transformative configurations in the present. The article in chapter four was co-authored with Sebastian Losacker and Bernhard Truffer, who contributed to the conceptual framework and minor parts of the writing. In this article, we explore how several socio-technical configurations interact and address research objective three (see chapter four). We propose a framework that conceptualizes how the interaction of emerging configurations in a technological field shapes its directionality. The emerging field of sustainable construction materials was examined through a comparative case study of India and Germany, which provided two geographical contexts with distinct institutional conditions and contrasting stages of maturation. Using socio-technical configuration analysis (STCA) and drawing on expert interviews, we identified two prevailing configurations in both countries: an incremental configuration centered on greening conventional building materials and a transformative configuration based on bio-based materials (bamboo in India and timber in Germany). We adapted and extended a framework for technology interaction by Sandén and Hillman (2011) to encompass the specific interactions between the configurations. This allows us to understand how different modes of interaction (e.g., symbiosis, neutralism, competition, parasitism, commensalism, and amensalism) impact a configuration's capacity to mobilize system resources, including knowledge, legitimacy, market formation, and financial investments. Our analysis reveals a polycentric field structure in India, characterized by strong interdependencies and synergies between bamboo and the incremental configuration. In contrast, the German technological field is more fragmented. The timber-based configuration is more mature and has a rather antagonistic relationship with the incremental configuration. Overall, our approach allows us to systematically map and assess field-internal interdependencies and their implications for the evolution of technological fields and directionality.

The last article takes a multi-scalar perspective and conceptualizes an emerging configuration as an object of (de-)legitimation. This addresses research objectives two and three (chapter five). In this article, we explore whether transformative knowledge translates into transformative change by linking the emerging debate on transformative knowledge to the literature on multi-scalar (de-)legitimation. We develop a conceptual framework that shifts the focus from legitimacy as an outcome to (de-)legitimation as a co-constitutive process that unfolds across geographical scales. Drawing on the transition work framework (Löhr et al., 2022), we show how emerging transformative configurations gain legitimacy by creating, maintaining, and disrupting transition-related processes, while established configurations maintain and repair their legitimacy through defensive work. We propose distinguishing the de-legitimation of an emerging configuration by incumbents as either implicit or explicit. Our findings suggest that, although transformative knowledge in Chennai is mission-oriented and based on experimentation, it remains constrained due to incumbent knowledge lock-in. These lock-ins are reinforced through established building codes, certification practices, and dominant narratives of growth, speed, and quality. Ultimately, the established configuration undermines bio-based materials in Chennai, limiting the configuration's ability to disrupt established institutions, incumbents, and technologies. Overall, this article emphasizes that overly optimistic expectations about transformative knowledge may be unrealistic. Diffusion and scaling depend on multi-scalar (de-)legitimation, as well as transformative capacities that extend beyond experimentation. In particular, weak institutional and adaptive capacities explain why transformative knowledge has so far not been sufficient to reconfigure the socio-technical system and why adapting regulatory and institutional arrangements is critical for emerging configurations pursuing bio-based construction. This article was co-authored with Sebastian Losacker, who contributed to the conceptualization of the framework and minor parts of the writing process. The results of each article are discussed in detail in the respective chapters and in the conclusion section below.

1.5 Conclusion

1.5.1 Theoretical contributions

In this dissertation, I have addressed *'how to build (in) a sustainable future?'* by conceptualizing desirable futures as geographically embedded and shaping directionality: actors articulate contested visions of the future, seek validation and legitimacy for those futures, and build or impede socio-technical configurations in the present through institutional work and resource mobilization. Building on the research objectives introduced in section 1.2.4, this dissertation provides theory-grounded inroads into what sustainable construction futures could look like and how they might be attained. This is explored by examining how visions, struggles over legitimacy and the relations between socio-technical configurations in the present jointly shape sustainability transitions. While the individual chapters (two to five) present the results in detail, the following chapter highlights the dissertation's key contributions and how they contribute to conceptualizing and extending existing work in the economic geographies of sustainability transitions and their futures (Benner, 2024; Binz et al., 2025; Gong, 2024).

Across chapters two to five, geographical scales and varying geographical contexts are identified as an active condition that shapes which futures appear appropriate, how configurations interact, and how legitimacy is mobilized across places and scales. The results of this dissertation emphasize that similar claims over e.g., what sustainability entails can be evaluated differently depending on values and rules that are bound to a particular geographical context, as well as due to multi-scalar influences. Starting with exploring possible futures in the construction sector, four countries were analyzed and compared in chapters two and three to identify the variety of visions. Afterwards the focus was narrowed to examine two contrasting contexts in chapter four. This sheds light on how geographical context needs to be considered for sustainability transitions, as the main conditions and contextual factors might vary from one place to another (as is the case with Germany and India). In our case, the contrasting stages of maturation in the technological field were particularly important in explaining how interactions between configurations affect the development of transformative configurations, as well as the directionality of the entire field. Lastly in chapter five, the geographical perspective zoomed in on one regional case, i.e. the construction sector in Chennai, while also considering multi-scalar influences of (de-)legitimation. Building on previous valuable contributions on this matter (e.g. Heiberg, 2022; Miorner et al., 2026), this dissertation provides a geography-sensitive understanding of configurations that 'work': configurations become viable when actor coalitions, institutional rules and values, as well as technologies align in place-specific ways, while also drawing on extra-local resources.

In research objective one, I aimed to analyze how and which futures are envisioned and to develop a framework to capture a crucial condition for visions to be generally validated and collectivized, i.e. their legitimacy. In chapter two, we first identified the prevailing visions of a bio-based construction sector. We highlighted how these visions often appear complementary in principle, for example, by addressing different market segments. However, we emphasized that their contested socio-technical logics lead to conflicts over how certain bio-based materials should be used. These different visions demonstrate the wide range of desirable futures in sustainability transitions. They also emphasize that, for the same materials, there are different visions and underlying socio-technical logics for using these materials in different countries. Thus, the findings reveal that the formation of desirable futures is geographically embedded: what constitutes a convincing and desirable (bio-based) future depends on local industrial capabilities, uneven geographical building traditions, and varying regulatory contexts.

The visions identified in chapter two raise the question of which of these diverse ideas might eventually become dominant in a sustainability transition. As Rudek (2022) also pointed out, the question of how visions coalesce into collectively held, desirable futures, i.e. socio-technical imaginaries, is a crucial area of research. Along with widely existing conceptual fuzziness of ideational concepts (Benner, 2024) and a lack of clarity of what scholars imply by 'the collective' (Kuchler and Stigson, 2024), chapter three contributes to the understanding of how visions are collectivized. We conceptualize a crucial condition for them to become dominant: the legitimacy of visions. This framework enables transition scholars to, first, identify which vision is more generally validated (legitimized) and thus, the dominant one in a given sector's sustainability transition. Second, it contributes to ongoing efforts to address the fuzziness in the use of ideational concepts by conceptualizing how 'imaginaries in the making' (Braun and

Kropp, 2023) are formed: individual (private) visions, shared visions and eventually collectivized socio-technical imaginaries can be distinguished along the level of collectivization. This framework has demonstrated its usefulness in conceptualizing the formation of ideations in socio-technical transitions. Based on this, I propose that scholars in sustainability transitions and economic geography might categorize ideational concepts using a simple, stylized progression (without implying linearity). First, individual expectations feed into private visions. When these visions are shared among actors in a transition, they coalesce into more widely shared imaginaries. Finally, these imaginaries stabilize into socio-technical imaginaries that are publicly performed and institutionally sedimented. Even though the relationship between individual and collective levels is mutually constitutive and not linear (Friedrich and Hendriks, 2024; Oomen et al., 2022), this could at least offer a heuristic for identifying where collectivization of ideation stagnates alongside other recent attempts (Benner, 2025; Friedrich and Hendriks, 2024).

Research on legitimacy in the fields of innovation and transition studies offers a coherent way to theorize why visions, technologies, and broader socio-technical configurations are perceived as desirable or appropriate and eventually do (or do not) become ‘configurations that work’ in sustainability transitions (Binz et al., 2016a; Markard et al., 2016). As the conceptual hinge linking possible futures in transitions and the progress of these visions in the presently ongoing transition, this dissertation explores struggles over legitimacy in the present and for the future. Research objective two was first addressed in chapter three, as outlined above, conceptualizing how visions not only help to legitimize socio-technical configurations in the present, but also have to be legitimized in order to eventually become performative in the future. In this dissertation, struggles over legitimacy are thus, developed as a mediating mechanism between the present and the future when analyzing and conceptualizing the economic geography of sustainability transitions. Chapter five analyzes how socio-technical configurations require legitimacy in the present to be built, to evolve and to be stabilized against incumbent resistance. Conversely, incumbent configurations must maintain and repair their legitimacy under pressure, or they may face deinstitutionalization and decline. To capture this interdependence, the developed conceptual framework combines both the mutually interdependent nature of (de-)legitimation across socio-technical configurations and the inherent multi-scalarity to unfold a broader understanding of how (missing) legitimacy shapes sustainability transitions. It builds on and extends recent work on (de-)legitimation (Schneider and Rinscheid, 2024; Schnell and Mattes, 2026) by a multi-scalar perspective and emphasizes that legitimacy is not merely local acceptance or bound to national regulation, but a shifting pattern of evaluations across places at different geographical scales. As elaborated in chapter five, we contribute to a multi-scalar interpretation of de-legitimation, as we developed how incumbent stability can be produced by defensive work that keeps evaluation criteria aligned with established routines, thereby limiting the impact on transformative change by transformative knowledge and alternative visions. Taken together, this dissertation also emphasizes that legitimation and de-legitimation are not separate processes: they co-occur in shared socially constructed systems and often operate through the same evaluators and institutionalized standards.

Legitimation is also one of the four system resources required for socio-technical configurations in order to evolve. The mobilization of such resources, however, happens not in isolation but in contestation of different configurations in the same socio-technical system (Binz and Truffer, 2017; Miörner et al., 2022a). Thus, chapter five also contributes to research objective three, by showing how one system resource (legitimation) is mobilized by contested configurations and how this shapes the relation between configurations across geographical scales. We conceptualized how the aim to mobilize legitimacy affects not only one's own configuration, but also other configurations within the same socio-technical system. This is because the relationship between two or more configurations leads to their (de-)legitimation. Research objective three also aimed to develop a conceptual framework that captures how socio-technical configurations relate to and interact with each other. Together with my co-authors, we addressed this objective in chapter four grounded in the seminal work by Pistorius and Utterback (1997) and Sandén and Hillman (2011) that theorizes multi-mode interaction between technologies. Our framework therefore complements the literature on technology interactions, by shifting the 'interacting object' from technologies toward entire socio-technical configurations. It supports understanding how configurations co-evolve and overlap beyond the level of technologies. We conceptualize what Miorner et al. (2026) refer to as friction and contestation between configurations as the specific interactions between configurations over the same institutional elements. The degree to which configurations form synergistic or antagonistic relationships, as measured by their interactions, enables us to identify those that benefit or are inhibited by different interactions. This is particularly important because it allows us to examine technological fields with transformative configurations, such as in our empirical case, to determine whether incremental or transformative changes to the status quo can be expected during a socio-technical transition. Furthermore, by contrasting India and Germany, we demonstrate that different geographical contexts influence the ability of transformative configurations to mobilize critical resources for evolution. The differing stages of technological field maturation (as observed in India and Germany) also shape the resulting diversity and directionality of these fields. More mature technological fields demonstrate stronger directionality but also a higher degree of contestation between co-evolving configurations. These results contribute to the ongoing discussion on diversity and directionality within the broader field of innovation and transition studies (Bulah et al., 2024; Stirling, 2011).

In addition to the theoretical contributions described above, a methodological contribution was developed to complement the theoretical understanding of interactions between socio-technical configurations. As part of research objective three, I aimed to improve the empirical operationalization of configurations and their interactions. This issue was addressed by expanding the socio-technical configuration analysis (STCA). In chapter four, together with Sebastian Losacker and Bernhard Truffer, we pursued this goal by complementing the previously identified configuration structures identified through STCA with a supplementary qualitative content analysis that systematically captures interaction patterns and their effects. This extension combines the strengths of both approaches. It retains STCA's ability to identify and map socio-technical configurations in a structured manner while adding an interpretive approach to examine and compare overlapping configurations and interactions across cases. In short, the methodological contribution lies in linking STCA's mapping of one-mode concept networks with a qualitative coding approach to identify, describe, and assess interactions. This approach allows for a more detailed analysis of where and how socio-technical configurations interact and influence one another.

1.5.2 Policy implications

Although most articles in this dissertation have a focus on conceptual contributions to the literature, the findings also have policy implications. I will reflect on different policy debates in the fields of transition and innovation studies before drawing out the specific implications for India and, in particular, Chennai, given the focus of my empirical research when conducting expert interviews in recent years. As indicated at different points of this dissertation, sustainability transitions are very complex and deriving specific policy implications is equally challenging. As other transition scholars have laid out, the following implications always have to be considered in policy mixes to assess their viability in complex and multi-scalar transition dynamics and to avoid unintended consequences (Raven and Walrave, 2020; Rogge and Reichardt, 2016).

As Hansen et al. (2024) have pointed out, policies always have a scalar orientation, which affects their legitimacy. In this way, policy rationales can be oriented both locally and globally with regard to the challenges to be addressed and the effects instigated. For the Indian case in particular, this perspective sheds light on the contrasting scalar orientation of the challenges and the effects of policies. While the national building code affects the entire country, different local challenges are largely ignored. These varying challenges are best symbolized by India's five different climate zones, which are not currently addressed by the national building code. Addressing the various local challenges faced by construction materials across India could also ultimately lead to higher local legitimacy of sustainable construction materials, as outlined by

Hansen et al. (2024). Policies should be capable of being adjusted at a regional level, based on the region's requirements for sustainable materials. In the case of Chennai, for example, this could lead to the tropical climate being considered when planning new buildings, as well as the local availability of bio-based materials. Thus, regional municipalities should assess and regulate which materials best fulfil regional requirements and can be considered sustainable in each context. This may include public procurement to facilitate innovation (Eriksson et al., 2026).

The debate on innovation policies has moved in recent years from focusing on 'innovation for growth' and 'national systems of innovations' toward 'transformative change' (Schot and Steinmueller, 2018; Weber and Rohracher, 2012). While transformative or mission-oriented innovation policy aims at specifically addressing grand societal challenges (Diercks et al., 2019; Kirchherr et al., 2023), they often disregard the geographical implications of such policies (Uyarra et al., 2025). Considering regional transformative capacities (see Hofstad et al., 2026) could help policymakers tailor policies to their geographical context. Transformative innovation policies often focus on aspects such as ideation or experimentation (Ghosh et al., 2021a). However, as shown in our empirical case study in chapter five, related capacities in Chennai are already well developed, while others are lacking. In the case study of bio-based construction in Chennai, policies aimed at strengthening weak institutional and adaptive capacities could help to overcome barriers and drive transformative change. Thus, understanding why local transformative capacities are lacking and require support can help shape impactful policies that may lead to transformative change.

The main principle of transformative innovation policies is often to provide directionality in a socio-technical transition (Andersson and Hellsmark, 2024; Bergek et al., 2023). While this is a desirable goal for most sustainability transitions, the construction sector has a wide range of potential sustainable solutions that need to be addressed differently in different geographical contexts. Building on the findings in chapter four, in less mature technological fields such as India, this diversity of solutions can lead to synergies. Accordingly, this diversity could be embraced in transformative innovation policies by improving standards in a way that benefits both configurations. Conversely, in more mature technological fields, such as in Germany, parasitic interactions that favor transformative configurations may be desirable in order to inhibit incremental configurations. Overall, the findings of this dissertation suggest that it is useful to consider the interaction of emerging socio-technical configurations when reflecting on directionality in transformative policy debates. The resulting effects of these interactions can be used as a basis for assessing the influence of policies on not only one configuration, but potentially the entire field or system. More specifically, policies should consider which instruments could create synergies between emerging and contested configurations and which could eventually lead to absorption or displacement.

1.5.3 Limitations

The findings of this dissertation have to be interpreted in the context of some limitations. The interview data used for all articles focused only on a snapshot of the socio-technical transition in the construction sector in terms of both the temporal dimension and geographical focus. I have taken into account perspectives on the present as well as on the future. However, unfortunately, the development over time is not included in the expert interviews conducted as part of the larger TRABBI research project. Accordingly, the socio-technical transition is only viewed at one point in time, rather than across its evolution. Legitimation and the formation of visions depend on time and may appear different over time due to institutionalization (Berkhout, 2006; Johnson et al., 2006). While the research articles in this dissertation reflect on the temporal dimension conceptually, the empirical data employed limit its operationalization. With regard to the countries studied, I tried to include those with rapidly growing construction sectors, such as India and China, as well as those with more developed built environments, such as Germany and Italy. However, focusing on these countries means that diverging technologies and visions in other countries are overlooked. Cross-national case studies cannot fully capture the regional diversity within each national case (e.g. subnational regulatory differences and regional industrial structures).

The selection of interviewees in our research design, of course, influences the visions that were identified later on to a large extent. In this context, it is important to acknowledge that some visions are always excluded or rendered invisible, as referred to by Jasanoff and Simmet (2021) as ‘excluded imaginaries’. Furthermore, the set of expert interviews included in all articles is based on professionals in the sector, supplemented by organizations such as interest groups and government bodies. However, this approach focuses on the experts’ perspective and largely excludes ‘public imaginaries’ (Cherry et al., 2017). Civil society actors and residents of such buildings are not included, even though they influence future-making (Friedrich and Hendriks, 2024; Rohde and Santarius, 2023). This also constitutes a limitation when examining legitimacy, as the evaluators analyzed are experts in their respective sectors. However, the legitimacy of a socio-technical configuration arguably also depends on a positive evaluation of the public and how legitimate it is perceived in public discourse (Schneider and Rinscheid, 2024; Schnell and Mattes, 2026). Put simply, if civil society does not want to live in bio-based buildings, this negatively affects the legitimacy of a socio-technical configuration that advocates the use of bio-based construction materials. This would further strengthen established configurations around cement and steel, undermining and de-legitimizing bio-based materials. In addition to the specific limitations outlined for this dissertation, the common limitations of qualitative analysis also apply. These include but are not limited to, the interview-based design, which reflects institutional interests and may include retrospective rationalizations that gloss over past events (Flick, 2004; Kracauer, 1952). The design and interpretation of the interviews in this dissertation are shaped by a Western academic perspective influenced by narratives of development and progress. This may unintentionally prioritize Western framings of what counts as relevant knowledge and desirable change (Arora and Stirling, 2023). This could result in neglecting the ways in which sustainability transitions in India (and the Global South more broadly) are shaped by historically produced inequalities, contested power relations, and epistemic hierarchies. This includes the areas of expertise that are recognized and the problems and solutions that are considered feasible (Ghosh et al., 2021b).

Although STCA enables mapping socio-technical configurations and overcoming the limitations of identifying reconfigurations through qualitative approaches (Heiberg et al., 2022; Svensson and Nikoleris, 2018), the method has limitations of its own. Overall, the complex transition dynamics inherent in socio-technical change are highly simplified. While mapping the configurations and relations between actors, institutions and technologies is analytically powerful, it necessarily compresses complex dynamics into a limited set of components and relations. Thus, careful interpretation of STCA is required to distinguish between different types of socio-technical configurations and avoid oversimplifying complex motivations of actors. Identifying actor and concept codes makes STCA highly sensitive, depending on how many statements are interpreted and where the boundaries between codes are drawn (Miörner et al., 2022b; Truffer et al., 2025). The proposed extension of STCA by a qualitative content analysis may be a way to address some of these limitations. It is, however, a new approach that requires revision and reflection by other scholars in the field in order to verify its feasibility. Accordingly, the findings in chapter four need to be treated with those limitations in mind. Similarly, the conceptualization of socio-technical configurations is a simplified way of summarizing how technologies, institutions and actors align, and this, of course, depends heavily on the data used to identify them. The two configurations identified in articles three and four may oversimplify a more heterogeneous field or socio-technical system. When interpreting the findings presented in this dissertation, these limitations of the conceptualization and operationalization of socio-technical configurations must be considered.

1.5.4 Further research

Based on the findings of this dissertation, several future research avenues are worth exploring. I will highlight a few that directly emerge from the results and limitations. In line with the structure of the dissertation, I first consider contested futures in sustainability transitions and the aspects that remain to be explored. Regarding the formation of ideations, this dissertation's suggested stylized progression of ideational concepts can be viewed as a starting point for understanding part of the collectivization process. Further work is needed, of course, to more clearly distinguish and conceptualize terms related to futures in sustainability transitions and economic geography, and to clarify their conceptual boundaries and relationships. Related to this, it is not conceptualized in detail how collectivized socio-technical imaginaries become reality. In line with the work of Friedrich and Hendriks (2024) and Oomen et al. (2022), future research investigating how visions become performative and the mechanisms through which they translate into material outcomes would facilitate a more systematic assessment of the nexus between ideations and socio-technical transitions. In this context, various visions co-exist and evolve in a co-constitutive way, not separately from each other. The reinforcing dynamics between individual and established visions throughout the collectivization process, need to be addressed in order to overcome the linear understanding of the future that often prevails in economic geography (Gong, 2024).

When analyzing visions or imaginaries, further research should explicitly engage with a more diverse range of futures by incorporating public ideation (see e.g. Friedrich and Hendriks, 2024; Rohde and Santarius, 2023). Since public imaginaries are often unevenly represented or excluded (Jasanoff and Simmet, 2021), future research could expand the empirical basis beyond expert interviews to include documents such as policy reports and newspapers, which may offer a more nuanced reflection of public imaginaries and their contestation. Additionally, the role of geography in shaping desirable futures could be examined beyond the observation that visions and imaginaries are geographically situated. Taking a dedicated, multi-scalar perspective on visions and imaginaries, building on the contributions by Benner (2025) or Lambert (2022), would reveal more specific, geography-related perspectives. One possible starting point is to study the scalar orientation of visions or imaginaries, as some may be anchored in a specific region, while others may be driven at a national or even global level. This scalar orientation may affect the collectivization and contestation of different visions. Overall, these approaches would provide a more nuanced representation of 'the future' of a transition as contested, non-linear, and multi-scalar.

There are also valuable avenues for further conceptualizing struggles over legitimacy. In this dissertation, I viewed legitimacy as 'stable' at a given point in time due to limited access to information on past developments. In contrast, recent contributions conceptualize struggles over legitimacy as much more fluid and dynamic (Schnell, 2025; Schnell and Mattes, 2026). In general, treating legitimation as a process of contestation and examining how configurations become legitimized or de-legitimized over time would improve our understanding of how struggles over legitimacy evolve. Similarly to the argument made above regarding the plurality of visions, future contributions examining legitimacy in transitions should also consider including the public and private users in order to capture the plurality of evaluators. These groups are also crucial to understanding what is perceived as legitimate (Schneider and

Rinscheid, 2024; Schnell and Mattes, 2026). In the construction sector, it is important to consider residents, affected communities and actors downstream of the value chain as evaluators of legitimacy. Moreover, future studies could more actively address their Western academic lens and foreground how transition pathways in India and other Global South contexts are negotiated by engaging more explicitly with decolonial and postcolonial approaches (Ghosh et al., 2021b; Torrens et al., 2021).

Finally, this dissertation opens up opportunities for further research on socio-technical configurations and their interactions. While this dissertation focused on relations and interactions within the construction sector, adopting a perspective of multi-system interactions (Andersen and Geels, 2023; Löhr and Chlebna, 2023) would reveal how other adjacent sectors influence and interact with the construction sector. As such, forestry, agriculture, finance, real estate and waste management influence transitions and legitimacy at their intersection with the construction sector. A multi-system lens would specify how transitions in the construction sector depend on cross-sectoral interdependencies in addition to internal dynamics. With regard to relations within the sector between socio-technical configurations, dedicated perspectives are required to validate our initial findings on how configurations interact through the mobilization of certain resources. Furthermore, the role of system resources (beyond legitimation) when multiple (emerging) configurations aim to mobilize knowledge, investments or market formation needs to be explored. This would provide a clearer identification of the effects of the relationships between socio-technical configurations. In addition, it would be beneficial to assess how overlapping configurations change over time, and consequently, how interaction modes evolve. Outside of the field of sustainable construction materials, the interaction between configurations could be examined in relation to other societal functions, such as mobility, energy and food, to identify instances where transformative configurations benefit from interdependence and instances where they are constrained by absorption into incremental configurations. As noted above, further work is required for the STCA to be refined in order to assess not only socio-technical configurations, but also their interactions and the effects of these interactions. For example, the feasibility and robustness of the qualitative extension proposed in chapter four need to be assessed across case studies.

To conclude, future research in economic geography and sustainability transitions is well positioned to explore the avenues highlighted above, particularly given the growing urgency of decarbonizing sectors in policy and practice. At the same time, if the geography of transitions community is to meaningfully contribute to real-world transformation, it will need to adopt a more holistic perspective on how transitions become reality. Examining only how new materials and technologies emerge or focusing predominantly on expert narratives will not be sufficient. Instead, future research should systematically explore how transformative configurations emerge and gain traction, mobilize resources and become institutionalized, or remain constrained and marginal. If future research engages with the outlined dimensions, it may be better positioned to explain why transformative configurations emerge and why they often struggle to scale, as well as identify potential leverage points for scaling.

Chapter Two

2 Competing or complementary?: Socio-technical imaginaries of a bio-based construction sector

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Abstract

The construction sector needs to transition towards using more bio-based building materials in order to reduce its environmental impact. However, it is unclear how exactly this future will look like, with different stakeholders in different geographical contexts having varying visions of the sector's future. Utilizing a comprehensive collection of expert interviews with stakeholders from the construction sectors in China, India, Italy, and Germany, we identify six primary visions. These are characterized by variations in their socio-technical logics, including preferred materials, targeted market segments, economic characteristics, and the stage of development. While many visions appear to be complementary in principle, our findings also reveal the presence of conflicts, often socially constructed. These conflicts may impede the progress of the transition toward a bio-based construction sector, as certain visions may delegitimize alternative uses of bio-based materials.

2.1 Introduction

The construction sector is a major contributor to climate change, much of which can be attributed to the materials used, particularly carbon-intensive materials like steel and cement (Churkina et al., 2020). Although many sustainable building materials are already available and many more are currently being researched and developed, the transition has not yet gained momentum (Dewald and Achternbosch, 2016; Jayaweera et al., 2023). In this paper, we argue that one of the reasons for the material transition not taking off is the variety of visions about how the construction sector should look in the future. These visions, which we will refer to as 'socio-technical imaginaries (STI) in the making', differ not only between countries, hindering a global material transition, but also within countries and are often conflicting (Mast 2022; Braun and Kropp 2023). This means that within certain socio-technical configurations (i.e., within a country or a stakeholder group) the construction sector struggles to provide a shared vision of how it will become more sustainable, thereby potentially delaying the transition process.

Against this background, the goal of this paper is to shed light on different visions of a future bio-based construction sector, analyzing to what extent these visions are conflicting or complementary. Our empirical analysis is based on expert interviews with stakeholders in the construction sectors of China, India, Italy, and Germany. This approach provides us with very diverse cases in terms of the state of the built environment, the progress of the transition, and, of course, in addition to the materials used, the social and institutional aspects inherent in the socio-technical transition. The paper provides important insights into visions of a bio-based construction sector and reveals how visions can compete in some dimensions, but also complement each other, towards a (collective) understanding of a decarbonized construction sector.

The article will proceed with a brief discussion on the concept of socio-technical imaginaries and their significance for sustainability transitions. We will then outline the research design, followed by a description of the imaginaries identified in our analysis. Next, we will delve deeper into the results, exploring whether these imaginaries are conflicting or complementary and how this influences the material transition in the construction sector. The article will conclude with a short summary.

2.2 Socio-technical imaginaries and sustainability transitions

The transition of sectors "*to more sustainable modes of production and consumption*" (Markard et al., 2012, p. 956) is accompanied by changing (formal and informal) institutions and is often facilitated by innovation and technological change. However, transitions are not solely about replacing environmentally harmful technologies (products, materials etc.) with more environmentally friendly ones; they also involve how these technologies are embedded in so-called 'socio-technical systems' (Geels, 2004). This means that transition processes depend on how society makes sense of technological change and how the usual logics (rules of the game) of a sector are transformed (Geels, 2004; Markard et al., 2012). This is particularly important for infrastructure sectors such as construction, where transitions are tangible and have an immediate impact on the way humans live. As such, we can expect that there are very different expectations for the future of the construction sector. These expectations translate directly into (private) visions of what the sector should look like in the future and how new materials and technologies should be used (Berkhout, 2006; Borup et al., 2006). Over time, visions can coalesce into collective imaginaries of the future, shared by multiple actors, which reveals potential pathways for sustainability transitions (Martin, 2021; Rudek, 2022).

The concept of 'socio-technical imaginaries', as proposed by Jasanoff and Kim (2009, 2013), is primarily used to describe strongly collectivized and shared visions that are publicly upheld, institutionalized, and provide a clear idea of the configuration of a socio-technical system. However, for many transition processes in their early stages, such as the material transition in the construction sector that we focus on in this paper, visions are less advanced and less concrete. In this paper, we therefore adopt the conceptualization proposed by Braun and Kropp (2023, p. 2) and refer to shared visions as "*imaginaries in the making: publicly performed and collectively held ideas about desirable futures shaped by and attainable through socio-technical advances but not yet fully and formally inscribed into institutional orders*." In the remainder of this paper, we will follow this definition when referring to visions, meaning that they are not yet widely held and institutionalized (imaginaries in-the-making). In the collectivization of actors' visions, socio-technical imaginaries can either become alternative or dominant (Rudek, 2022), and they can be 'contradictory but also complementary' (Trencher and van der Heijden, 2019). We also anticipate that visions may compete or complement each other. Thus, we assume that the interplay of different STI in the making could also affect which of these will become dominant and, consequently, drive the future transition process (Rudek, 2022; Trencher and van der Heijden, 2019). In this context, the socio-technical logics of competing visions are crucial to consider, since the transition in a sector and its envisioned future involve more than just contemplating which materials and technologies to use (Geels, 2004). Consequently, a 'material transition' must always be a 'socio-technical transition', which encompasses considerations about how these elements might alter the internal logic of the sector, making visions 'socio-technical'. As such, the visions of the future construction sector differ not only in the materials utilized and technologies or techniques used but also in the way how materials are used and the inherent changes, for example, in norms or social practices. These aspects are represented in the market segments these technologies can address and the economic characteristics that would change during the transition (Mast, 2022; Muehlberger et al., 2024). From this perspective, one can also deduce how different a vision is from the current socio-technical configuration of the sector, i.e., the regime logic, and assess how far developed the vision is in niche applications (Beck et al., 2021; Geels, 2004).

2.3 Research design

For the empirical part of the paper, we compare visions in four different countries (Germany, Italy, India and China). This enables the investigation of different configurations of socio-technical systems, as Germany and Italy both focus on timber due to its local availability, while India and China are at the forefront with their bamboo industry. In addition, both country pairs have comparable socio-economic contexts. We particularly focus on bio-based building materials and the various imaginaries regarding how to increase their use. We follow the idea of distinguishing expert and public imaginaries (Cherry et al., 2017), and focus on the former, as we are especially interested in expert visions. These may be shaped and co-produced by interactions with public imaginaries, which is also evident from our data. We conducted semi-structured (online) interviews with several stakeholders (experts) in each country, ranging from material suppliers, researchers and bioeconomy startups to architects, engineers and planners. Additionally, we conducted interviews with industry associations and governmental authorities. Stakeholders were selected using a purposive sampling approach, with a strong emphasis on their involvement in the field of bio-based construction in each country. The majority of interviews were conducted between August and December 2023, with a few additional interviews conducted until April 2024 to ensure theoretical saturation. The interview guideline was tailored to the professional role of the stakeholder as well as to the country context. It involved questions concerning their perspectives on the future of the construction sector and the role of (novel) bio-based building materials and techniques within it. The final dataset includes 20 interviews from Germany, 19 from Italy, 17 from China, and 28 from India, with an average duration of 50 minutes. To identify STI, our analysis focuses on the visions articulated by different actors and their respective roles within the discourse on the future of the construction sector. We examine different narratives and alliances in the discourse, drawing on the framework outlined by Hajer (2010) and adopting a deductive coding approach based on the STI framework. It was followed by an inductive analysis to assess the different socio-technical logics between visions and, in particular, to unfold how different actors' visions using varying bio-based materials compete or complement each other along these dimensions. The interview and coding process was conducted by several researchers of the same research project, ensuring robustness of the results based on triangulation and intercoder reliability tests.

2.4 Different socio-technical imaginaries of a bio-based construction sector

Visions of a future bio-based construction sector are multifaceted, encompassing more than the preferred bio-based materials. They also differ in the desired changes in social practices and norms, which is represented (among others) by their economic characteristics, market segments, socio-technical configuration and, consequently, in their development stage. From the interview data, we have identified six STI in the making of a bio-based construction sector that vary across the four countries and along their socio-technical logic (Table 2). When we discuss the current regime in the construction sector, we are referring in particular to the use of globally established materials such as cement and steel, which constitute a stable regime. However, there are differences between the regime logics of the European countries and India and China, which can also be seen in the described proximity of the visions to the existing regime.

Vision 1: Engineered bamboo construction

Some stakeholders in India and China view the use of processed (engineered) bamboo as one of the key levers in the transition towards a bio-based construction sector. While the envisioned use (market segment) in both countries primarily consists of aesthetically pleasing public buildings for showcasing purposes, public procurement plays an increasingly important role in some regions of China. The alignment with the existing construction sector regime is low because currently, contrary to its envisioned logic, only a few bamboo buildings are in place, and the technology has not yet matured enough to meet the demand for mid- and high-rise buildings. This vision is more advanced in China than in India (development stage) due to its wider application of upstream actors and greater efforts towards institutionalization.

Vision 2: Frugal use of bamboo

Other key actors in India and China deviate from Vision 1, in the way bamboo is being used. They envision a construction sector that relies on unprocessed, locally sourced bamboo in a frugal way, in contrast to the values embedded in the logic of exporting highly processed bamboo around the world (Vision 1). The frugal use of bamboo has very low similarity to the existing construction regime but is more prevalent in rural areas, especially in India, due to the traditional use of bamboo in construction driven by local architects. In this context, actors also highlight the significant human resources involved in the Indian construction sector. Chinese actors in particular are driven by the expectation that, compared to Vision 1, fewer industrial structures are required, as they can utilize existing agricultural systems that already provide bamboo.

Table 2: Socio-technical logics of STI in the making
Reference: Author's own compilation based on the interview data

STI in the making	Countries	Description	Market segment	Simila-rity to regime	Economic characteristics	Development stage
Vision 1: Engineered bamboo	India & China	Using processed bamboo in various forms such as reconstituted, glue-laminated or scrimber	Detached luxury buildings for tourism or commercial mixed use	Low	Prefabrication & long transport routes: high prices but potential to reduce costs due to economies of scale	Small entrepreneurial ecosystems for engineered bamboo exist, but lacking standardization in national policies (*)
Vision 2: Frugal bamboo	India & China	Buildings constructed primarily of full-culm bamboo from local sources with emphasis on sustainability	Sustainable, simple and affordable bamboo buildings	Very low	Uniqueness of material and projects based on local resources & avoiding new technologies and further processing	Traditional construction methods increasingly adopted by local architects, but lack of skills & low trust of consumers in quality and function (*)
Vision 3: Selective mix with conventional materials	India, China, Germany & Italy	Using bio-based materials combined with established technologies (non-bio-based materials) in construction	Higher prized buildings often with aesthetic design	Medium	Drop-in solutions: selected bio-based materials in combinations where it is economically feasible	Wide range of applications and comparatively low barriers, but in contrast to regime, still low awareness by actors (***)
Vision 4: Serial timber	Germany & Italy	Large scale timber construction enabled by new technologies such as cross-laminated timber	Multi-story timber construction, including affordable housing	Low	very high degree of prefabricated or modularized parts and recyclability	Few pilot projects done, but lack on incentives and on standardization. Bad public perception of timber (fire and weather resistance) (**)
Vision 5: Eco-balanced timber	Germany & Italy	Storing CO_2 in timber construction but ensuring a sustainable use of (locally sourced) wood	Detached residential and commercial buildings	Low	Extension of the cascade use of timber: sustainable forestry, less processing and less amount of glue or glue-free	First pilots done, but regulatory requirements and price disadvantage to serial timber construction decrease progress (*)
Vision 6: Circular bio-economy	India, Germany & Italy	Innovative technologies using bio-based materials and aiming for a circular use	Green premium buildings for any use, as well as affordable housing	Low	Cradle-to-cradle use of materials, resource circularity & prefabrication	Increase of new innovative technologies but difficulties to convince architects and contractors, due to high prices and bad public perception (*)

* Early stage, ** Increasing adoption, *** Most evolved among shown STI

Vision 3: Selective mix with conventional materials

In all four countries, there is a relatively broad vision to selectively include some bio-based materials in established construction technologies. These comparatively minor modifications to conventional solutions or changes in norms are closest to the existing regime, as they are driven by similar values and expectations. As such, incorporating bio-based materials either as structural or decorative elements is relatively straightforward and more easily envisioned. Consequently, while drop-in solutions change the materials used, institutions and established rules would mainly be conserved. However, the envisioned materials used vary in the extent to which they replace established materials and differ from country to country: While India and

China are primarily considering a mix that includes engineered bamboo, Germany and Italy are seeking to incorporate cross-laminated timber wherever economically feasible.

Vision 4: Serial timber construction

Some stakeholders in Germany and Italy view serial timber construction as the cornerstone of a bio-based construction sector. This vision is closer to the existing regime than using engineered bamboo in India and China, as the envisioned use of the material (the market segment) covers a broader range of buildings. Actors view a great potential in the value to emphasize a serial use, particularly in Germany. However, stakeholders in Italy point to the absence of standards for mass implementation and the fact that the Italian timber industry is predominantly concentrated in South Tyrol, due to a long tradition of timber carpentry and the local availability of timber.

Vision 5: Eco-balanced timber construction

Other actors also pursue the sustainable use of timber, but are driven by different socio-technical logics (compared to Vision 4) in the way they use the material. In their vision, sustainability consists of utilizing local resources, avoiding adhesives, or repurposing waste wood. This approach is slightly less similar to the existing regime than Vision 4, primarily because it has so far pursued detached houses. This does not readily facilitate affordable housing, which also implies higher prices. The values of the Italian actors associated with this vision are slightly different from those in Germany; Italian stakeholders envision using less processed materials and no adhesives, whereas German actors focus on ensuring sustainability through the type of wood used and its potential for reassembly.

Vision 6: Innovation for a circular bioeconomy in construction

Some stakeholders in India, Germany, and Italy are pursuing a vision of circular use of bio-based materials, driven by innovation. The socio-technical logic to use materials in a circular way is different to the existing regime, as it involves novel technologies for constructing walls or developing bricks from agricultural waste—both representing new types of construction. The specific technologies developed according to this vision vary across the countries, reflecting differences in the envisioned use and development stages. These variations are influenced by the material and its characteristics: agricultural waste is used to produce bricks or insulation in India and Italy; innovative technologies for assembling or printing bio-based materials were identified in interviews in India, Italy and Germany.

2.5 Competing or complementary imaginaries?

The visions described above do not exist in isolation; they are co-produced, interact, and compete to become dominant and institutionalized. Therefore, we continue to discuss, based on our empirical data and some selected examples, the extent to which these different visions and related socio-technical logics might complement each other or, conversely, if they are competing.

We offer a stylized visual representation of our main findings in Figure 3. This figure depicts visions as polygons within the overarching discursive space. The size of each polygon reflects the significance of its corresponding vision, while overlaps between polygons signify complementarities in the socio-technical logic[5]. In India, China (visions 1 & 2) and Italy (visions 4 & 5) the main contradiction is the emphasis either on a more frugal and ecologically balanced use of bio-based materials or on the processing of materials and the focus on prefabrication. The clearer these emphases are in the visions advocating bamboo or wood, the more they are competing and conflicting. If the socio-technical logics of both visions are similar, as in the case of Germany, visions can be complementary.

Vision 6 can to some extent complement most of the other visions, as it includes both the use of new technologies and prefabrication, but also emphasizes the circularity of resources. Therefore, it can complement the socio-technical logics of other visions of a bio-based construction sector by co-creating ideas such as circularity of resources among actors, thus paving the discourse and institutions towards the adoption of key values of this vision. As described, Vision 3 remains relatively broad, which also reflects that on the one hand it competes with all other STI, as it envisions only small changes in norms and social practices and also still relies on mineral materials. On the other hand, it also complements most of the other STI, as the paving of the discourse towards the (selective) use of bio-based materials sheds light on them, co-produces similar socio-technical logics and enables a broader adoption of related visions.

[5] The discursive space depicted in Figure 3 represents the outcomes of the discourse analysis in a highly stylized manner. The sizes and overlaps of polygons are not derived from a statistical approach, and we do not assert to offer a quantitative assessment of the visions.

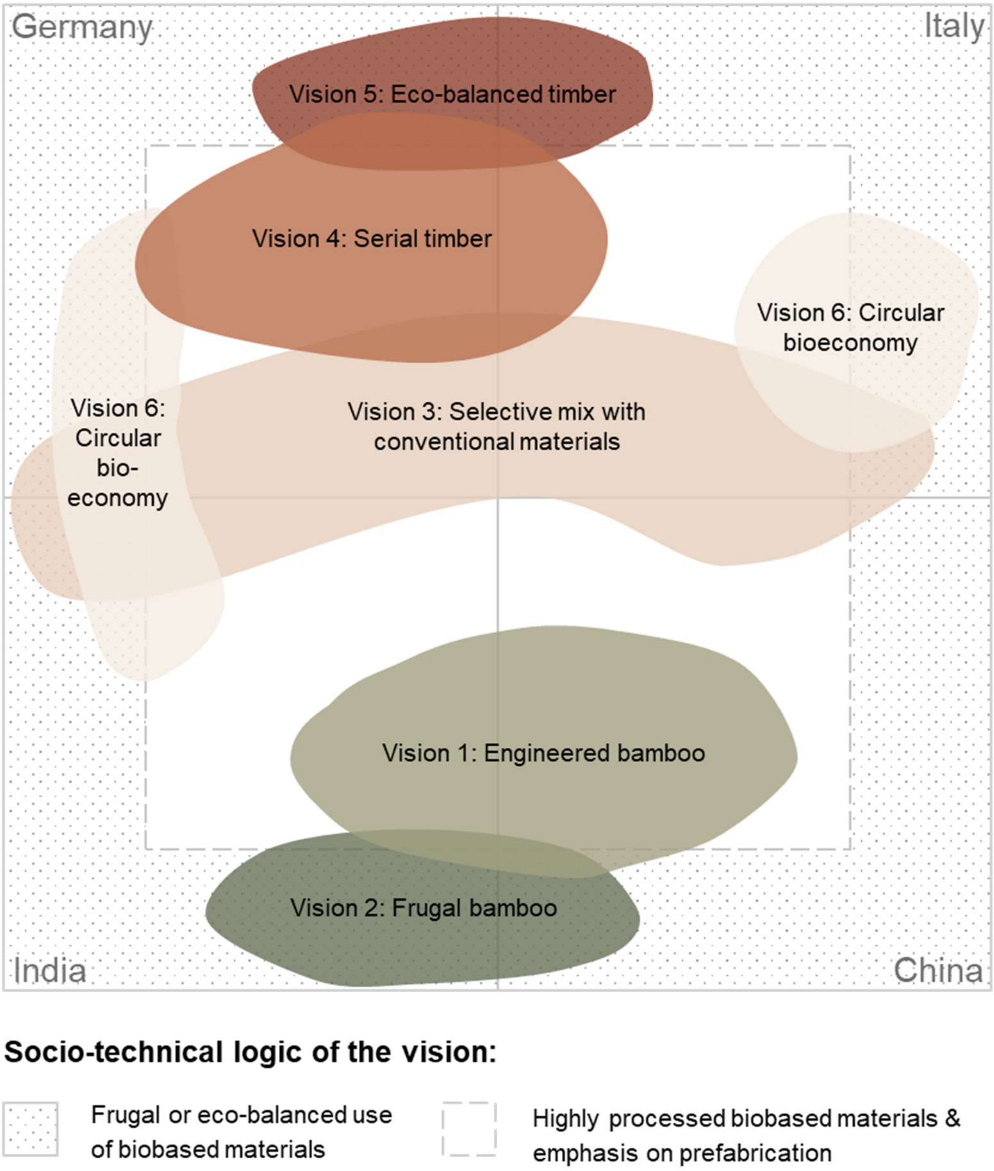

Figure 3: *Discursive space of the future bio-based construction sector*
Author's own compilation based on the interview data

In India and China, the visions around the use of bamboo in construction could be seen as complementary in terms of targeted market segments: Stakeholders that envision engineered bamboo could focus on luxury buildings, while affordable and simple buildings can be assembled by actors pursuing the frugal use of bamboo. Nevertheless, the desired change in social aspects is contradictory in both discourses in the way stakeholders view bamboo as either the material of 'the very poor' (frugal use) or 'the very rich' (engineered bamboo), which overall tends to hinder further adoption of these visions by more actors. Otherwise, especially the limited local availability of bamboo makes these two visions very competitive, although both visions claim that their desirable future with bamboo is ideal for a bio-based construction sector.

We see divergent patterns for the interplay of visions 4 and 5 relating to the use of wood in Europe, with these visions being competing in Italy and complementary in Germany. Stakeholders in Italy pursuing Vision 5 emphasize that the value of environmental sustainability is only incorporated in unprocessed timber construction, looking for policy interventions and enabling economic sustainability. At the same time, stakeholders advocating Vision 4 claim that economic sustainability is only possible with a differing logic of a serial use, indicating that these STI in the making are competing for further adoption.

However, the same visions in Germany tend to be complementary in their socio-technical logic, as they target similar market segments and related changes in social aspects. Therefore, the discourse contributes to spreading the vision of using timber construction among additional stakeholders. This is probably due to the relatively similar economic characteristics and key actors representing the entire value chain, compared to the other imaginaries, which allow for a faster adoption of both visions at the same time. In addition, the stage of development is also more advanced than for the bamboo visions, making it easier to complement each other's visions through a higher degree of shared beliefs.

2.6 Concluding remarks

The aim of this article was to illuminate various visions of a future bio-based construction sector in China, India, Italy and Germany, and to understand the extent to which they compete or complement each other. We drew on a recent reconceptualization of 'socio-technical imaginaries in the making' developed by Braun and Kropp (2023), enabling us to understand how collectively held visions interrelate and how they might become institutionalized into clear socio-technical imaginaries that influence current and future transition processes.

We have uncovered six visions across the four countries that differ in their socio-technical logic. The main difference relates to how bio-based materials should be used in the future, with some visions centered around a mass use of processed bio-based materials and some visions centered around a more frugal and ecologically-balanced use. The varying socio-technical logics between the identified visions allowed us to discuss that many socio-technical imaginaries are, in theory, very complementary. For example, they may serve different but complementary market segments and involve a variety of actors. This can be seen in the case of bamboo, either in simple and affordable housing, e.g. by architects pursuing a frugal use of bamboo, or in premium buildings for eco-tourism with engineered bamboo, often pursued by suppliers or planners. Advocating a specific vision of bio-based construction does not necessarily entail rejecting related visions concerning the same building materials. As a result, the future bio-based construction sector could be quite multifaceted.

However, there is another side to the coin. In fact, our results suggest that many socio-technical imaginaries appear to be quite conflicting in their values, normative rules and socio-technical logic. As such, the envisioned social and institutional changes that visions entail, that are advocated by the involved actors, lead to competing socio-technical logics. In this sense, as described for bamboo, only certain actor groups tend to pursue these (alternative) STI, prioritizing their own interests while promoting their visions. Consequently, socio-technical imaginaries are found to be socially constructed and legitimized in a way that suggests the use of bio-based materials should be limited to a certain logic, implicitly and sometimes explicitly denying other envisioned uses (e.g. 'bamboo for the poor'). However, the image of the material could also create obstacles in the envisioned transition path, as social dynamics could make both rich and poor reluctant to live in bamboo houses (Haque et al., 2021).

Our findings offer important insights for the global material transition toward a bio-based construction sector, among which the most critical is that the existence of various (and partly conflicting) imaginaries may reduce the pace and progress of the transition. In short, change could be slowed down if the direction is unclear. However, complementarities in competing imaginaries can also lead to synergies, as shown in the case of timber construction in Germany. Consequently, co-producing activities towards a material transition seem to function only when key actors pursuing a particular bio-based material share similar socio-technical logics. It is important to acknowledge that some imaginaries about the bio-based construction sector described in this paper are also to some extent in competition with globally dominant imaginaries (for example, those promoting the continued use of cement and steel) that are both strongly institutionalized and unsustainable. Future research could address this, as well as include public and expert documents in the empirical analysis to further unravel the discourse on the future of the sector.

CHAPTER THREE

3 How to build (in) the future? Legitimacy of socio-technical visions in a bio-based construction sector

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Abstract

The use of bio-based materials offers opportunities to mitigate the climate impacts of construction, with buildings potentially acting as carbon sinks. However, it remains unclear what a future bio-based construction sector will look like. One reason for this are diverse socio-technical visions for the use of bio-based construction materials. In this paper, we use discourse analysis across a comprehensive set of expert interviews to pinpoint (competing) socio-technical visions of a bio-based construction sector in China, India, Germany and Italy. Drawing on the sociological literature on legitimacy, we examine the legitimacy of socio-technical visions as a necessary condition for their collective adoption by stakeholders in the sector. It enables us to conceptualize the development and validation of visions, providing a framework for transition studies to track one part of the collective adoption of visions. This, in turn, adds to the understanding of the formation of ideations that potentially influence transition processes.

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3.1 Introduction

The construction sector significantly impacts climate change, not just through energy consumption in buildings, but more critically due to its reliance on materials like steel and cement, which are challenging to decarbonize (Zhong et al., 2021). In sustainability transitions research, the construction sector has therefore received increasing attention in recent years. Empirical studies emphasize the rigid regime in the use of steel and cement (Jayaweera et al., 2023), while disruptive innovations with more sustainable cements have failed so far (Dewald and Achternbosch, 2016). Against this background, utilizing bio-based materials emerges as a promising strategy to decarbonize the construction sector. These materials not only offer an alternative to carbon-intensive ones like steel and cement, but they also have the natural capability to capture and store carbon. Bio-based construction thus holds the potential to transform buildings and cities into carbon sinks, paving the way for a more sustainable future (Amiri et al., 2020; Churkina et al., 2020). In the European discourse, timber is often highlighted as a promising accelerator for a more sustainable construction sector, whereas in Asia, the focus is on bio-based building materials made from bamboo (Mazzoni and Losacker, 2024; Mishra et al., 2022; Vihemäki et al., 2020). However, the future of the sector remains uncertain, and there is no collective understanding of how to decarbonize it effectively. This issue can be explored by examining the conflicting ideas about the sector's future, which reveals how contested visions regarding material use inhibit shared ideas about potential paths the sector could take (Fischer and Losacker, 2024; Mast, 2022; van Veelen and Knuth, 2024). Our paper adds to this growing body of research, providing insights on the (future) role of bio-based materials in the sustainability transition of the sector.

Although the environmental benefits of bio-based construction are evident[6], the *vision* of what a future bio-based construction sector should look like, and the underlying reasons for

[6] There is growing scientific evidence highlighting the benefits of bio-based building materials as a carbon sink, along with studies supporting the potential availability of biomass for large-scale use (Amiri

adopting it, are not straightforward. These socio-technical visions diverge among various stakeholders within the construction sector. Additionally, they show differences across nations and geographical contexts, reflecting the unique needs, priorities, and environmental circumstances of each region. This situation gives rise to contested socio-technical logics about how and why one should encourage a transition towards a bio-based construction sector (Fischer and Losacker, 2024; Mast, 2022; van Veelen and Knuth, 2024).

For the theoretical background of this paper, we draw upon and refer to existing literature on sustainability transitions (Köhler et al., 2019; Markard et al., 2012) to explore and understand the complex dynamics of moving towards a bio-based construction sector. We align this with the emerging literature on socio-technical visions (Berkhout, 2006; Sovacool, 2024). Ideations, i.e. the formation of ideas such as visions or imaginaries allow to broaden the backward-looking perspective in transition studies by taking into account collective imaginations of future socio-technical trajectories, making them highly relevant for sustainability transitions research (Benner, 2025; Friedrich and Hendriks, 2024).

Scholarly research has so far paid limited attention to the formation of ideations and how collectivized visions and imaginaries come about, e.g. on 'what is collectivized' (Kuchler and Stigson, 2024). While the dynamics of how private visions of relevant actors evolve towards alternative or dominant socio-technical imaginaries (STI) are often acknowledged in the literature, detailed elaboration on this aspect is lacking.[7] Therefore, there is a gap in the literature on the conditions that explain why and how a socio-technical vision is collectivized and shared by multiple stakeholders. In this paper, we aim to address this gap by shedding light on the formation of ideations, focusing on how individual (private) visions get adopted towards collectively embraced visions by looking on legitimacy as a crucial condition, using the case of bio-based construction.

et al., 2020; Churkina et al., 2020). Bio-based materials are increasingly recognized as solutions to mitigate climate change, as acknowledged by organizations like the UN and the IPCC (Cabeza et al., 2022; UNEP, 2022). These materials include not only timber and bamboo but also insulation materials made from straw, typha, and hemp, as well as innovative uses of agricultural waste, such as rice husks. However, the climate benefits of bio-based materials depend heavily on sustainable practices, such as responsible reforestation. Additionally, the increased use of biomass in construction could lead to land-use conflicts, monocultures, and biodiversity loss. Furthermore, retrofitting existing building stock is often more sustainable than constructing new bio-based buildings. Therefore, while transitioning to a bio-based construction sector offers significant potential for mitigating climate change—especially given the challenges of a growing global population—it is not a panacea to the sector's sustainability issues. Instead, it should be viewed as one important lever among many in addressing these challenges.

[7] In line with Rudek 's (2022) elaboration, in the STI literature imaginaries are understood as ideas that are collectively held and dominant. However, he also notes that alternative visions, which are not dominant, are frequently discussed in the literature (e.g. Longhurst and Chilvers, 2019).

The paper therefore seeks to contribute to the following research questions: *How can we understand the collectivization of socio-technical visions through legitimacy? What is the role of different dimensions of legitimacy in the collectivization of socio-technical visions?*

We provide inroads to answer these questions, utilizing the seminal conceptualizations on *legitimacy* by Suchman (1995) and Johnson et al. (2006). Building on this, we analyze one crucial part of the ideational formation; how legitimacy is a condition to transform individual visions into collectively adopted visions by key actors. We focus on identifying legitimacy dimensions applicable to actors' visions, providing a framework to delineate components that categorize socio-technical visions as either alternative or dominant. The framework contributes to transition studies by making sense of how to conceptualize the formation of ideations and to assess which visions may be more popular than others for future transitions. Empirically, the paper draws on a discourse analysis of a comprehensive set of expert interviews with key actors in the construction sectors of China, India, Italy, and Germany.

The remainder of the paper is structured as follows. First, we discuss previous research on futures and ideations in the context of sustainability transitions. We then elaborate on the relationship between visions and legitimacy and develop our conceptual framework to unfold the formation of ideations (Section 3.2). Based on this framework, we describe how we empirically analyze legitimacy as necessary condition in the collectivization of visions among key actors in the construction sector, using interview data and discourse analysis (Section 3.3). Subsequently, we provide a brief description of the dominant socio-technical logics currently prevailing in the construction sector (Section 3.4). We then describe the visions identified in the interview data and analyze their legitimacy and the resulting dominance of each socio-technical vision (Section 3.5). We then provide a brief discussion of the paper's contribution to the literature, along with its research limitations (Section 3.6). We conclude with a summary of our findings (Section 3.7).

3.2 Legitimizing socio-technical visions

3.2.1 Futures and ideations in sustainability transitions

The progress of sustainability transitions is based on the integration of novel technologies into socio-technical systems, changing the configuration of a sector's modes of production and consumption (Geels, 2002, 2004). How such a transition might be achieved, and which technologies might be desirable for a more sustainable future of a sector, is subject to different actors' ideas about the future (Bauer, 2018; Martin, 2021). While ideation reveals potential future trajectories, many 'ideational concepts' are often used interchangeably in the social sciences. Among others, researchers refer to and study expectations, visions, imaginaries and narratives, often lacking a definitional consensus (Benner, 2024). For research on sustainability transitions, we propose that the study of different ideational dimensions becomes valuable when referring to different levels of collectivization in the formation process, which we conceptualize as follows: all actors working on new ideas or technologies are surrounded by expectations (Borup et al., 2006). These expectations prompt actors to consider the future, influencing their decisions and ideas. Consequently, expectations can develop into more concrete visions of the future, having a normative character and being either private (individual) or shared among different actors (collective) (Berkhout, 2006). When visions become 'collectively imagined and co-produced' Jasanoff and Kim (2009, 2013) refer to them as socio-technical imaginaries. The notion of STI has been frequently used for the study of imagined future transitions pathways, often for the case of energy transitions (Carvalho et al., 2022; Eaton et al., 2014; Longhurst and Chilvers, 2019; Muehlberger et al., 2024; Trencher and van der Heijden, 2019). More recently, scholars are increasingly exploring how ideas that address societal problems are collectivized, and how contested futures might lead to desirable or undesirable transitions (Bauer, 2018; Friedrich et al., 2022; Kester et al., 2020; Sovacool et al., 2019; Wiarda et al., 2023).

Shedding light on ideations in transition studies provides insights into potential configurations and the ability of countries to create the necessary conditions for transitions (Coenen and Morgan, 2020). Potential pathways are framed both by actors' past experiences and expectations for the future (Steen, 2016), which are constituted in individual visions (Berkhout, 2006). Actors' (contested) visions indicate where a transition could lead and thus, they are considered to be the beginning of transition processes (Bauer, 2018; Hansen and Coenen, 2015). As described above, individual visions can transform into collective socio-technical imaginaries of the future. This process can thus shed light on potential pathways for sustainability transitions, revealing how private ideas and perspectives coalesce into shared, future-oriented imaginaries that influence the direction of transition processes (Bauer, 2018; Martin, 2021). We focus on this stage of the formation process, 'imaginaries in the making' (Braun and Kropp, 2023), describing the collectivization of individual visions into shared socio-technical imaginaries. In this paper, we examine a critical aspect of the process of creating and developing socio-technical imaginaries: the mechanisms through which key actors of a sector collectively embrace and adopt a shared vision.

The investigation of imaginaries in the making is of particular interest because many scholars analyze STI through different lenses, but overlook the phase of imaginary formation (Rudek, 2022). For example, it has been demonstrated that STI can be 'contradictory but also complementary' (Fischer and Losacker, 2024; Trencher and van der Heijden, 2019), influencing which ideas about desirable futures spread and become more dominant. While such studies serve as examples of how the emergence of visions at the individual level towards collectivized STI have been studied so far (Kuchler and Stigson, 2024), there exists a research gap on how visions are collectivized among key actors. Some recent contributions have addressed this gap to some extent: Rohde and Santarius (2023) have studied the emergence of STI by analyzing collectively shared visions. They describe legitimation and justification as a crucial part of emerging imaginaries; however, they do not specify these legitimation processes or elaborate on how legitimacy influences the dominance of STI. Similarly, a literature review of existing STI studies identified a lack of understanding of '*what* is collectivized' in imaginaries (Kuchler and Stigson, 2024). We aim to fill this gap by examining in detail what Rudek (2022) calls 'negotiation and coalition building'.

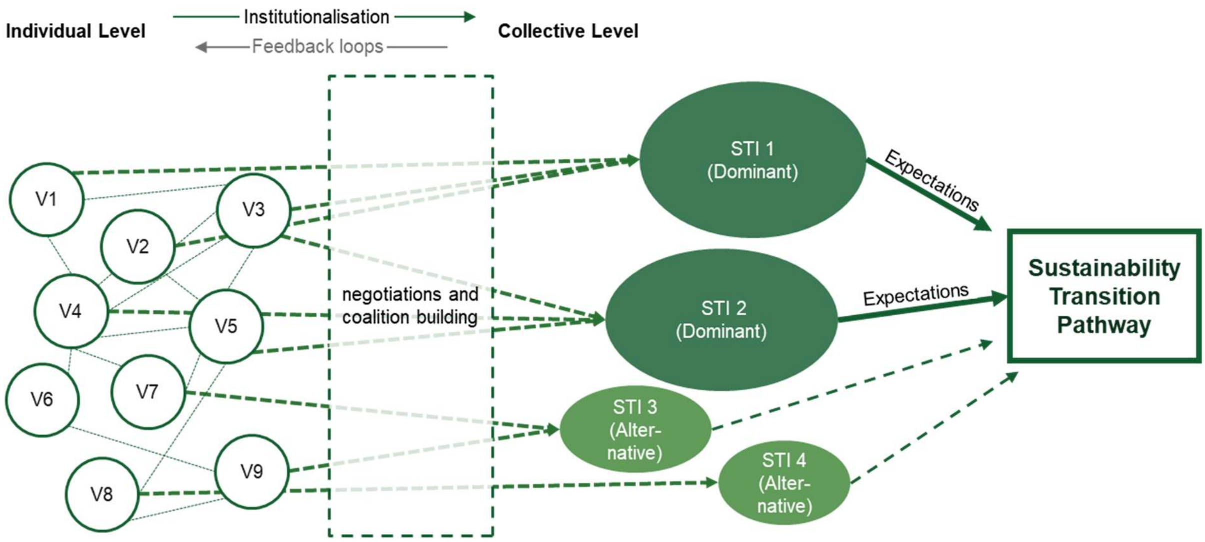

Figure 4: *Collectivization of visions and formation of socio-technical imaginaries (Own elaboration based on Jasanoff and Kim (2009, 2013), Berkhout (2006) and Rudek (2022)).*

Researchers in transition studies argue that alignment of contested ideas (Wiarda et al., 2023), trust in visions of other actors (Koole, 2022) and formation of advocacy coalitions (Haukkala, 2018) are the ideational foundations towards a collectively held idea of a transition. Drawing on recent work on the formation of STI (Figure 4), the study of collectivization unfolds the logic of how visions become dominant at the collective level.[8] In this way, we can show which collectively held ideas are envisioned for the sustainability transition pathway, since (collectivized) actors' visions and related narratives 'constitute paths in the making' (Christley et al., 2024, p. 11). Against this background, we argue that it is necessary to explore the 'legitimacy of socio-technical visions' to learn about both their collectivization and how they

[8] In the collectivization of STI, power and co-production also play a crucial role in shaping the dominance of imaginaries (Polzin, 2024).

become dominant. Nevertheless, besides legitimacy, the institutionalization of visions[9] into STI also requires the co-production of socio-technical advances and power (Longhurst and Chilvers, 2019; Oomen et al., 2022). Moreover, collectivization is a mutually constitutive relationship, as individual visions depend on and adapt to collective processes, i.e. they also evolve through feedback loops (Friedrich and Hendriks, 2024). In this paper, however, we focus only on one crucial part of the formation process of socio-technical visions: legitimacy as a condition for unfolding the first step of collectivization. The role of legitimacy has received little attention in previous research on socio-technical futures, and we argue that it complements perspectives on how visions are co-produced, gain power, and become the collectively imagined desirable future (Altstaedt, 2024; Polzin, 2024). The conceptualization of a legitimized vision, however, can provide insights into the first step of ideational collectivization (Rohde and Santarius, 2023).

3.2.2 Legitimacy of socio-technical visions

Scholars generally recognize that different ideations; varying states and forms of imagining the future, serve to some extent to provide legitimacy for a shared understanding of the future: Expectations navigate and provide structure (Borup et al., 2006; van Lente, 2012), visions ensure credibility (Berkhout, 2006), and STI often justify policy decisions (Jasanoff and Kim 2009). Therefore, it is evident that ideations of the future, both individually and particularly when shared collectively, provide legitimacy for specific socio-technical configurations. In this paper, we follow the seminal definition of legitimacy by Suchman (1995, p. 574): '*Legitimacy is a generalized perception or assumption that the actions of an entity are desirable, proper, or appropriate within some socially constructed system of norms, values, beliefs, and definitions*.' Aligning this generalized perception with the socially constructed system is crucial for the success of emerging innovations in sustainability transitions (Dehler-Holland et al., 2022; Gong et al., 2022; Harris-Lovett et al., 2015; Markard et al., 2016). Therefore, legitimacy is considered an important cornerstone in the analysis of new technologies in transition studies (Alsheimer et al., 2025). For instance, in the realm of technological innovation systems, the creation of legitimacy paves the way for sustainability transitions and is considered one of the core resources of functioning innovation systems (Bergek et al., 2008; Binz et al., 2016a; Markard and Truffer, 2008; Rohe and Chlebna, 2021). Consequently, we can anticipate a

[9] While we focus on the aspect of collectivization of visions, institutionalization (of visions) is a crucial part of it and related to it: Following the logic of previous contributions to what is collectivized in STI (Kuchler and Stigson, 2024; Rohde and Santarius, 2023; Rudek, 2022), institutionalized visions drive collectivization, which we conceptualize through the legitimacy of socio-technical visions.

causal relationship between ideations of the future and the legitimacy of certain technologies in the present (*visions build legitimacy*).

However, we contend that the (causal) relationship between legitimacy and ideational concepts in transition studies is more complex. Similar to Rohde and Santarius (2023), we argue that an ideation must be legitimized itself to progress from an individual vision into a shared vision (*legitimacy constitutes visions*).[10] This side of the coin is certainly less well studied than the one described before, but we argue that making use of the rich literature on legitimacy helps to make sense of how socio-technical visions become collectively held.

To achieve this, we build upon the literature review by Alsheimer et al. (2025) on individual acceptance and legitimacy to develop our conceptual framework of how legitimacy can drive the formation of ideations: an actor's individual vision is an object (of legitimacy) and other key actors are the evaluators of the vision, influencing the socially constructed system that helps to collectivize it. In this line of reasoning, we understand legitimacy as the outcome at the collective level, while legitimation is the process that leads to the outcome, inspired by the notion of 'legitimacy as a social process' as discussed by Johnson et al. (2006). Figure 5 visualizes our conceptual understanding of this process.

Figure 5: Legitimation from local validation to general validation (Own elaboration based on Alsheimer et al. (2025) and Johnson et al. (2006))

Thus, legitimacy of the object (the vision) functions as a necessary condition for its general validation and adoption by further stakeholders. In this sense, we can examine the extent to which visions are validated (legitimized) and thus assess the dominance of a vision. In the phase of local validation[11], individual visions are (locally) accepted by few actors, through alignment of ideas and gained trust (Wiarda et al. 2023; Koole 2022). In this context, the interaction of actors with (slightly) different visions results in adaptations and alignment of

[10] There are certainly more complex dynamics at play in the formation of STI than the legitimation of a vision by key actors. However, we argue that to shed light on which ideas about desirable futures are collectivized among stakeholders in a sector, analyzing the legitimacy of visions is a major factor.

[11] In this context, following Johnson et al. (2006), 'local' refers to the degree of collectivity in the validation process. For instance, that a vision is only validated by some actor groups. In certain contexts, this may be expressed in a geographical sense, but is not necessarily the case when we refer to a vision that is locally validated.

visions. Following Berkhout (2006), these can be rooted in existing or new visions, and thus, this process is not unidirectional but rather a complex alteration driven by interaction. A general validation, in contrast, requires a broad adoption and high diffusion of the individual vision among different actors and has to be widely recognized and/or adopted (Johnson et al., 2006). Legitimation can thus be understood as the agentic process that leads to a general validation of a vision on a collective level. To analyze in more detail how key stakeholders evaluate other actors' visions (validation) we refer to Suchman's (1995) legitimacy types that help to unfold how the object (the vision) is evaluated (Table 3).

Table 3: General validation and legitimacy of socio-technical visions (Suchman, 1995)

Legitimacy type	**Pragmatic** (Evaluation based on self-interest)	**Moral** (Evaluation based on norms/societal values)	**Cognitive** (Evaluation based on deeply held customs and beliefs)
Legitimacy dimension	Exchange Influence Dispositional	Consequential Procedural Structural Personal	Comprehensibility Taken-for-grantedness

The evaluation of key actors leads to successful legitimation if the different dimensions of legitimacy are fulfilled, or in other words, if the evaluated object is generally validated. We assess the outcome of the described legitimation processes, the legitimacy of the socio-technical vision. Thus, the degree of legitimated dimensions, and consequently the degree of general validation for a vision, indicates the dominance of a socio-technical vision. Different types of legitimacy help us distinguish how various approaches are used to support and promote a vision. These approaches facilitate negotiations with evaluators who are trying to advance their own ideas (the object of legitimacy). However, the legitimacy subdimensions of visions operate under different logics compared to the legitimacy of other socio-technical objects. This is because the object being evaluated (the vision) is socially constructed and imagined. Building on Suchman's (1995) legitimacy types, we argue that, in order to be positively evaluated and adopted by additional actors, visions (1) need to provide individually perceived benefits to other actors (*Pragmatic legitimacy*), (2) resonate with existing norms and values of the sector (*Moral legitimacy*), and (3) be in line with existing deeply held customs and beliefs of key stakeholders in the sector (*Cognitive legitimacy*). We explain this in more detail below.

Bridging the literature on socio-technical visions and legitimacy thus allows us to make sense of how socio-technical visions can be collectively embraced. We show a visual representation of our conceptual framework in Figure 6. Along the collectivization process from the individual to the collective level, we observe several ideational dimensions. At the individual level, key actors have different (private) visions of what the future of a sector might look like, while these eventually coalesce into shared visions that collectivize ideas about desirable futures.

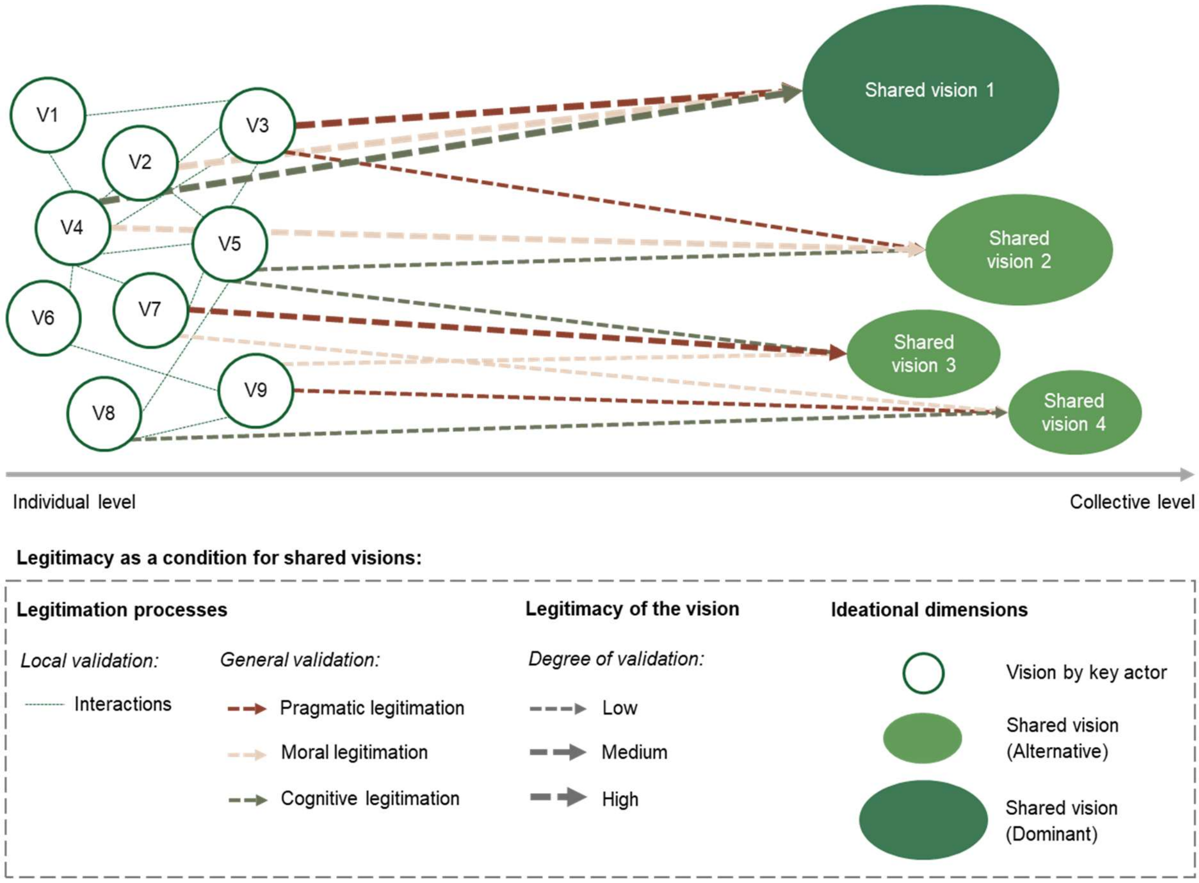

Figure 6: Legitimacy as a condition for the collectivization of socio-technical visions (Own elaboration)

These can be alternative or dominant, determined by legitimacy as a condition. Local validation occurs at the individual level through interactions among actors with competing and/or complementary visions. These interactions build trust, align contested ideas, and consequently, lead to changes and consolidations of visions, each seeking local validation.

These locally validated (individual) visions require general validation in order to be further collectivized and to gain relevance. At this stage, there are several approaches to gain legitimacy with their respective subdimensions, which can be distinguished by *pragmatic*, *moral* and *cognitive* legitimacy (Suchman, 1995). These are fundamental for identifying factors that hinder or accelerate the adoption of actors' visions.

Pragmatic legitimacy validates visions by advocating individually perceived benefits to other key actors if the vision were adopted. It includes the perceived value to other stakeholders of pursuing that vision (*Exchange*), the sharing of decision-making power that enables participation (*Influence*), and the belief that the vision has 'good character'; thus, is in the best interest and paves the way for the sector's transition (*Dispositional*).

Moral legitimacy refers to various dimensions of existing societal values that make a vision appear similar to existing norms and therefore legitimate. This includes legitimacy through already achieved accomplishments or outcomes that reinforce the vision (*Consequential*), specific procedures that appear promising to align the vision with existing norms and societal values (*Procedural*), categories and structures such as physical characteristics that indicate the ability to pursue the vision (*Structural*), and leaders and representatives who advocate for the transition (*Personal*).

Cognitive legitimacy occurs when the vision is consistent with the deeply held customs and beliefs of other key actors. This requires that the vision is consistent with the everyday experiences and cognitive frames of other key stakeholders (*Comprehensibility*), and that actors view alternatives for the transition as 'unthinkable' and appearance of inevitability to follow the vision (*Taken-for-grantedness*).

The dominance of the socio-technical vision is defined by the degree of legitimacy. High general validation of visions across all types of legitimacy constitutes a dominant vision. If legitimacy is present but lacking in some dimensions, a vision remains alternative. The dominant socio-technical vision of a sector's future then leads to expectations among other key actors. In particular, the dominant vision can affect the envisioned directionality of the sustainability transition pathway, as legitimacy can act as one crucial function in collectivizing socio-technical visions in the formation towards STI.

3.3 Research design

In the empirical section of this paper, we employ an embedded multiple case study design (Yin, 2009), examining the bio-based construction sector of two European countries (Germany and Italy) and two emerging economies in Asia (India and China). With this approach, we consider two pairs of case study countries, where the countries within each pair have comparable socio-economic contexts, i.e., similar populations, built environments, and preferred building materials, while differences between the pairs are significant. In other words, the context conditions of the construction sectors are similar between India and China, as well as between Germany and Italy, while they differ when comparing the Asian countries with the European ones. These similarities and differences are reflected in the socio-technical configuration of each country's construction sector and the visions that emerge there.

We analyze the 'legitimacy of socio-technical visions' across the different national contexts and their unique socio-technical configurations. Recent research analyzing ideations (visions or STI) has focused on either interviews with key actors, or on public and expert documents, or on both (Kuchler and Stigson, 2024). Distinguishing between expert and public imaginaries

(Cherry et al., 2017), we are particularly interested in the 'expert visions' held by key stakeholders, which in this logic differs from public visions. We thus focus on semi-structured expert interviews to provide a snapshot of the outcome (the legitimacy of visions) of the collectivization process of actors' visions. This choice is driven by our interest in exploring envisioned pathways and actors' expectations within the discourse. Observing a diverse range of interviewees who elaborate on the views of different stakeholder groups enables us to assess the legitimacy of socio-technical visions[12], necessary to collectivize ideas on a desirable future. Based on these insights, we can add to the understanding and draw one crucial part of the ideational formation from visions to STI for the bio-based construction sector.

We conducted (online) expert interviews in the mentioned countries with a wide range of stakeholders, including material suppliers, researchers, startups, architects, engineers, and planners. We also interviewed industry associations and government authorities. In the selection of interviewees, we focused on key actors in each stakeholder group who are regarded as influential for certain ideas or visions.[13] These experts were selected through a purposive sampling approach, focusing on their standing and dedication to bio-based construction in each country.[14] We identified experts through desk research of successful projects and examples within the relatively small bio-based construction sector in each country. Additional experts were identified using snowball sampling methods. Most interviews took place between August and December 2023, with a few carried out until June 2024 to ensure theoretical saturation (Saunders et al., 2018). The interview guideline was tailored to each expert's professional role and the country specific context, exploring their perspectives on the future of the construction sector and the role of new bio-based building materials and techniques. The final dataset includes 20 interviews from Germany, 19 from Italy, 20 from China, and 28 from India, each lasting an average of 50 minutes.[15] The interviews are part of a larger research project investigating the transition to a bio-based construction sector. The first author of this

[12] The analyzed legitimacy of the visions in our empirical case does not cover all stakeholders in the (bio-based) construction sector, but informs about the legitimacy among the interviewed key actors. In other words, when we refer to legitimacy in the results of this paper, we cannot claim to have captured all relevant stakeholders, particularly those related to legitimacy in marginalized actor groups, as these are not part of our database. When interpreting the results of our paper, this is an important limitation to keep in mind.

[13] Given this selection of interviewees, which is driven by the aim of exploring how experts working in the construction sector envision its future, we neglect potentially relevant visions from other stakeholder groups, including environmental associations and other NGOs, as well as civil society and (local) communities.

[14] The purposive sampling approach constitutes an effective method for identifying stakeholders who can provide insights. However, the selection of interviewees is influenced by the discursive power within the sector, thus the visions captured may deviate from its reality, i.e. they are not free from bias (Sovacool, 2024) and some (alternative) ideations are excluded (Jasanoff and Simmet, 2021).

[15] Details on the background of the conducted interviews are summarized in the appendix (Table 6 in Section 3.8).

paper carried out all interviews in India, while other researchers involved in the project conducted the interviews in the remaining countries. All interviews were transcribed, translated into English, and analyzed using MAXQDA. The coding process was conducted by the entire research team, with intercoder reliability testing to ensure robust results. The coding scheme was developed and revised in the research team to increase the intercoder consistency (O'Connor and Joffe, 2020). In addition, all researchers involved in the coding process triangulated multiple codings to ensure the consistency and reliability of the findings (Flick, 2004).

To identify shared socio-technical visions, our analysis focuses on actors' visions and their roles in the discourse surrounding the future of the construction sector. We examine various storylines and discourse coalitions, using the approach of Hajer (2010). Therefore, we use a deductive coding approach based on the described literature on socio-technical visions and corresponding socio-technical logics (Berkhout, 2006; Sovacool, 2024). This allows us to identify which socio-technical logics are embedded in discourse coalitions and storylines and which are captured by (shared) socio-technical visions of different interviewees. Following the local validation of the actors' ideations developed in our framework, we code (locally) held visions that are aligned in their desirable future of bio-based construction and have gained support among various interviewees. This analysis uncovers actors' experiences and expectations of a decarbonized construction sector as represented in competing visions. In a subsequent step, we examine the outcome of the general validation of the identified visions by investigating the legitimacy of shared visions and unfolding which visions are likely to get adopted by additional key actors. In this step, we coded the subdimensions of legitimacy (of visions) as presented in our framework. It allows us to delineate visions shared among multiple interviewees and assess their legitimacy, offering insights into how socio-technical visions are becoming dominant and are envisioned to influence the sector's transition to sustainability. Therefore, we are able to identify locally validated visions of a bio-based construction sector and unfold legitimacy as a condition for the collectivization of these visions.

3.4 Case description of the construction sector

In order to better comprehend the results of our empirical analysis, this section provides a brief overview of the construction sector and its current socio-technical modes of operation. Specifically, the section describes the construction sector's current regime logic, against which the visions identified in our analysis compete.

The construction sector, in its current mode of operation, is highly unsustainable, as buildings account for approximately 21% of global greenhouse gas emissions (Cabeza et al., 2022). While some emissions related to energy use are already being addressed—such as improving building energy efficiency and increasing the use of renewable energy for heating—challenges persist, particularly those associated with the environmental impacts of construction materials (Zhong et al., 2021). Specifically, around 18% (approximately 2.2 GtCO2e in 2019) of greenhouse gas emissions from buildings are linked to the use of cement and steel (Cabeza et al., 2022). Global emissions from steel production (7.2% of global CO2e, including iron) and cement production (3% of global CO2e) are heavily attributed to the construction sector, with approximately half of steel emissions and nearly all cement emissions stemming from construction (Churkina et al., 2020; Zhong et al., 2021). Even if the energy used in steel and cement production shifts to renewable sources in the future, emissions from the c—such as calcination during the production of cement and the utilization of coke in steel production for the reduction of iron oxide—will remain (Davis et al., 2018). Therefore, the use of cement, steel, and other environmentally harmful materials presents a significant challenge for the sustainability transition of the construction sector, as also highlighted in recent IPCC and UN reports (Cabeza et al., 2022; UNEP, 2022, 2023).

Besides these well-known environmental impacts, the construction sector remains heavily centered on the use of steel and cement on a global scale. Reinforced concrete has been the de facto standard building material for decades, primarily due to its material properties, including high strength, durability, low technological complexity, and comparatively low costs (Geels and Deuten, 2006). In other words, the construction sector serves global mass markets with standardized building materials. Particularly, from a geographical perspective, the use of steel and cement constitutes a globalized socio-technical regime (Fuenfschilling and Binz, 2018), with little to no adaptation of construction practices to local contexts, such as physical or climatic conditions (Jayaweera et al., 2023; Mazzoni and Losacker, 2024). The use of construction materials is governed by (national) building codes and is highly regulated around the world. As such, there are strongly institutionalized norms and regulations regarding the use of building materials. In addition to formal institutions (i.e., norms), the construction sector is also shaped by various informal institutions that influence how the sector functions. These informal institutions include, among other things, expectations about the appearance and construction methods of buildings, with steel and cement dominating the institutional landscape. For instance, steel and cement are often associated with modernity, robustness, and longevity, reinforcing their dominance in construction practices (Fahl, 2024; Leeuw and Vogl, 2024; Losacker and Fastenrath, 2022).

In addition to the aspects mentioned, the construction sector faces significant innovation challenges due to its inherent structure. The sector is generally considered low-tech, innovation-averse, and risk-averse, with a sharp division between material supply and material use along the value chain, which hinders user-producer learning and knowledge flow (Mazzoni and Losacker, 2024; Rohracher, 2001). Combined with the sector's strong institutionalization and its project-based nature, these characteristics create an environment that scholars have referred to as an innovation gap, highlighting that the sector's inherent structure acts as a natural barrier to innovation and change (Butzin and Rehfeld, 2013; Dewald and Achternbosch, 2016).

In summary, the current socio-technical regime of the construction sector is shaped by the dominant use of steel and cement, underpinned by technological, institutional, economic and social factors. While these materials have enabled the sector to meet the demands of global mass markets, their widespread use also presents significant challenges to sustainability, as their production and use contribute heavily to greenhouse gas emissions and environmental degradation.

Given the state of the construction sector as described above, there is an increasing number of voices advocating for a disruptive change in the material fabric of the sector, transitioning to the use of bio-based materials (Amiri et al., 2020; Araujo et al., 2025; Churkina et al., 2020; Pramreiter et al., 2023). However, there is still no consensus on what the socio-technical transition to bio-based construction should look like, and various visions have emerged that, to some extent, are already translating into changes in the built environment (Fischer and Losacker, 2024; Mast, 2022; van Veelen and Knuth, 2024; Wiarda et al., 2023).

3.5 Legitimacy of socio-technical visions in a bio-based construction sector

3.5.1 Visions of a bio-based construction sector

Desirable futures for a bio-based construction sector vary according to different countries and the envisioned socio-technical logics, i.e., the preferred materials and the related social and institutional changes. As such, the socio-technical visions outlined incorporate different norms, values and beliefs that indicate contrasting changes in the socio-technical logics of the construction sector. However, these socio-technical logics differ from the current socio-technical configuration in the construction sector: Incumbents follow the established norms and (societal) values (*Moral legitimacy*) of the (mineral-based) sector. These are established practices, unwritten rules and the proven value chain around buildings based on cement and steel. In addition, these actors aim to maintain their individually perceived benefits and decision-making power (*Pragmatic legitimacy*), which appears to be stable and rooted in regime structures, with little concern for environmental consequences. Deeply held customs and beliefs (*Cognitive legitimacy*) in the construction sector consist of the use of mineral-based construction materials (cement and steel) as they have been used in buildings for decades. Consequently, they are perceived as legitimate and taken for granted. While the extent of such values and beliefs and the type of materials differ between the four countries, the overall patterns described are prevalent in the sector globally and they are similar across the considered countries.

The imagined socio-technical configuration of a bio-based construction sector differs between visions: While some socio-technical visions emphasize a frugal or eco-balanced use of materials, others envision a focus on highly processed materials (Fischer and Losacker, 2024). Given that the transition towards bio-based construction primarily focuses on the use of timber in Europe and bamboo in most Asian countries, it is not surprising that we find similar visions for the use of timber in Italy and Germany, as well as similar visions for the use of bamboo in China and India. We have identified six locally validated visions of a bio-based construction sector from the interview data.[16] Key actors in India and China envision the use of engineered bamboo in various forms, such as reconstituted, glue-laminated or scrimber. The pursuit of **engineered bamboo** (Vision 1) involves prefabrication and export of engineered bamboo to reduce costs through economies of scale. Conversely, the **frugal use of bamboo** (Vision 2) aims for buildings constructed primarily of full-culm bamboo from local sources with an emphasis on environmental sustainability. Stakeholders pursuing this vision aim to avoid the use of new materials and further processing. While we found these competing visions for the use of bamboo to be less widely adopted, there is one vision that is quite popular across countries that proposes the **selective mix with conventional materials** (Vision 3). It involves the use of bio-based materials combined with established technologies (non-bio-based materials) in construction. This allows for a comparatively broader range of applications and facilitates adoption by additional actors. In European countries such as in Germany and Italy several key stakeholders favor **serial timber construction** (Vision 4). This involves large-scale timber construction using new technologies such as cross-laminated timber. The focus here is on a high degree of prefabrication and modularity, while other stakeholders in Europe advocate for an **eco-balanced use of timber** (Vision 5). They point to storing CO_2 in timber construction but ensuring a sustainable use of (locally sourced) wood. Another vision seeks to make use of novel **innovation towards a circular bioeconomy** (Vision 6). Such stakeholders envision a future construction sector with innovative technologies using bio-based materials and aiming for a strictly circular use.

These visions of a bio-based construction sector are locally validated and, therefore, (locally) accepted by a few actors. However, they differ in the extent to which they are adopted by additional actors (general validation). Based on the respective *pragmatic*, *moral* and *cognitive* legitimacy, these visions are either alternative or dominant. Consequently, in the next section,

[16] More detailed descriptions of the identified visions can be found in the appendix in Section 3.8.

we explain the legitimacy of socio-technical visions as a condition for their collectivization, which simultaneously determines the dominance of visions in the bio-based construction sector.

3.5.2 Legitimacy of socio-technical visions in bio-based construction

A general validation of (local) visions is required for them to be collectivized into shared and legitimized socio-technical visions. The state of this general validation is shown in Table 4 for Visions 1-3. In India and China, key stakeholders envision the future bio-based construction sector using **engineered bamboo**. The vision to use mainly processed bamboo in construction has started to diffuse among the relevant stakeholders, but it is not yet widely legitimized. In particular, the positive evaluation of existing categories and structures by key actors indicates the ability to enforce the vision and contribute to collectivization (*M: structural*).[17] For example, the governments in some regions in China have begun to demand that bamboo is used wherever possible:

> *"But the government here has mandated that all procurement for government related projects has to go through a review process of, can bamboo be used in that application?" (China_18)*

This provides a high level of legitimacy, especially since it shows promising *procedures* that lead to outcomes that prove that the vision is *consequential*, in addition to the described *structural* subdimension. Consequently, it accelerates the alignment of this vision with existing norms and values of key stakeholders in the construction sector (*Moral*). However, especially in India, there is a lack of approaches that demonstrate the individual added value for key actors in adopting this vision (*Pragmatic*), which is why its legitimacy in India has been rather limited so far. To use processed bamboo is also more consistent with the existing deeply held customs and beliefs of key stakeholders in China (*Cognitive*), due to a higher level of *comprehensibility* of bamboo as a material among actors in the construction sector, as well as the *taken-for-granted* use of bamboo resulting from the widely accepted belief that 'bamboo is Chinese':

> *"The fact that culturally they accept bamboo and they feel that bamboo is Chinese, even though there is bamboo everywhere. (…) But they feel that bamboo is theirs." (China_8)*

[17] For a better understanding, we add a short form of each type of legitimacy related to the subdimensions in the text: *P* (*Pragmatic*), *M* (*Moral*), *C* (*Cognitive*).

Table 4: Legitimacy of visions in a bio-based construction sector (Visions 1-3)

Socio-technical vision	**Pragmatic** (evaluation based on self-interest)	**Moral** (evaluation based on norms/societal values)	**Cognitive** (evaluation based on deeply held customs and beliefs)
Vision 1: Engineered bamboo	Providing standardized engineered bamboo enables easier adoption; treating bamboo as a premium product through luxury buildings and showing aesthetic values (*Exchange*), High influence of customers in developing standards and product categories (*Influence*), High value of stored carbon in bamboo; pursuing recycling of bamboo waste to generate composite materials or fuels (*Dispositional*)	Tourism as a success story; achieved higher grown bamboo plantations as well as new dimensions in bamboo roofing; Bamboo is now in the Indian national building code (*Consequential*), Training of farmers and artisans for better practices of growing and processing bamboo; longer durability due to treatment and quality control, prefabrication of components (*Procedural*), Local policies require use of engineered bamboo in construction wherever feasible; established processing facilities for bamboo: primary processing, construction components and a pressure treatment plant ensuring durability (*Structural*), Increasingly global presence due to international advocacy organization (*Personal*)	Local initiatives to replace plastic with processed bamboo as well as use of engineered bamboo in public buildings increase public awareness for the building material (*Comprehensibility*), Locally high cultural acceptance based on the public belief that 'bamboo is Chinese' (*Taken-for-grantedness*)
Vision 2: Frugal bamboo	Providing (affordable) housing, easily available in some rural areas; cheaper and lighter than engineered bamboo (*Exchange*), Creating standards adjusted to local conditions with actors in rural areas (*Influence*), Eco-balanced treatment: using bamboo-based agroforestry for restoring degraded land, water recharge and biodiversity; addressing increasing housing shortage (*Dispositional*)	Traditionally lot of rural houses made out of bamboo; internationally proven solution for affordable and simple housing in rural areas; large network of architects implementing frugal practices with bamboo (*Consequential*), Working together with the bureau of standards to simplify the national building code; creating tailored policy strategies and training such as capacity development, e.g. documenting traditional building processes (*Procedural*), Large amount of human resources in rural areas to implement frugal use of bamboo; control authorities to address the lack of standardization: ensuring wind protection, thermal insulation and other functions (*Structural*), Representatives for frugal bamboo as part of the C40 women for climate program (*Personal*)	High in certain rural areas because of its traditional usage and due to resource availability; high attention on policy debates (*Comprehensibility*)
Vision 3: Selective mix with conven-tional materials	Getting 'sustainable' buildings while keeping familiar building components; provide customized solutions with different (conventional) technologies that add value in the local context (*Exchange*), All stakeholders can continue to rely mainly on their practices (business-as-usual) with a high degree of flexibility and influence on what exactly will be changed (*Influence*), Selective use demonstrates sustainability and attracts increased attention through public focus on such projects (*Dispositional*)	Well-known lighthouse projects present bio-based materials in an aesthetic way: shows that the (mixed) application is known and proven; enabled fast-growing bio-based materials as substitution options in conventional solutions (*Consequential*), Application in combination with a high variety of different technologies; ensuring high flexibility & advocating for more standardized methods for growing and trading bamboo (*Procedural*), Leverage existing capabilities and value chains, while selectively developing new knowledge and facilities as needed (*Structural*), Advocates for this change through studies and public opinion building (*Personal*)	Popular lighthouse projects demonstrating feasibility and increasing visibility (*Comprehensibility*), Conventional technologies are maintained, which are taken for granted in the majority of buildings (*Taken-for-grantedness*)

The higher legitimacy of Vision 1 in China, which is based on the sectors' societal values (*Moral*) and deeply held beliefs (*Cognitive*), in this case both stems, at least to some extent, from the political system in China, which promotes the wider use of engineered bamboo. Policy is also inherent to the dominance of ideations (Jasanoff and Kim, 2009, 2015), which is why we argue that in some cases the legitimacy and collectivization of visions is not limited to the societal values held by key actors, but is significantly driven by (formal) institutions (and related societal values and beliefs). The lead in legitimacy in China makes the vision legitimized to a larger extent, and thus more widely adopted, in China than in India.

We identify an alternative socio-technical vision in India and China centered around the **frugal use of bamboo**, building on traditional knowledge and practices. This vision represents a simple, yet effective solution that leverages skills passed down through generations, aiming to address both affordability in housing and sustainability. Its legitimacy falls short in personal added value (*Pragmatic*) and is not consistent with existing customs and beliefs (*Cognitive*). Nevertheless, this vision is compatible with existing norms of the construction sector (*Moral*). In this context, however, we found very low degrees of legitimacy in the structural dimension in China. This suggests that the key actors promoting this vision do not provide the necessary physical characteristics, such as the required facilities in the value chain, to legitimize their idea of decarbonizing the construction sector (*M: structural*). This gap in legitimacy prevents the vision from becoming dominant or significantly accelerating the bio-based transition in the construction sector in India and China, as it lacks the broader collective values necessary for widespread adoption and impact. However, key stakeholders in India achieve stronger *moral* legitimacy because, particularly in rural areas, bamboo has been a key component of construction for many decades, making it consistent with existing norms and societal values among actors in some rural areas.

> *"We have lot of rural houses built out of bamboo. So traditionally, actually, people are using bamboo as an easily available kind of material for making their houses in rural areas."*
> *(India_18)*

This advantage in *moral* legitimacy across all subdimensions indicates that the vision of following a frugal use of bamboo is slightly more adopted in India than in China, but overall, it still remains an alternative socio-technical vision. These two visions centered around the use of bamboo are alternative visions in India and China, as shown in Figure 7, among other visions that will be analyzed below.

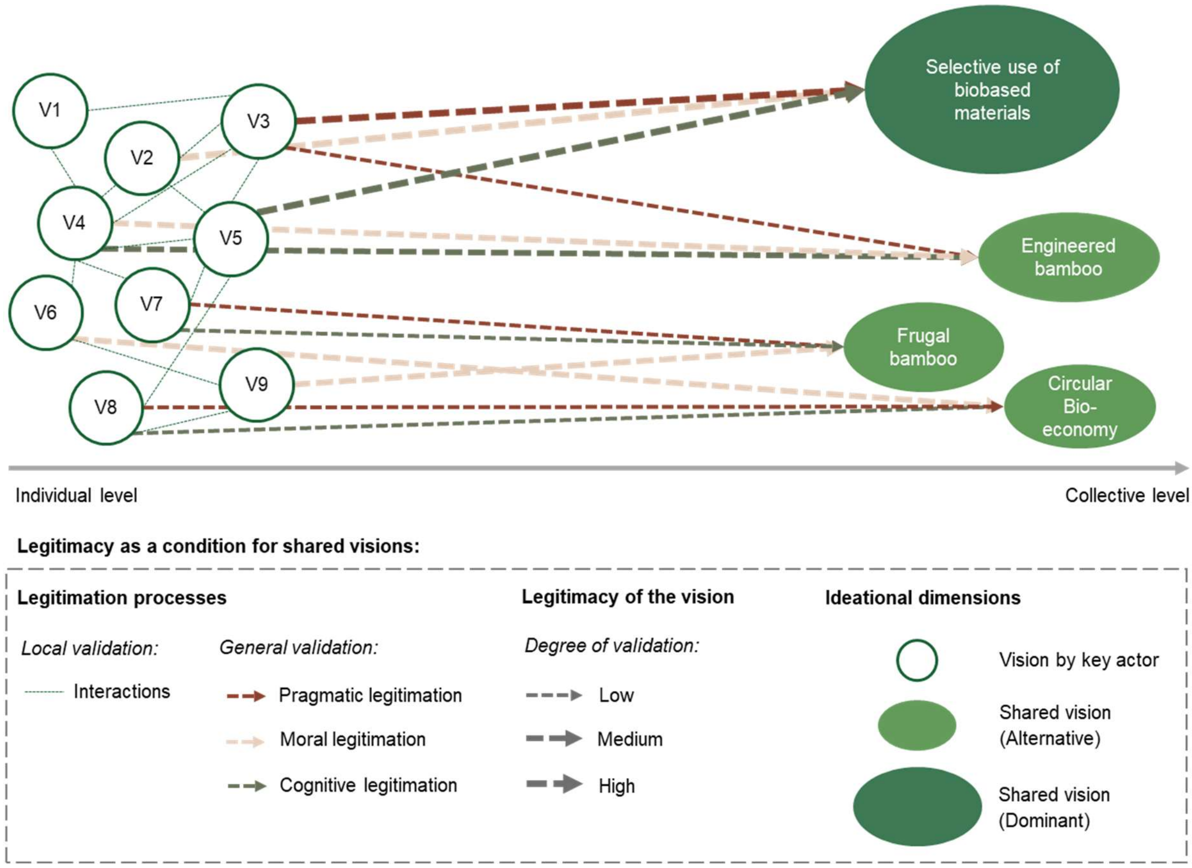

Figure 7: Legitimacy of socio-technical visions in bio-based construction in India and China

Vision 3, the **selective mix with conventional materials**, is increasingly seen as a desirable future by key actors in all four countries, as it offers lower barriers to adoption than other alternative visions. The legitimacy of this vision is the strongest among all identified visions of a bio-based construction sector across all legitimacy types and, consequently, it is the dominant socio-technical vision in this segment. It serves as a benchmark case to simulate how much and what kind of legitimacy is needed for each dimension for a vision to be widely adopted by stakeholders and become the dominant vision: Key actors often perceive individual benefits when they begin to pursue this vision (*Pragmatic*). It provides an approach to make construction more sustainable, but still allows actors to use familiar building components and techniques. This adds value to the adoption of the vision, as they can use bio-based materials, but still rely on conventional technologies that meet the needs of the individual characteristics of a construction project (*P: Exchange*). At the same time, this enables each actor a high degree of flexibility and *influence* in deciding which (bio-based) materials to incorporate and how much will be changed compared to conventional construction (*P: Influence*).

> *"People would not like the old structures of a single small storied [building] (...). Maybe they want to go for two or three [storeys]. Then you will have to have some sort of a composite structure, which will have to*

come up. (...) They use some sort of metals for joineries and other things." (India_11)

The very selective use also proved to be a legitimate instrument to demonstrate the 'good character' of this vision, as such projects receive increased attention. For instance, the use of processed bamboo, primarily in facades to aesthetically demonstrate the sustainability of new public buildings, such as in the Bengaluru airport, receives a great amount of public attention and is thus used as a lighthouse project by key actors to demonstrate how this vision is in best interest of facilitating the transition towards a bio-based construction sector (*P: Dispositional*).

The proximity to established technologies also contributes to increasing *moral* legitimacy, as this vision represents existing norms and values of key stakeholders in the sector. In this sense, accomplishments such as the aforementioned lighthouse project reinforce that the vision is achievable and establish the idea of replacing some parts with bio-based materials (*M: Consequential*).

"It is a substitute (...) for steel and wood. It is known. Even the Bengaluru airport now they had a reconstituted bamboo with which they have made all the structures and all along with steel and other things. So, the application is known." (India_11)

There are additional approaches that appear promising to align the vision with existing societal values in the construction sector, as this vision can be realized by substituting a variety of different materials. Against this background, continuous development of new solutions in pursuit of the vision allows for a positive evaluation (higher legitimacy) by additional stakeholders (*M: Procedural*).

"Some high-performance materials that modern industry can provide, such as steel, we also adapt it to the economic and technical conditions of rural construction to develop some prefabricated light steel structure buildings [including bamboo] suitable for use in rural areas" (China_11)

In particular, the *structural* dimension provides a high degree of legitimacy in all countries, since existing capacities and value chains can be used and new knowledge and facilities need only be selectively developed as required.

"And now we know bamboo, there are a lot of modern applications, there are a lot of treatment methods, and a lot of new architecture coming in. (...) It can go hand in hand with other materials, (...) because bamboo reinforced concrete is there." (India_11)

The initially stated broad public recognition of lighthouse projects is a matter for additional representatives, CEOs of construction firms or government officials, to advocate for this vision (*M: Personal*).

The selective use of bio-based materials is also consistent with the existing cognitive frames of key actors, as the deeply held customs and beliefs related to conventional construction are only slightly challenged (*Cognitive*). More specifically, the increasing visibility in public discourse demonstrates feasibility as well as it meshes with everyday experiences of actors (*C: Comprehensibility*). Moreover, the stakeholders following this vision see it as the only way to pave the way to a bio-based construction sector, since it maintains to some extent the conventional technologies that are *taken-for-granted* in the majority of existing buildings. In this sense, they consider the alternatives (the other visions) as 'unthinkable'. Thus, this vision is highly legitimized, as it shows high legitimacy across all dimensions, and can therefore be considered the dominant socio-technical vision. However, we found differences in comparing the different cases. The legitimacy of Vision 3 seems to be slightly stronger in India & China compared to the European cases in Germany and Italy. This is mainly due to a slightly higher legitimacy of some of the remaining alternative visions in Germany and Italy, which favor timber (Visions 4 & 5), when compared to the alternative socio-technical visions in India and China, which center around bamboo (Visions 1 & 2). This is because more European actors are already pursuing a broad application of timber in buildings (Visions 4 & 5), which competes with the selective involvement of some timber, e.g. as structural elements (Vision 3).

In Germany and Italy, we found an alternative socio-technical vision to use **serial timber construction** (Vision 4). The legitimacy of Vision 4 and of the remaining Visions 5 and 6 can be retrieved from Table 5. In some regions with existing timber value chains, this vision is already validated (legitimized) because key actors perceive individual added value for pursuing this vision (*Pragmatic*). The same applies to the positive evaluation based on the similarity to existing norms and societal values of these key stakeholders (*Moral*). Both aspects are particularly true in Germany, where a higher degree of legitimacy, based on achieved outcomes and ongoing procedures, facilitates alignment with existing norms among construction actors, driving collectivization (*M: Consequential & Procedural*).

> *"We initiate [2 large] pilot projects because we think that it is very important to show that building with wood is also possible on a large scale and that we might also look at problems in such projects, such as fire protection and moisture protection. These are issues that perhaps still hinder others in their decision to implement the entire project in timber construction." (Germany_13)*

Table 5: Legitimacy of visions in a bio-based construction sector (Visions 4-6)

Socio-technical vision	**Pragmatic** (evaluation based on self-interest)	**Moral** (evaluation based on norms/societal values)	**Cognitive** (evaluation based on deeply held customs and beliefs)
Vision 4: Serial timber	Faster construction process through prefabrication; availability to disassemble and reuse timber components; better quality of life in timber buildings (*Exchange*), Involvement of the customer in the planning process from the beginning to meet individual requirements (*Influence*), CO_2 mitigation by storing CO_2 in timber and off-site production (*Dispositional*)	Locally established institutional networks; timber construction is part of architecture in higher education; pilot projects demonstrating fire and moisture protection (*Consequential*), High level of automation throughout the construction process: very high level of prefabrication and recyclability; training and education for architects and planners to improve and disseminate the skills required for serial timber construction (*Procedural*), Large local capacity in the upstream timber value chain that could easily be used for more timber construction (*Structural*), Various networking initiatives to make wood construction visible and to convince other key players (*Personal*)	Increased awareness through education of planners and architects; pilot projects demonstrating the feasibility of multi-storey timber construction (*Comprehensibility*)
Vision 5: Eco-balanced timber	Reusability at the end of the building lifecycle; enabled a broader range of wood to be used in walls, adding value to a previous waste material; better quality of life in timber buildings (*Exchange*), Reduce of wood waste, ensuring circularity; emphasis on using only timber that can be managed sustainably (*Dispositional*)	Locally timber-construction high-rises possible; speeds up the construction process compared to conventional materials (*Consequential*), Fire protection, sound insulation tests and lifecycle-assessment ensuring requirements; holistic planning process that involves all stakeholders from the start (*Procedural*), Highly automated production facilities, but high customization in projects as an obstacle to establishing organizational structures (*Structural*), Local networks covering the entire value chain create opportunities for cooperation; star-scientist expects walls made of waste wood to last a thousand years (*Personal*)	Locally broad attention and curiosity through emerging media appearance (*Comprehensibility*)
Vision 6: Circular bio-economy	Providing a modular technology for affordable housing; enabling faster construction and higher efficiency (*Exchange*), Technologies can be customized based on specific needs (*Influence*), Addressing the housing shortage (in particular in cities); using cradle-to-cradle to enable a circular use of materials in construction (*Dispositional*)	Reduced time, cost and CO_2 impact by prefabricating and design to reassemble; using bio-based materials while maintaining regime standards through the standardized character of bio-based bricks/walls (*Consequential*), Collaboration with research institutes for categorization, testing and validation, as well as with industry partners, to enable use in products; efforts in education, awareness and coaching to reduce skepticism about new technologies (*Procedural*), Local supply chains are established: decentralized manufacturing units; broad access to material procurement (*Structural*), Seek to advocate for this vision through education and networking (*Personal*)	New materials lack comprehensibility, although increasingly demonstrated by pilot projects (*Comprehensibility*)

This alignment with the existing norms is lacking in Italy, because its timber construction is highly localized and mainly concentrated in South Tyrol, which makes it challenging to increase the legitimacy in these dimensions (*Moral*). This has so far hindered the further adoption of this vision in Italy, in addition to the negative evaluation of Italian actors in terms of their personal perceived benefits (*Pragmatic*). Conversely, we found a higher level of *pragmatic* legitimacy in Germany, as the economic characteristics inherent to serial timber construction offer advantages due to a faster construction process through prefabricated components (*P: Exchange*).

> *"You have completely different possibilities for prefabrication. You can span widths that were previously only possible with larger dimensions, i.e. with larger cross-sections. As a renewable raw material, wood has huge potential. It is a high-tech building material."*
> *(Germany_13)*

In both cases, however, the legitimacy of the vision is generally low in terms of the *cognitive* dimensions. While there is some local *comprehensibility* among key actors, the serial use of timber in construction is not *taken-for-granted*. Therefore, this vision remains alternative and is (so far) expected to have a limited impact on the sustainability transition pathway in most regions.

For Vision 5, to pursue an **eco-balanced use of timber**, we find only low legitimacy among key stakeholders in Italy across all dimensions. In Germany, the diffusion of this vision has begun, primarily enabled by increased legitimacy through alignment with existing norms in the construction sector (*Moral*). Recent developments in new technologies provide validation, reinforcing that the vision constitutes legitimacy to meet the required norms and values among construction actors (*M: Consequential & Procedural).*

> *"We are significantly expanding the range of wood that can be used in load-bearing shell construction and thus using a lot of wood that would otherwise have been burned directly or would have quickly gone into thermal utilization in very short cascade uses" (Germany_16)*

The described legitimacy of this vision shows a certain similarity with the validation of the idea to use serial timber construction. In particular, as it is barely consistent with the deeply held customs and beliefs of other key actors, which prevents them from adopting the vision (*Cognitive*). However, the described rationales for *pragmatic* legitimacy of the serial use of timber (Vision 4) are stronger than for the eco-balanced use of timber (Vision 5). This is mainly due to the more complex nature of the use of eco-balanced techniques and technologies; the sharing of decision-making power and potential participation (*P: Influence*) is not provided to additional stakeholders if this vision would be adopted. These socio-technical visions pursuing timber construction remain alternative in Germany and Italy among additional desired futures held by key actors (Figure 8), but are more adopted in Germany.

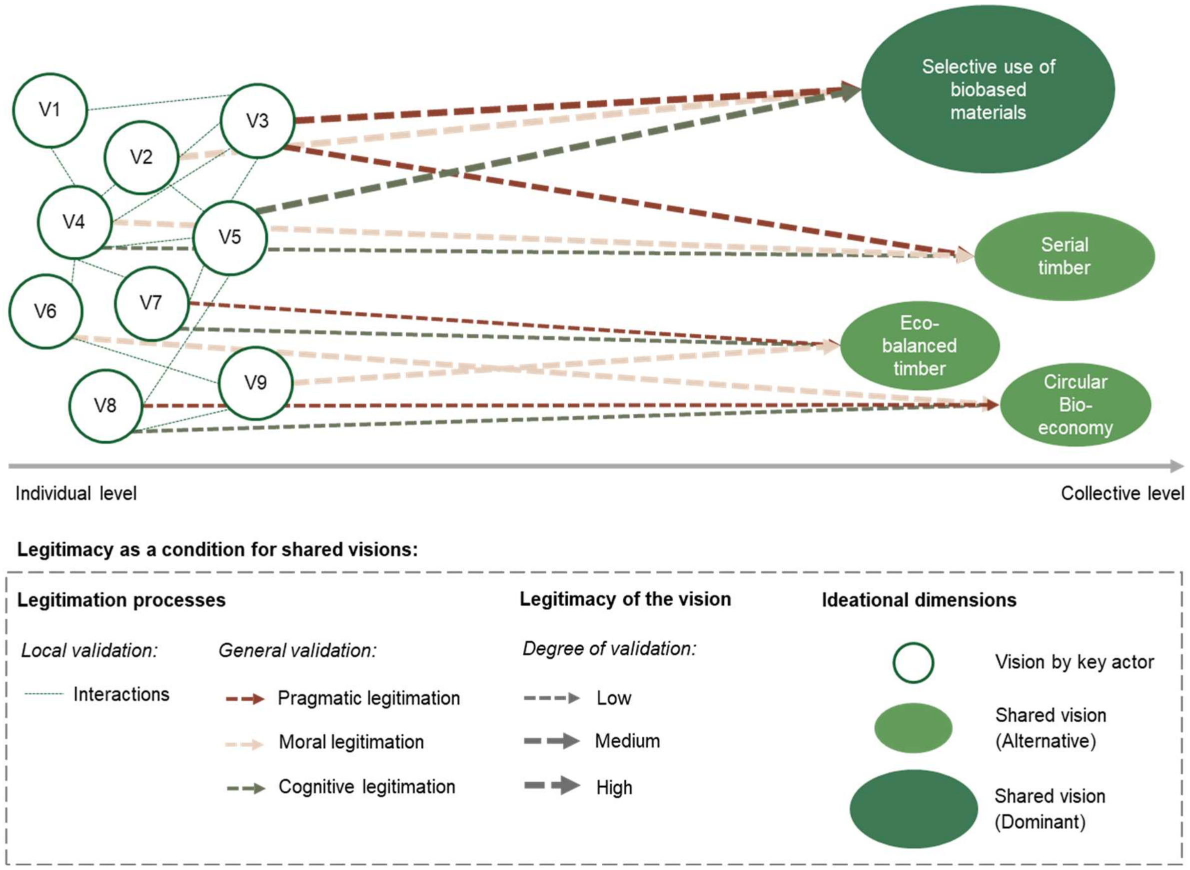

Figure 8: Legitimacy of socio-technical visions in bio-based construction in Germany and Italy

In India, Germany and Italy, we identified the vision of leveraging **innovation for a circular bioeconomy** in the construction sector (Vision 6). Similar to Vision 3, this desirable future implies a wide range of different techniques or technologies, all aiming at using novel bio-based technologies to turn the (bio-based) construction sector into a circular one. However, this idea is less popular among construction actors because the developed bio-based bricks or walls require a complete validation of the promising new approaches, the achieved outcomes, and the necessary physical characteristics indicating, that they can be aligned with existing societal values in the construction sector (*M: Consequential*, *Procedural & Structural*). This low legitimacy stands in contrast to Vision 3, where actors provide most of the *moral* legitimacy based on the inherent similarity to existing norms and values, e.g. by using the existing categories and structures and mainly adapting them to a vision (*M: Structural*). Nonetheless, some gained legitimacy by providing added-value for other actors and aligning the vision with existing norms, which has initiated the spread of Vision 6 (*Pragmatic & Moral*). However, further consistency with deeply held customs and beliefs is needed for widespread adoption (*Cognitive*). Consequently, transforming the construction sector into a circular bioeconomy is an alternative vision. We found that this vision is further legitimized in India and Italy concerning *moral* and *pragmatic* dimensions compared to Germany. This may be due to the higher legitimacy of Visions 4 and 5 in Germany, which are competing and (so far) appear more legitimate for key actors to adopt.

3.6 Discussion

We found the pattern that certain legitimacy dimensions (especially *Moral*) seem to appear first along the collectivization process of visions, while others (*Cognitive*) are typically lacking in the case of alternative visions. Consequently, achieving resonance with deeply held customs and beliefs seems to be the major challenge in advocating visions towards transitions. We contend that in order to achieve *cognitive* legitimacy for a vision, *pragmatic* and *moral* dimensions are usually validated first: *Pragmatic* legitimacy, to serve individual perceived benefits for additional actors for adoption, and *moral* legitimacy, to ensure that the desired future is consistent with existing norms and values among key stakeholders in the construction sector. If these dimensions are not legitimized (generally validated), our results suggest that key actors may find it challenging to provide legitimacy for *comprehensibility* and, in particular, to make the adoption of their own vision *taken-for-granted* by other stakeholders in the sector. In this context, we can also see differences when comparing the European cases with India and China, as e.g. in China the use of engineered bamboo is to some extent *taken-for-granted*. This level of *cognitive* legitimacy is the highest among the identified alternative visions. Taking this into account, the identified visions also vary in their degree of materialization, which is carried out in particular through demonstration and pilot projects. Along the presented framework, the degree to which visions are materialized can be retrieved by analyzing the *consequential* legitimacy. Our findings also suggest that higher legitimacy of a vision indicates higher implementation, i.e. materialization. As shown for Vision 3, the high legitimacy among bio-based visions also leads to higher material outcomes, such as large and popular demonstration projects. Vice versa, this vision gained *consequential* legitimacy through the achieved outcomes. Nevertheless, compared to the incumbents in the sector following (green) conventional visions, this vision is not (yet) widely implemented and remains an ideation, while its realization into material outcomes depends on future legitimation. In this sense, it acts as a fluid interface between the first achievements of the present and its envisioned future.

Some previous studies have noted that the type and institutional context of an actor affects their respective visions or imaginaries (Carvalho et al., 2022; Hawxwell et al., 2024; Martin, 2021; Muehlberger et al., 2024), while other empirical cases did not find this relation (Wiarda et al., 2023). In light of these studies, our results show that the collectivization of visions is carried out by different actor groups depending on whether the socio-technical vision is alternative or dominant. For example, the alternative visions are often driven by one actor group that seems to lead the validation of the vision. As such, the key actors pursuing innovation towards a circular bioeconomy (Vision 6) are mostly start-ups that have developed an innovative bio-based technology, while to some extent, researchers also play a role. For visions centering around existing bio-based materials, such as wood or bamboo, we see a broader range of actor groups, i.e. upstream stakeholders (suppliers), researchers, architects, as well as interest groups. This implies that for visions that pursue more incremental changes in both socio-institutional and technical dimensions, such as novel bio-based technologies, one stakeholder group usually leads the discourse. Other desirable futures, which are to some extent based on existing socio-technical elements (bio-based materials), involve a wider range of stakeholders. We also found that the prevailing socio-technical logic among architects is a frugal or eco-balanced use of bio-based materials. Upstream actors, including suppliers and start-ups, instead often pursue serial use with prefabrication. Looking at the dominant socio-technical vision, we observe that it is present in all stakeholder groups, which is similar to research findings on advocacy coalitions (Haukkala, 2018). In particular, actors at the core of the construction sector (architects, planners, engineers) seem to find it legitimate to adopt this vision. This suggests that in a process towards a collectivized (dominant) socio-technical vision, core stakeholder groups in a sector may be the last to be convinced of a vision, which points in the same direction as recent research on knowledge gaps in the bio-based construction value chain (Mazzoni and Losacker, 2024). We point to the role of different actor groups in the collectivization of ideations as an area of interest for further research.

Overall, we found that the selective use of bio-based materials is (so far) the dominant socio-technical vision of a bio-based construction sector and therefore it may influence the sustainability transition pathway. In some countries, we found certain alternative visions that could soon gain legitimacy (general validation) and thus could also shape the transition in some regions of these countries. Specifically, the serial use of wood in Germany, the use of engineered bamboo in China, and the frugal use of bamboo in India play an important role in this regard. They also benefit from the legitimacy of the dominant vision, which can be seen as a ‘light’ version of their vision to build entirely with bamboo or timber. On the other hand, in line with Wesche and Skjølsvold's (2025) typology, powerful actors can ‘capture’ legitimacy from other (weaker) actors by selectively including bio-based materials. That is, actors promoting the selective use of bio-based materials (Vision 3) are likely to ‘capture’ the legitimacy of bio-based materials, which has been gained through the arguably more disruptive, purely bio-based visions. In this way, Vision 3 captures legitimacy for bio-based materials, even though its use of these materials is limited and much of the sector’s status quo, including a continuously high use of steel and cement, is intended to be preserved. This emphasizes the role of power (imbalance) in legitimizing visions and it highlights the complex interplay and co-constitutive nature of different visions. In this context, it is also crucial to consider the additional competition of the described bio-based (alternative) visions with the globally dominant STI based on the use of cement and steel, which were not the focus of this paper. In sum, our developed framework leads to a more comprehensive conceptualization of how actors’ ideations of the sustainability transition in a sector differ in the degree of collectivization and consequently in their potential influence on the sustainability transition pathway.

However, the results and the discussion should be considered with the following limitations in mind. Our framework does not capture the entire collectivization process of actors' visions, but provides rather a snapshot of the general validation of (individual) visions depicted by legitimacy as a necessary condition for further adoption. Further research is needed to elucidate collectivization as a process by examining the collectivization of one imaginary over time. In this regard, it is also necessary to further conceptualize how institutionalization (inter)relates with collectivization and how other crucial conditions, i.e., power and the idiom of co-production, unfold in the ideational formation of STI. In line with Leeuw and Vogl (2024), our results show that the (dominant) vision favors industrial futures instead of pursuing more sustainable transition pathways. Consequently, following this imaginary could lead to further (unintended and/or negative) consequences and might not lead to a truly 'sustainable' transition in the construction sector. Similarly, as shown for energy transitions, there are (alternative) visions that are excluded from the public discourse (Jasanoff and Simmet, 2021). As such, our analysis does not take into account more disruptive visions emerging in civil society. This also entails that the analyzed legitimacy of the identified visions only refers to the legitimacy of the key actors in bio-based construction as included in the data collection, and not the legitimacy of all actors pursuing a bio-based transition. We leave it to future research to explore how such visions might differ from the expert visions examined in this paper, taking a more inclusive approach. This could involve analyzing visions of more diverse and critical actors, as well as user perspectives on the materials and technologies being discussed. In addition, scholars have observed that experts who advocate for specific visions influence the perspective of scientists (Sovacool, 2024), and thus the identified visions are not free from bias.

The empirical focus of this paper was on the relation between legitimacy and socio-technical visions, while the complex interactions between established and (private) visions and related changes in established visions are another subject for further research (Berkhout, 2006). In particular, future approaches should seek to unravel the mechanisms behind the mutually constitutive relationship between visions at the individual and collective levels. The process by which a socio-technical vision becomes a dominant imaginary is, of course, a question of power and power relations. We do not focus on the aspect of power in this paper, but it certainly plays a key role in understanding ideational formations and we consider it another relevant and closely related condition alongside legitimacy. Some previous studies have explored the role of power in the diffusion of visions (Jasanoff and Kim, 2015; Muehlberger et al., 2024; Shrestha et al., 2024), and there is a related strand of research on the role of power in sustainability transitions more broadly (Avelino, 2017). In transition studies, there are other strands of literature that offer different perspectives for examining the collectivization process of ideations, which we were not able to consider in-depth. Specifically, related studies highlight the importance of change agents in conveying and diffusing their visions, thereby driving the collectivization process (Duygan et al., 2019; Grillitsch and Sotarauta, 2020).

3.7 Conclusion

The aim of this paper was to understand the formation of ideations of a bio-based construction sector and their resulting dominance. In order to make sense of this process in a conceptual framework, we connected two strands of literature, drawing on the literature on legitimacy (Suchman 1995; Johnson et al. 2006) and the literature on socio-technical visions (Berkhout, 2006; Sovacool, 2024). This allowed us to distinguish between the local validation of (individual) visions and the general validation of socio-technical visions as a subprocess of collectivization of ideations in sustainability transitions, driven by different dimensions of legitimacy. Along this process, we considered the different states of key actors' ideations and analyzed how the general validation of (individual) visions leads to legitimized and collectively embraced socio-technical visions. Depending on the degree of general validation, we were able to identify whether a socio-technical vision becomes alternative or dominant: A vision is legitimized (generally validated), and thus becomes a dominant one, when a positive evaluation of all legitimacy types is achieved, indicating that it is legitimate for key stakeholders in a sector to adopt the vision. This sheds light on the collectivization of visions, reveals which characteristics of a vision in sustainability transitions lead to its adoption (validation), and contributes to the understanding of the formation of ideations. This adds value to the study of futures in sustainability transitions, as dominant socio-technical visions are expected to influence the sustainability transition pathway. In other words, by investigating how a desirable future became the dominant one among key actors in a sector, we learn which socio-technical visions and related technologies potentially play a role in the transition and which are likely to remain niches. While the legitimacy of socio-technical visions is a necessary condition for collectivization, further perspectives on STI formation are needed, including the co-production and materialization of activities and practices, as well as the 'politics of the future' (Longhurst and Chilvers, 2019; Oomen et al., 2022). Accordingly, further research is needed to investigate how collectively held desirable futures (STI) specifically lead to the (co-)production of e.g. new practices or social orders, how this affects the transition pathway ('paths in-the-making' (Christley et al., 2024)), and how (the dominance of) STI changes during a transition. For example, certain events and external influences that reconfigure the discourse can also have an impact on how visions are formed and the extent to which they can then influence transition processes. In this context, it is critical to further examine the role of power dynamics between relevant stakeholders and their impact on visions as another crucial aspect of ideational formation in transitions (Avelino, 2017).

The case studies presented offer a forward-looking perspective on the (emerging) transition in the construction sector. We identified six socio-technical visions, some of which are prevalent in all countries: The selective use of bio-based materials alongside conventional materials and techniques turned out to be the dominant socio-technical vision in all countries, thus influencing the expected sustainability transition pathway of the bio-based construction sector the most. However, alternative visions centered around the use of wood in Germany and Italy and the use of bamboo in India and China are highly legitimized (validated) in some regions. In these regions, they can also be expected to have an increasing influence on the sustainability transition pathway towards a bio-based construction sector, if they are able to align their vision with existing deeply held customs and beliefs. Considering the geography of desirable futures along the described formation of ideations, further research is needed to provide perspectives on the multi-scalarity of visions (Gong, 2024) and how this aspect might affect their collectivization in transition studies.

In transition studies, visions or imaginaries have often been seen as a subject to provide legitimacy for innovations. We argue, however, that legitimacy can, in turn, unfold one necessary condition in the process of collectivization of new ideas. The relationship between ideations and legitimacy in the context of transition studies is, therefore, a multifaceted and complex one that requires both more theoretical engagement and more empirical research. Our study represents an initial step in this direction, but it also contributes to the ongoing discussion about 'what is collectivized' in desirable futures and how this collectivization of visions is achieved (Kuchler and Stigson, 2024; Rohde and Santarius, 2023). By distinguishing the legitimacy of visions into three types (*Pragmatic*, *Moral* & *Cognitive*) as suggested by Suchman (1995), we proposed a detailed conceptualization of which aspects of general validation are lacking in legitimacy for a vision to be collectivized. In the case studies on the construction sector, we found that key actors in particular have difficulties in ensuring that their vision is consistent with the deeply held customs and beliefs of current stakeholders (*Cognitive*). Instead, the easier task seemed to be to provide legitimacy that indicates alignment with existing norms and values (*Moral*), as well as to offer personal added value to additional key actors in adopting the vision (*Pragmatic*). These observations highlight the challenges that niche actors face in successfully advocating their vision for future sustainability transitions.

3.8 Appendix

Table 6: Details on the conducted interviews used for article 2

Interview name	Interviewee role	Organization Size	Organization details
China_1	CEO	Medium	Construction project management consulting company
China_2	CEO	Medium	Architectural office focused on sustainable, bio-based construction
China_3	Director	Small	Bamboo design center
China_4	Managing Director	Medium	Architectural firm focused on sustainable building solutions
China_5	CEO; Professor	Big	Architecture firm; Research on sustainable architecture
China_6	Head of Global Construction	Small	Industrial company with international industrial construction projects
China_7	Managing Director	Medium	General contractor specialized on international (sustainable oriented) clients
China_8	Senior Engineer	Big	Planning, engineering and design of sustainability-oriented construction projects
China_9	CEO	Small	Architectural firm focused on bamboo architecture
China_10	General Manager	Small	Engineering consulting company for sustainable engineering solutions
China_11	Professor	Medium	Research on bio-based architecture
China_12	Associate Professor	Medium	Research on energy efficiency & green building materials
China_13	Professor	Big	Research on bio-based architecture
China_14	Programme Coordinator	Big	International organization promoting bamboo
China_15	Professor	Medium	Research on bio-based construction materials
China_16	Professor	Small	Research on bio-based construction materials
China_17	Professor	Big	Research on engineered bamboo and timber
China_18	CEO	Medium	Engineered bamboo supplier
China_19	CEO	Big	Bamboo construction material supplier
China_20	Sales Director	Big	Bamboo construction material supplier
Germany_1	Project Manager	Medium	Architectural firm focused on wood construction
Germany_2	CEO	Medium	Architectural firm focused on wood construction
Germany_3	CEO	Small	Architectural firm focused on repurposing/upgrading existing buildings with sustainable materials
Germany_4	CEO	Medium	Architectural firm focused on wood construction
Germany_5	CEO	Medium	Architectural firm focused on bio-based materials (mainly timber)
Germany_6	Founder	Medium	Planning and design of engineering structures focusing on sustainable projects
Germany_7	Team Leader	Medium	Planning office in civil engineering with structural engineering projects using timber construction
Germany_8	Head of Sustainable Structures	Small	Engineering firm focused on wood construction
Germany_9	CEO	Medium	Planning firm focused on timber construction
Germany_10	Project Coordinator	Medium	Timber construction campaign, initiated by a German state to promote climate-friendly construction with wood
Germany_11	Director Network & Consulting	Medium	Network for sustainable buildings that develops sustainability certifications.
Germany_12	Project Manager	Small	Organization promoting timber construction in Saxony funded by the state
Germany_13	Head of Research	Big	Research on bio-based building materials (engineered bamboo and mycelium-bound)

Interview name	Interviewee role	Organization Size	Organization details
Germany_14	Professor	Big	Research on timber construction and structural timber engineering
Germany_15	CEO	Small	Supplier of low carbon and reusable concrete bricks based on geopolymers
Germany_16	Head of Public Relations	Small	Supplier of timber and modular wooden building blocks
Germany_17	R&D Program Manager	Big	Global R&D department of large cement supplier with focus on sustainability
Germany_18	Head of Sustainability Strategy & Engagement	Big	Large cement supplier focused on clinker reduction
Germany_19	Key Account Manager	Big	Supplier of cross-laminated timber
Germany_20	Project Developer Modular Design	Medium	Project developer with investments wood construction projects
India_1	CEO; Professor; Director in government (Retired)	Big	Government (urban planning), University (sustainable construction), Large architectural firm
India_2	CEO (Person 1) & Project Manager (Person 2)	Medium	Non-profit organization for sustainable housing
India_3	CEO	Small	Architectural firm focusing on bio-based materials (stabilized earth)
India_4	CEO (Person 1) & Architect (Person 2)	Medium	Architectural firm focusing on bio-based materials & intelligent water and sanitation designs
India_5	General Manger	Big	Large contractor of industrial, infrastructure and public projects
India_6	CEO	Medium	Architecture consultancy focusing on bio-based resources such as waste or flash
India_7	Managing Director (Person 1) & Associate Architect (Person 2)	Medium	Architectural firm focusing on passive and low energy architecture
India_8	CEO	Small	Architectural firm focusing on bio-based materials (e.g., poured earth concrete)
India_9	CEO	Medium	Architectural firm focusing on sustainable designs
India_10	Assistant Manager	Big	Large contractor of industrial, infrastructure and public projects
India_11	Managing Director	Medium	Supply and construction with various bio-based materials (bamboo, mud, recycled wood)
India_12	Senior Consultant	Big	Consultancy advising the government on the development of a bamboo-based supply chain
India_13	Assistant Professor; prior Industry Manager	Big	Research institute focusing on sustainable construction management
India_14	Consultant & former director of a research institute	Medium	Research institute for bamboo construction & advising an international interest group for bamboo
India_15	Executive Director	Medium	Research institute on earth construction and architecture
India_16	Director	Medium	Government council for the promotion of construction materials and technologies
India_17	Director	Medium	Government institution for R&D in construction
India_18	Regional Director	Big	International organization promoting bamboo
India_19	CEO	Small	Investor focusing on construction and agricultural bamboo projects
India_20	CEO	Small	Provider of a novel bio-based technology for constructing walls
India_21	CEO	Small	Supplier of bio-based bricks
India_22	CEO	Small	R&D and supplier of waste-based sustainable concrete
India_23	CEO	Small	Supplier of bricks based on recycled plastic waste and industrial waste
India_24	CEO	Medium	Supplier of bamboo and planning & implementation of bamboo construction
India_25	CEO	Big	Bamboo advocate: R&D, architecture, education & training

Interview name	Interviewee role	Organization Size	Organization details
India_26	Postdoctoral Researcher	Medium	Research institute focusing on recycling of construction materials
India_27	Professor; Head of Department	Medium	Research on sustainable architecture focusing on waste materials
India_28	Assistant Professor	Medium	Research on sustainable reinforced concrete
Italy_1	Architect & Engineer; R&D specialist	Big	Architectural firm focused on sustainable construction
Italy_2	Architect & Engineer	Small	Architectural firm focused on bio-based architecture (raw earth, bamboo, straws)
Italy_3	CEO	Small	Architectural firm focused on bio-based architecture
Italy_4	Project leader	Big	Architectural firm focused on sustainable buildings
Italy_5	CEO	Small	Architectural firm focused on bio-based architecture (wood)
Italy_6	Associate Engineer	Medium	Engineering firm focused on wood construction
Italy_7	CEO	Small	Supplier and construction company focused on wood
Italy_8	CEO	Small	Supplier and construction company focused on different natural materials
Italy_9	CEO	Small	Supplier and construction company focused on clay
Italy_10	CEO	Small	Supplier and construction company focused on different natural materials
Italy_11	R&D	Small	Provider of sustainability certification, training and education
Italy_12	CEO	Medium	Planning studio focused on wood construction
Italy_13	CEO	Small	Supplier of materials derived from recycled natural waste
Italy_14	Technical Sales Manager; Architect	Small	Supplier of clay, wood and other natural materials
Italy_15	Marketing & Communication	Small	Supplier of cork products
Italy_16	CEO	Medium	Supplier of wood and cross-laminated timber
Italy_17	CEO	Small	Supplier of hemp products
Italy_18	Product director; Engineer	Big	Supplier and construction company focused on clay
Italy_19	Sales manager	Big	Supplier of wood

Identified visions

Vision 1: **Engineered bamboo**

Some stakeholders in India and China see the use of engineered bamboo as one of the key levers in the transition to a bio-based construction sector. The targeted market segment in both countries is primarily aesthetically pleasing public buildings for showcase purposes, with public procurement playing an increasingly important role in some regions of China. The alignment with the existing construction sector regime is low, as there are currently few bamboo buildings and the technology is not mature enough to meet the demand for mid- and high-rise buildings. However, the envisioned change is to provide large scale serial bamboo buildings, accelerating a bio-based transition. Economically, this approach is seen as significant for innovation and job creation, with potential for high growth, but currently facing challenges related to standardization and scaling.

Vision 2: **Frugal use of bamboo**

In India and China, other key actors are pursuing the use of bamboo with a different socio-technical logic. They envision a construction sector based on unprocessed, locally sourced bamboo that is used frugally. This vision targets rural areas, particularly in India, due to traditional bamboo construction practices. It has little similarity to the existing construction regime, emphasizing the use of minimal resources and leveraging existing agricultural systems in China. The socio-technical logic of the transition is characterized by low cost, high manual labor involvement and sustainability, promoting self-sufficiency in rural areas. In contrast to Vision 1, the frugal use of bamboo is more grassroots and community-driven, emphasizing traditional methods over industrialized processes.

Vision 3: **Selective mix with conventional materials**
In India, China, Germany and Italy, there is a vision to selectively incorporate bio-based materials into established construction technologies. This approach targets mainstream residential and commercial buildings that are closest to the existing regime, with minor modifications to conventional methods. While this overall socio-technical logic is the same for all four countries, the norms and values differ from country to country. As a result, the preferred materials and their intended use vary, with India and China primarily considering a mix including engineered bamboo, while Germany and Italy focus on incorporating cross-laminated timber wherever economically feasible. Moreover, the norms and values also deviate between India and China, as well as Germany and Italy, similar to the differences in Visions 1 & 2 and 4 & 5, i.e. stakeholders in the Indian (bio-based) construction sector often emphasize a frugal use (in combination with conventional materials), while Chinese institutions enforce a serial use. Economically, this vision is seen as cost-effective, allowing for the gradual adoption of sustainable materials without significant disruption. The envisioned transition represents a practical step forward, with moderate progress in implementation in different countries.

Vision 4: **Serial timber construction**
Stakeholders in Germany and Italy see serial timber construction as the cornerstone of a bio-based construction sector. This vision targets a wide range of buildings and is therefore more aligned with the existing regime than the use of engineered bamboo in India and China. The transition associated with this vision has a strong focus on standardization and mass production in Germany, while Italy faces challenges due to the lack of standards for mass implementation and the concentration of the timber industry in one region. The socio-technical logic emphasizes efficiency, scalability, and potential cost reductions through standardization. It shows significant potential for growth, particularly in Germany, with ongoing efforts to overcome regulatory and industrial hurdles.

Vision 5: **Eco-balanced timber construction**
Actors focusing on ecologically balanced wood construction emphasize the sustainable use of wood, the use of local resources, the avoidance of adhesives, and the reuse of wood waste. These

logics contrast with those described in Vision 4. This vision targets environmentally conscious residential and commercial buildings and is slightly less similar to the existing regime than serial timber construction. The associated changes in the sector vary from country to country: In Italy, stakeholders prefer to use less processed materials and no adhesives, while German stakeholders focus on the type of wood and its potential for reuse. Economically, a transition following this vision involves higher costs due to its sustainability focus, but offers long-term environmental benefits. It shows a commitment to sustainability, with varying degrees of adoption in Germany and Italy.

Vision 6: **Innovation for a circular bioeconomy**

In India, Germany and Italy, some key stakeholders are pursuing a vision of circular use of bio-based materials enabled by innovation. This vision deviates from the existing regime and involves novel technologies, such as the construction of walls or the development of bricks from agricultural waste, which represent new types of construction. Accordingly, a transition following this vision would alter the socio-technical logics of the sector. The specific technologies developed vary from country to country, reflecting different market segment sizes and stages of development. Economically, this approach emphasizes innovation and long-term sustainability, potentially reducing waste and resource consumption. The envisioned socio-technical logic in each country is adapted to its specific technological capabilities and market needs, with varying levels of technological development and market integration.

CHAPTER FOUR

4 Partners, foes or parasites? How interacting socio-technical configurations shape the directionality of technological fields

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Abstract

Socio-technical configuration is a key concept in transition studies for understanding deep sectoral change. While much research has focused on the emergence of single configurations, less attention has been given to the interaction and mutual interdependence of diverse configurations within an emerging technological field. These interactions may determine which of several configurations will become dominant, in particular when incremental configurations compete with more transformative ones. In this paper, we study the shape and impact of such interdependencies for the emerging field of sustainable construction materials, drawing on two cases at contrasting stages of maturation in Germany and India. By applying socio-technical configuration analysis (STCA) based on expert interviews, we identify two emerging configurations in both cases, a more incremental one centered on the greening of conventional building materials and a more transformative one based on bio-based materials – timber in Germany and bamboo in India. Our findings reveal a polycentric field structure in India with strong interdependencies and synergies between the bamboo and the incremental configuration, seemingly typical for the early stage of a transformative configuration. The German field is more fragmented, with the wood-based configuration being more mature and having a rather antagonistic relationship with the incremental configuration. The approach proposed in this paper enables to analyze the dynamics within socio-technical fields, advancing the so far dominating single configuration focus in much of the extant innovation studies literature.

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4.1 Introduction

The construction sector is a major contributor to climate change and environmental degradation, primarily driven by the building materials used (Cabeza et al., 2022; Zhong et al., 2021). Given its unsustainable mode of operation, the construction sector is currently pushed to develop more sustainable building materials, involving not only changes in technologies and material composition (Churkina et al., 2020) but also changes in institutional dimensions, such as societal rules, norms, regulations and practices (Fischer and Losacker, 2024; Jayaweera et al., 2025). On a global level, this transition follows two main types of configurations: a rather incremental change for the currently dominant construction regime centered around the greening of conventional building materials, including green cements and steel (Dewald and Achternbosch, 2016; Leeuw and Vogl, 2024). These are contrasted by more disruptive and transformative configurations around bio-based building materials, such as timber or bamboo (Mazzoni and Losacker, 2024; Fischer and Losacker, 2025), potentially enabling cities to become carbon sinks (Amiri et al., 2020; Churkina et al., 2020). Both types of configurations aim to decarbonize the construction sector and rely on similar external resources, such as policy support and legitimacy. In this sense, they constitute a common technological field, in which they interact to co-produce or compete over essential resources for their further development (Havinga et al., 2024; Mäkitie et al., 2022; Sandén and Hillman, 2011).

This interaction has important implications for the development of bio-based materials, and thus, on the direction of potential sustainability transitions in the sector. The two dominant configurations could either accelerate a transition of the construction sector because of a synergistic development of critical resources or could slow it down substantially, due to competition over scarce resources. We argue that synergistic or antagonistic relationships between socio-technical configurations influence their ability to tap into resources like knowledge, legitimacy, markets and financial investments, which are necessary for their maturation (Binz et al., 2016; Binz and Truffer, 2017; Mazzoni et al., 2025). These interactions will not only influence the magnitude of development within the field but also shape its specific directionality, thereby determining the extent to which the resulting changes contribute to a more or less sustainable future sector structure. While the extant transition literature has mostly remained silent on such interactions, we follow earlier calls addressing this issue (Bergek et al., 2015; Mäkitie et al., 2022; Nesi and Truffer, 2025). To achieve this, the paper builds on recent scholarship on co-existing socio-technical configurations (Heiberg and Truffer, 2022a; Miörner et al., 2022a; van Welie et al., 2018) and conceptualizes their interactions by drawing on a framework for technology interaction introduced by Sandén and Hillman (2011).

Empirically, the paper is based on a comparative case study design, using two country cases, India and Germany, which exhibit quite distinct institutional conditions and different building material logics (Fischer and Losacker, 2025). The contrasting case study design allows us to firstly identify the emerging socio-technical configurations in the sector, and secondly draw conclusions relating to the socio-economic and geographical contexts in which transitions are taking place (Coenen et al., 2012). The German case provides an example of a rather established technological field, while the Indian case is at an earlier stage of maturation. The empirical part of the paper is based on a set of expert interviews conducted with professionals from the technological field of sustainable construction materials in each country, analyzed using socio-technical configuration analysis (STCA), a methodological approach to map and analyze socio-technical configurations (Heiberg et al., 2022; Truffer et al., 2025). While the method has been applied to several empirical contexts (Heiberg and Truffer, 2022a; Miörner et al., 2022a; Yap et al., 2023), it has not yet been used to analyze interactions between configurations. Specifically, the paper first uses STCA to analyze the emerging technological field of sustainable construction approaches in Germany and India, mapping the existing, partly overlapping configurations. Second, and more importantly, we will reconstruct how interactions between configurations impact each configuration's ability to mobilize resources to advance its evolution or reinforce existing barriers. From this we explain for both cases how the transformative configuration is likely to develop, taking into account its maturity and how it interacts with the incremental configuration.

The remainder of the paper is structured as follows. In Section 4.2, we discuss the theoretical background and develop a conceptual framework for categorizing the interactions among socio-technical configurations. In Section 4.3, we describe the research data and how we identify the different types of interactions among the socio-technical configurations. We also briefly explain how STCA works and how we use it in this paper. In Section 4.4, we first map the emerging sustainability-oriented socio-technical fields in the construction sectors of India and Germany. Next, we identify interaction patterns among socio-technical configurations within each field. In Section 4.5, we discuss these findings in light of the recent literature in innovation and transition research. Section 4.6 concludes.

4.2 Theoretical background

Sustainability transitions unfold through changing configurations of networks of actors, institutions, technologies, and material artifacts (Rip and Kemp, 1998). These configurations constitute systemic interdependencies, which determine the shape of development trajectories of an emerging technological field (Geels, 2002, 2004; Kemp, 1994). In the widely popularized MLP framework, the dominant socio-technical configuration within a sector is mostly understood as constituting a socio-technical regime, while emergent, transformative configurations are typically framed as representing socio-technical niches (Markard et al., 2012). As this dichotomy tends to oversimplify the actual dynamics of many transitions (Geels, 2011), many scholars have adopted a broader understanding of socio-technical dynamics. Regimes are often only semi-coherent, combining a diverse set of actors, institutions, and technologies into a multitude of configurations that “work,” which compete with one another over how to best provide societal functions (Fuenfschilling and Truffer, 2014; Miörner et al., 2022a; van Welie et al., 2018). Also, emerging socio-technical configurations do rarely match the model of neat outsider-driven radical alternatives that have informed much of the early transitions literature but typically combine transformative and incremental innovations to various degrees. Recent scholarship has therefore proposed to analyze transitions as occurring within rather contiguous organizational or action fields, rather than in dichotomous regime-niche oppositions (Bergek et al., 2015; Fligstein and McAdam, 2011; Fuenfschilling and Truffer, 2014; Kungl and Hess, 2021). Furthermore, as most transition cases involve new socio-technical configurations that are partly competing and partly complementary, it is important to consider how these initiatives interrelate (Fischer and Losacker, 2024; Markard and Hoffmann, 2016). At an aggregated level, the co-existence and co-evolution of diverse alternatives may give rise to polycentric, splintered, or fragmented field structures, rather than a single, monolithic regime configuration (Madsen et al., 2022; Mäkitie et al., 2022; Miörner et al., 2021; van Welie et al., 2018).

4.2.1 A typology of relationships between socio-technical configurations

Multiple co-existing configurations may generate complementarities, which support the development of the whole field (Markard and Hoffmann, 2016), but they may also lead to contestation and friction. Following Madsen et al.'s (2022) conceptualization of contestation axes, frictions exist not only between established configurations and emerging configurations, but also within and between several emerging socio-technical configurations, resulting in complex coupled dynamics. Contestation can occur in various forms, for example between several emerging socio-technical configurations, each claiming to provide the ideal pathway to a sustainable future. The envisaged transformation of the incumbent socio-technical system typically varies between different emerging configurations. While some opt for more restricted, incremental changes, others require more fundamental, even disruptive changes to the status quo, i.e. transformative change (Hawxwell et al., 2024; Madsen et al., 2022; Weber and Rohracher, 2012). Earlier scholars had captured these alternative transition dynamics as either following a “fit-and-conform” or a “stretch-and-transform” pattern (Smith and Raven, 2012). In other words, emerging socio-technical configurations often differ over the required radicality for changing an established regime (Mäkitie et al., 2023). This induces emergence of both incremental and transformative socio-technical configurations.

In transition studies, scholars have long tended to view antagonistic relations primarily to exist between niches and the socio-technical regime as the most likely form of interaction between two socio-technical configurations (Smith and Fressoli, 2024). However, as we will outline below, this perspective has proven overly simplistic. We argue instead that interactions between different socio-technical configurations, may they be established or emerging, need to be unpacked for their synergistic and antagonistic relationships and how this impacts growth and directionality of the respective field. These interactions may couple dynamics across different technologies and institutional elements (Hughes, 1987; Markard and Hoffmann, 2016; Markard and Truffer, 2008) in an either synergistic or antagonistic way. They may for instance share specific goals, like contributing to a more sustainable construction sector, or compete over rules and resources that would favor their own configuration at the expense of all the others (Havinga et al., 2024). It is thus crucial, when analyzing transitions, to understand not only the internal alignment of socio-technical configurations, but also the interactions between different configurations (Bergek et al., 2015; Havinga et al., 2024).

We will therefore have to scrutinize where different configurations overlap in terms of actors, technologies and institutions. Actors can be individuals, firms or not for profit organizations, as well as more loosely connected networks of individuals or organizations (Carlsson and Jacobsson, 1994). One actor can support more than one technology, thereby creating a systemic overlap between resources – or a structural coupling – between two or more socio-technical configurations (Bergek et al., 2015; Binz and Truffer, 2017; Löhr and Chlebna, 2023). Thus, actors or networks involved with multiple technological solutions will couple the dynamics of these socio-technical configurations mediated by their capabilities, resources and interests (Lesch et al., 2023). Institutions influence how actors operate in a technological field consisting of rules that are widely accepted in a society (Markard et al., 2016; Scott, 2014).

Institutions therefore may create structural couplings through the degree that different configurations comply with or depend on the application and prevalence of the respective rules. Conventionally, three types of institutions are differentiated (North, 2009; Scott, 2014): The cognitive dimension relates to the accepted state of knowledge to operate a safe and beneficial service offering, be this by established ways how engineers or users leverage certain aspects of a configuration. The normative dimension comprises those rules that guarantee congruence with widely shared values, such as fair price-performance ratios, or the prevention of harm when applying a technology. It also shapes the desired outcomes of innovation dynamics in terms of projected visions and expectations. The regulatory dimension represents those rules that have been codified in law and which are implemented by the state. Several configurations in a field may relate to similar or different technological and institutional dimensions and therefore lead to coupled system dynamics, depending on how these elements impact the configurations or how specific actors are able to shape the elements in their favor (Heiberg and Truffer, 2022a).

Given the many and diverse elements that may exist in a given technological field, it is rather unlikely that the overall relationship between any of the corresponding configurations can be classified as either being synergistic or antagonistic. We would rather expect to observe gradients of more or less synergistic or antagonistic relationships to exist across several structural couplings. The specific profiles of synergies and frictions will furthermore have a decisive impact on the directionality of the field. Either by favoring one alternative over the other, or by impacting the resource structure in the field to push all configurations in a particular direction. We therefore argue, in line with earlier work, that it is important to expand the received typology of relationships between configurations beyond the dichotomous niche-regime pattern (Lesch et al., 2023; van Welie et al., 2018). In order to specify this gradient, we build on the seminal work of Sandén and Hillman (2011), who explored how interactions between different technologies can be classified. Specifically, we conceptualize (and then examine) these interaction types in order to identify frictions and potential synergies among emerging configurations within a defined socio-technical field (Miörner et al., 2021). Figure 9 provides a stylized representation of the interaction between two configurations in a technological field.

The different modes of interaction can be classified as proposed by Pistorius and Utterback (1997) and further substantiated by Sandén and Hillman (2011). Interaction can result as *competition*, where technologies, for example, vie for the same resources, inhibiting each other's success, such as in competitive access to investment funds. *Symbiosis* arises when technologies benefit mutually from accessing or producing a specific element, enhancing each other's performance such as a mutual reinforcement of legitimacy for the field in fighting against the incumbent configurations' perceived problems. In *neutralism*, technologies operate independently, with no significant impact on one another, as there is no overlap or contestation of elements. For example, electric and internal combustion engine vehicles use the same roads without affecting each other. *Parasitism* involves one technology benefiting from e.g. the resources or policy frameworks developed by another, often at the latter's expense. As such, public research and development (R&D) programs and subsidies focused on 'alternative fuels' initially supported biofuels, but were subsequently redirected towards electric mobility, which in turn constrained the further development of biofuels. *Commensalism* occurs when one technology benefits from an element developed by another configuration without affecting its availability for this configuration. For instance, vertical farming can benefit from cold chain logistics and food safety regulations developed by conventional industrial agriculture without affecting those technologies. Finally, *amensalism* describes a situation where one technology is inhibited by the presence of a certain element in a technological field, while the other remains unaffected. For example, in the construction sector, this occurs when an established building standard prohibits the use of timber yet poses no constraint for green concrete.

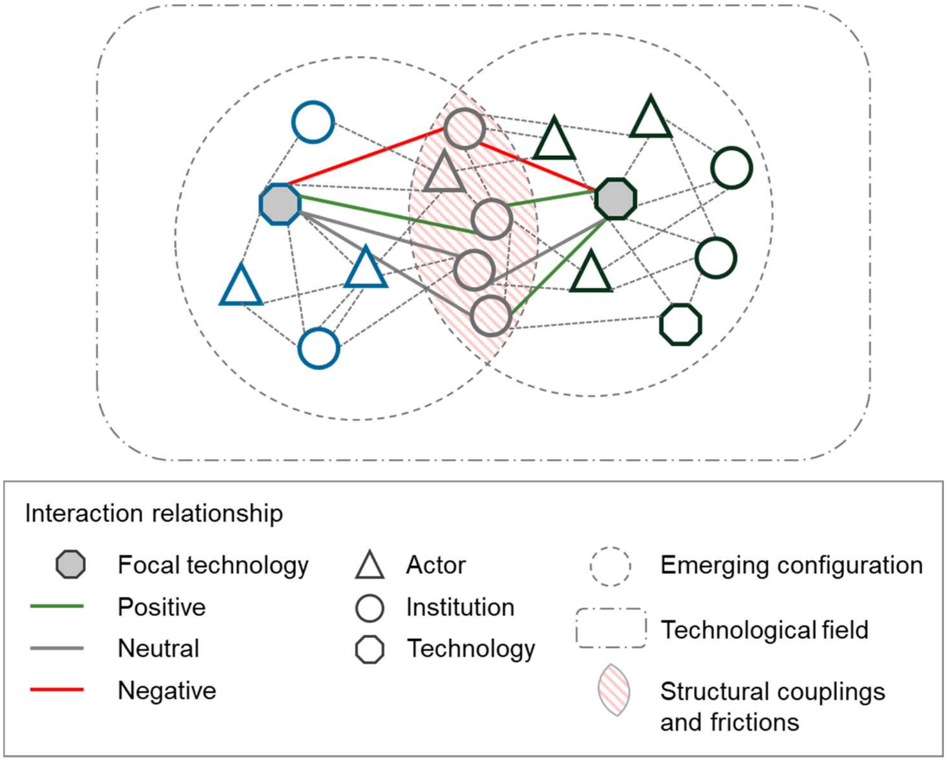

Figure 9: Interaction of emerging socio-technical configurations

While Sandén and Hillman (2011) provided a systematic discussion of different types of relationships, based on technology characteristics they did not explain how these interactions could be identified and operationalized in the context of broader socio-technical configurations. We take as a first intuition that interactions will impact the development of a configuration through its reliance on different kinds of resources that are essential for their maturation and scaling. In this regard, we draw on the classification of resources proposed by

Binz et al. (2016b) to identify different types of resources that have been shown to contribute to innovation success: knowledge, legitimacy, market formation and financial investments. We argue that socio-technical configurations essentially represent networks of technological and institutional elements with the latter typically regulating access to these resources. The institutional resource base that configurations can access comprises values and goals. These are accompanied by resources that are either context-related to a particular configuration, in order to leverage its evolution, or act as barriers. We therefore extend the originally technology-focused approach of Sandén and Hillman (2011) to account for interactions among entire socio-technical configurations, which we will further operationalize in the empirical section.

4.2.2 Interactions shaping the course of a more transformative configuration

To reduce the complexity of the causal relationships that may unfold from the interactions between several configurations in a given technological field, we will focus in the following on how a more transformative solution might be affected by the existence of more incremental alternatives in that field. In our empirical case study, these represent the bio-based configurations of wood and bamboo respectively, and their interdependencies with the more incremental sustainability strategies based on conventional building materials. The following elaborations are, however, meant to be generically applicable to any set of configurations in a technological field.

Relating to the types of resources proposed by Binz et al. (2016b), we may further specify how structural couplings with other configurations may influence the development prospects of the transformative configuration. We assume that the transformative configuration might benefit from developments in the broader field in terms of knowledge creation by profiting from research capacities that are built up for all alternatives. The transformative configuration may also be able to mobilize higher levels of legitimacy by co-constituting a field as more sustainable, while also being realistically implementable, which may incite policy makers to leverage support programs for the whole field. Linking to broader values in a sector could enable the transformative configuration to facilitate market formation because users would already get accustomed to alternatives to conventional building materials. The mobilization of financial resources might also be eased by building up expertise in banks and investment firms to deal with green alternatives.

Couplings might, however, also have negative effects. For instance, if a more incremental configuration had existed for longer and had been able to influence regulations, standards and norms, a configuration that emerged later would have to adapt to these existing institutions.

This would result in a reduced set of development prospects. Claims for legitimacy might also be hampered if several configurations engage in public battles over which alternative is the "truly" sustainable option. Knowledge related resources might hamper development prospects for the more transformative configuration if it is perceived as being too immature and risky to devote capacities and research programs. Finally, in terms of mobilizing financial investments there might be competition for scarce resources.

The transformative configuration's ability to mobilize resources necessary for its further development depends also on the specific contextual settings in which the actors operate, and in particular the specific geographies that provide resources and therefore condition the relationship between emerging configurations (Binz et al., 2025; Hansen and Coenen, 2015). Furthermore, we also expect the relationship between emerging configurations to depend on the maturity stage of the field. A transformative configuration might benefit from a synergistic relationship with more mature, incremental configurations during the early stages of technological field maturation, as this enables critical system resources to be mobilized for the transformative configuration to evolve (Mazzoni et al., 2025). The field might benefit for instance from shared promises about a better, more sustainable future, which might lead to increased resource flows by support programs or venture capital. In later stages of maturation, we would expect more conflict over the access to resources, leading to a higher number of antagonistic relationships. For instance, the transformative configuration might have built up a specific market position, where attaining higher market shares at the expense of the other configuration becomes an important option. One core battlefield could be that the more transformative configuration can more easily claim benefits in sustainability or other distinguishing aspects compared to the dominant sector technologies. Also, the mobilization of investments might become more and more competitive over time. Taken together, the conceptualization outlined above enables us to analyze the different stages of maturation, the varying relationships between the emerging configurations, and ultimately to draw conclusions about which contexts are conducive or obstructive to the transformative configuration mobilizing knowledge, legitimacy, markets, and financial investments.

At the level of the entire socio-technical field, we expect these interactions to have an aggregate effect on the field's structure and development potential. In the literature we see two types of expectations relating to the field structure. A homogeneous field structure is more suitable for overcoming coordination deficits and mobilize system resources. This is the general assumption of most of the innovation system literature (Bergek et al., 2008; Bergek et al., 2015; Hekkert et al., 2007). On the other hand, narrowing down the options too quickly might reduce the necessary diversity of potential technological solutions, thereby prematurely closing down non-optimal sustainability transition pathways (Bulah et al., 2024; Stirling, 2011). Diversity might also result from different value positions adopted by various stakeholders, preventing them from forming alliances too quickly. For instance, they may have different ideas about what sustainability means for the sector (Heiberg and Truffer, 2022a). As the field matures, we would expect to see a shift from a more diverse constellation to the convergence to a more consolidated field structure, potentially resulting in a dominant design within the field (Bulah et al., 2024). However, in terms of relationships between the remaining configurations, this could go along with a heightened degree of frictions and competition.

We may therefore conclude our conceptual elaborations by calling for the analysis of couplings between emerging configurations in a field to determine how this will influence the development prospects of a transformative option. This requires a specific methodological approach, which we will elaborate in the following.

4.3 Methods

We apply this framework to a comparative case study examining the emerging socio-technical configurations in the technological field of sustainable construction materials in India and Germany. Both countries have been witnessing the emergence of two co-existing major configurations. The more incremental approach focuses on greening conventional building materials – such as cement and steel – through technical innovations like green cement, low-carbon steel, or carbon capture and storage (Leeuw and Vogl, 2024). The second one advocates for a more transformative shift toward bio-based construction materials, including timber and bamboo (Mazzoni et al., 2025; Mazzoni and Losacker, 2024), which promise to significantly reduce embodied emissions and even turn buildings into carbon sinks (Churkina et al., 2020). While similar approaches may be observable globally, their specific manifestations differ across national contexts due to institutional differences, availability of materials, and construction practices (Fischer and Losacker, 2024; Jayaweera et al., 2025).

In Germany, for instance, the construction sector is highly institutionalized and heavily regulated, with strong norms and expectations centered on reinforced concrete and steel as standard materials. Bio-based construction is gaining traction, particularly in the form of timber-based multi-story buildings but continues to face regulatory and cultural barriers. By contrast, in India, informal construction practices are more widespread, and building codes are more loosely enforced. While concrete and steel also dominate urban construction in India, there is a long-standing tradition of using natural and locally available materials, such as bamboo, particularly in rural or low-cost housing segments. Yet, such materials often lack formal recognition and institutional support.

These differences provide opportunities to explore how socio-technical configurations emerge, interact, and evolve under two sets of context conditions and different maturation stages of the emerging transformative configuration. That is, the transformative configuration in India faces institutionalization difficulties and technological barriers to the large-scale application of bamboo, constituting an early stage of maturation. In contrast, the transformative configuration of timber in Germany is increasingly capable of providing larger-scale construction projects and has been endorsed by governmental institutions. Accordingly, it represents a higher stage of maturation. Thus, by comparing India and Germany, we can better understand how the interplay of actors, technologies, and institutions shapes emerging socio-technical configurations in sustainability transitions in the construction sector, and how interactions between contested configurations might unfold in diverse socio-technical and geographical contexts.

In both countries, we conducted (online) expert interviews with a wide range of stakeholders, including material suppliers, researchers, startups, architects, engineers, and planners. We also interviewed representatives from industry associations and government authorities, resulting in 21 interviews for Germany and 28 for India.[18] The interviews took place between August 2023 and June 2024, with an average duration of 50 minutes. The semi-structured interview guide was tailored to each expert's professional role and the country-specific context, exploring their perspectives on the construction sector and the role of different building materials and techniques. For the Socio-Technical Configuration Analysis (STCA) applied in this paper, we considered a stratified subset of the interviews in our database, aiming for a balanced sample. We identify comparable subsets in both countries based on two stratification criteria: stakeholder type and focal technology. This creates a balance in the actor networks as well as regarding the focal technology, ensuring that the relative importance of a certain focal technology is not magnified in one of the two countries. The subset includes ten interviews from each country to facilitate comparison between the two country analyses (Robinson, 2014).

We analyze this data using STCA, a semi-quantitative method designed to reconstruct socio-technical configurations from references of actors to the interrelation of technical and institutional elements (Heiberg et al., 2022; Truffer et al., 2025). STCA captures these relationships through coding textual data, such as interviews or newspaper articles, which are then analyzed using tools from social network analysis (Miörner et al., 2022b). For this paper, we use STCA to reveal how experts in the construction sector describe and associate specific technologies, practices, and norms. The resulting one-mode concept networks enable us to visualize the degree of relatedness between elements, identify competing configurations, and examine how different actor groups stabilize or challenge these configurations.

[18] A table with detailed information on all interviews is provided in the appendix in Section 4.7 (Table 9).

Table 7: Categorization of the focal technology and institutional dimensions: elements in the technological field of sustainable construction materials

Categorization	**Definition**
Focal technology	Material or technology that is preferred in the transition towards a decarbonized construction sector
Technology characteristics	Mediating characteristics or specification of a focal technology
Values	Value orientations of actors that guide their behavior and rationalize their actions
Goals	Broadly defined goals that are viewed as rather abstract or vague
Levers	Conditions that support the development of a socio-technical configuration
Barriers	Conditions that hinder the development of a (transformative) socio-technical configuration

We code interview transcripts by tagging each relevant text fragment with codes for technologies, institutions, and actor type. Actor codes indicate the type of stakeholder making a statement, such as R&D actors, the government, or architects, who (co-)mention different elements. The categorization of element codes consists of technological and institutional references (Table 7). In the context of the construction sector and derived from the coding process, we conceptualize *technology characteristics* that function as mediating resources and that are most likely bound to and addressed by one particular socio-technical configuration. Furthermore, configurations can draw on *value orientations*, as well as on *goals* that promise to implement certain values. Some conditions act as core *resources that leverage* the evolution of an emerging configuration. Finally, we conceptualize some institutions as *barriers* to transformative configurations. We employed an abductive coding approach (Vila-Henninger et al., 2024) starting by developing a coding scheme with several subdimensions based on the aforementioned categories. The coding scheme can be found in the appendix.[19] After several rounds of triangulation with other researchers of our working group, we identified the most relevant elements in the technological field of sustainable construction materials. In the resulting socio-technical field, the STCA sheds light on the overlap of two overall emerging socio-technical configurations: a green conventional (incremental) and a bio-based configuration (transformative).

[19] Table 10 in the appendix lists and explains all element and actor codes (Section 4.7).

To illustrate the coding process underlying the STCA, we provide a simple example:

> *"You have completely different possibilities for prefabrication. You can span widths that were previously only possible with larger dimensions, i.e. with larger cross-sections. As a renewable raw material, wood has huge potential. It is a high-tech building material."* (Germany_13)

This passage is coded with the elements *Timber* (as a focal technology) and *Prefabrication* (highlighting the potential of modular and off-site construction) and is assigned to the *R&D* actor code to reflect the interviewee's role as head of research. In the example above, within a two-mode network, the *R&D* (actor) node would be linked to both a *Timber* node and a *Prefabrication* node. In the corresponding one-mode representation, *Timber* would be linked to *Prefabrication*. As such, when multiple actors mention similar combinations of elements, they are interpreted as indications of relatedness and visualized as links in the resulting network graphs.

After conducting intercoder reliability tests, we created one-mode data matrices using Jaccard normalization to measure the similarities and connections among the elements. Next, we performed network analyses and developed corresponding visualizations. Lastly, we adjusted and combined coding schemes and recoded the interviews. In this sense, we follow previous research that has used STCA in other contexts for the step-by-step application (Heiberg et al., 2022; Heiberg and Truffer, 2022a; Lesch et al., 2023; Miörner et al., 2022a). This allows us to depict the current state of configurations in the socio-technical field and discuss their implications. The resulting one-mode concept networks allow us to examine the internal coherence of configurations that group around specific focal technologies.

Subsequently, we identified the emerging configurations by highlighting links to those institutional codes that had strong association with either the bio-based or the green conventional material nodes. This way we could graphically depict the socio-technical configurations as two networks and identify the elements where they potentially interact (see figures 2 and 3). This served as a starting point to identify their relationships by attributing each association to one of the six interaction modes presented in Table 8 (Sandén and Hillman, 2011). As a first step, we selected the most relevant links between each focal technology and all the institutional elements, based on the highest Jaccard similarity values (i.e. those institutional elements that were most consistently associated with the focal technologies in the interviews). In a second step, we qualified these associations between each focal technology and the shared institution as positive, neutral or negative for the further development of the respective configuration by going back to the original interview text parts that were coded for the respective institutional element. This assessment was backed by triangulation and discussion with other researchers familiar with the data to ensure robust results. The interaction modes were then determined from the perspective of the more transformative, bio-based material configuration. For example, if an institutional element had a positive association with the bio-based technology, while the incremental configuration had a negative association, the corresponding element was classified as representing a *parasitic* relationship between the two configurations. On this basis, we created two additional STCA networks, classifying the institutional elements according to the type of relationship they represent (see figures 4 and 5).

Table 8: Interaction modes of two socio-technical configurations (own elaboration based on Sandén and Hillman (2011))

Mode of interaction	Incremental configuration	Transformative configuration	General nature of interaction
Competition	–	–	Inhibition when configurations compete for common resources
Symbiosis	+	+	Interaction favorable to both
Neutralism	0	0	Neither configuration affects the other
Parasitism (and predation)	–	+	Transformative configuration is benefited and incremental configuration is inhibited
Commensalism	0	+	Transformative configuration is benefited, incremental configuration not affected
Amensalism	0	–	Transformative configuration is inhibited, incremental configuration not affected

4.4 Results

For the presentation of our main results, we start with providing some context for the technological fields of sustainable construction materials – first for India and then for Germany in Section 4.4.1. Then, we reconstruct these fields using the STCA approach in Section 4.4.2. This leads to the identification of the two core socio-technical configurations in these fields, the main structural couplings and frictions between them and an overall characterization of the structure of the field. In 4.3, we analyze the interactions between the two configurations to determine their synergistic or antagonistic quality.

4.4.1 The socio-technical field of sustainable construction materials in India and Germany

In India, bamboo has a long history as a construction material but has not been widely adopted outside rural areas. Many traditional practices remain informal and are weakly represented in official standards and procurement. This helps explain why this socio-technical configuration is still in its early development. Long-standing bamboo construction applications persist in areas where construction is less standardized; however, these applications lack recognition within the sector's norms and rules. Recently, bamboo has re-entered professional discussions as a viable option, prompting initiatives to improve quality, develop skills, and construct demonstration buildings. In this sense, bamboo's emergence in the field of sustainable construction materials became apparent in the 2010s when reviews and experiments began positioning it as a sustainable alternative and documenting its performance, costs, and life-cycle aspects (e.g., studies on reinforcement and life cycle assessment (LCA)) (Sharma et al., 2014; Yadav and Mathur, 2021). The green conventional configuration in India pursues a rather incremental logic implementing sustainable practices in the use of cement and steel. In 2008, the National Action Plan on Climate Change (NAPCC) established a foundational policy framework that promoted sustainable practices in the use of conventional construction materials, such as cement and steel. This framework prioritized energy efficiency and the adoption of efficient, clean, and sustainable production and consumption systems (Dhar et al., 2020; Singh et al., 2020). Under the NAPCC's National Mission for Enhanced Energy Efficiency, the Perform, Achieve, and Trade (PAT) scheme gained regulatory support in 2012 by requiring reductions in energy consumption in cement and steel industries (Chauhan and Thangavel, 2025; Singh et al., 2020). This led to the emergence of a green conventional configuration. The sustainable use of cement and steel is primarily achieved through green building certification schemes such as GRIHA and LEED. These programs focus on aspects such as energy efficiency in buildings and are supported by emerging governmental institutions, such as the Building Materials and Technology Promotion Council, as well as public procurement initiatives (Manna and Banerjee, 2019; Verma et al., 2022). Although we observe emerging institutionalization in both configurations, these activities suggest that the socio-technical field is still in its early stages of maturation.

The socio-technical field of sustainable materials in the German construction sector contains a strong configuration based on timber, which draws on a long craft tradition. Since the 1990s, this tradition has been reshaped by engineered wood, especially cross-laminated timber (CLT), which received a renewed professional and public attention since the 2010s. During this last decade, mass produced timber moved from a marginalized topic to the center of debate due to highly visible multi-story projects and the rise of industrial prefabrication narratives. Together, these developments made timber appear as a forward-looking option rather than a purely traditional material (van Veelen and Knuth, 2024). In terms of development, Germany is part of a well-established, institutionally supported international innovation system for timber. Engineered wood markets are substantial, actor networks are well-established, and standards and supply chains are comparatively codified (Mazzoni et al., 2025). Germany's CLT production signals depth and stability rather than early experimentations (EOS, 2023; UNECE, 2023). Nevertheless, public discourse remains pluralistic, with competing visions emphasizing different combinations of environmental claims, speed, cost, regional sourcing, and architectural distinction. This indicates that the field is consolidated enough to host divergent visions while still negotiating its broader societal role (Fischer and Losacker, 2024; Mast, 2022).

In the German socio-technical field, the incremental configuration revolves around the production of green cement and steel. Preliminary work was carried out in the 1990s. Then, around 2010, sustainable cement and steel received more institutional support and attention in Germany. Although the initial development was challenging (Dewald and Achternbosch, 2016), these technologies have recently advanced and begun to enter the market (Alsheimer, 2025; Hüttel and Lehner, 2024). This is accompanied by certification systems for green buildings and energy efficiency (Fastenrath and Braun, 2018). Starting in the 1990s, both emerging configurations in Germany have developed market-ready products that receive comparatively large institutional support, constituting a higher stage of maturation of the socio-technical field of sustainable construction materials in Germany when compared to the Indian case.

4.4.2 Overlapping socio-technical configurations in India and Germany

In terms of diverse socio-technical configurations in the sustainable construction materials field, the Indian case reveals two distinct yet interconnected emerging configurations. One configuration centers around the bio-based material *Bamboo*[20] and is represented by purple links in the networks in Figure 10, while the other revolves around conventional materials (steel and concrete, *Conventional*) represented by blue links. Although other focal technologies exist in the socio-technical field (e.g. *Earth* or high-tech bio-based innovations, *HighTechBB*), the corresponding configurations are less developed and were therefore excluded from the analysis.

[20] Unless otherwise specified, we have set direct references to node labels in Figure 10 respectively in italics in order to enable the reader to follow the argument in the networks. A detailed list of descriptions for all element and actor codes used in the STCA can be found in the appendix in Section 4.7 (Table 10).

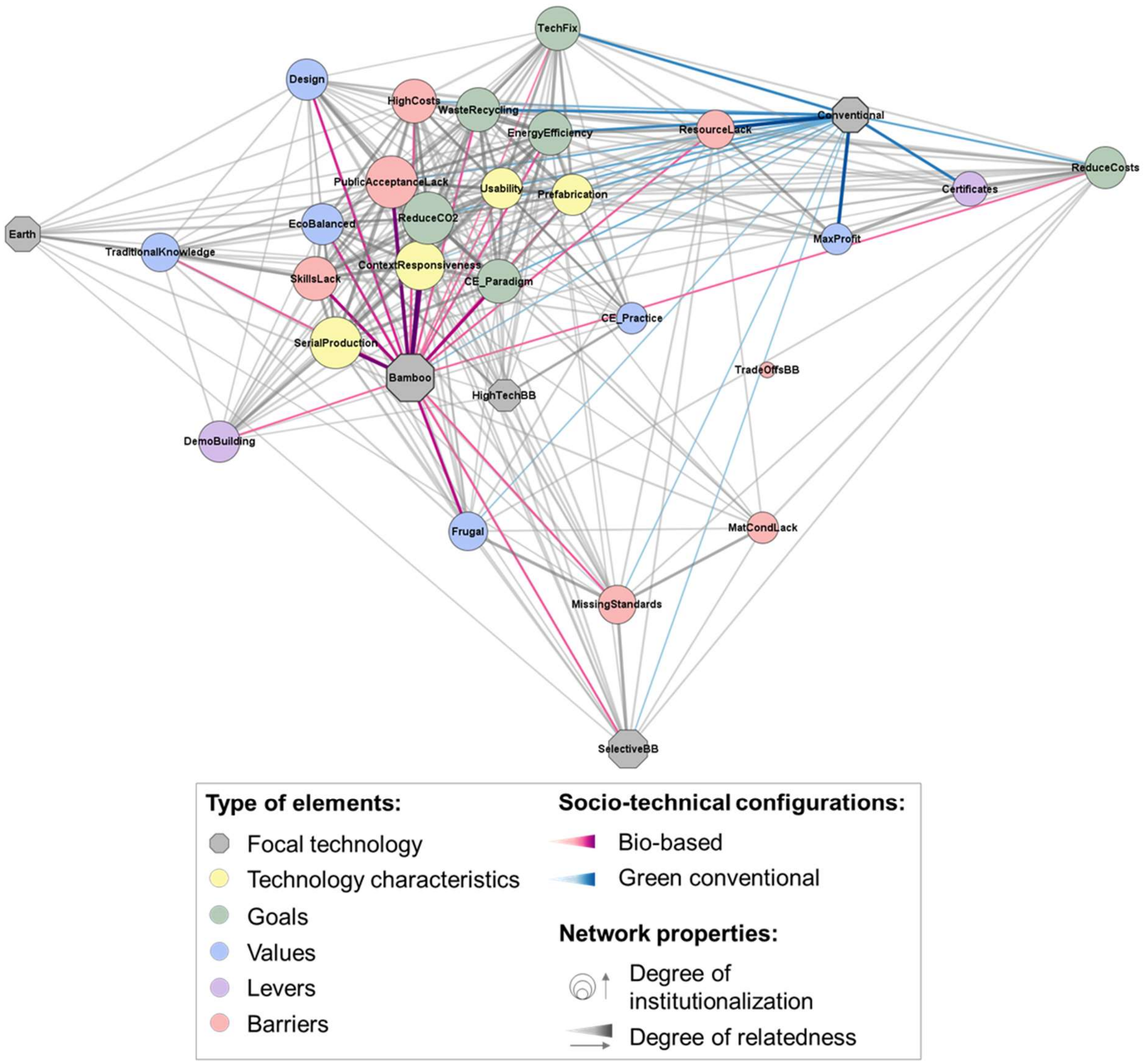

Figure 10: STCA – network (one-mode concept) in India

The transformative, bio-based configuration is strongly associated with two technology characteristics. The first one (*ContextResponsiveness*)[21] highlights the ability to provide diverse, context-dependent solutions while recognizing the need for locally adapted materials and institutional logics for sustainable construction. The second technology characteristic relates to the potential for *serial production*, mobilizing economies of scale by standardizing previously customized processes. The comparatively large size of the nodes in these networks indicates that these two characteristics are fundamental to this configuration, as the node size represents the number of different actor groups that have drawn upon the technology characteristic at least once. Furthermore, the bio-based configuration claims to contribute substantially to the reduction of CO_2 emissions (*ReduceCO2*) and implementing a circular economy paradigm (*CE_Paradigm*), positioning itself strongly in a sustainability narrative.

[21] Given the huge number of relations in the networks, we limit the presentation of the results to the most important ones.

Indian actors supporting this configuration distinctly value *frugality*, prioritizing minimal processing, locally sourced materials, and *ecological balance*. This underlines their commitment to the responsible use of resources. These actors are primarily architects, planners and applied researchers who advocate the use of bio-based materials in India. A key specificity of the Indian context is the role of *traditional knowledge*. Many actors prefer to utilize and advance traditional methods rather than new technologies. Additionally, bamboo is strongly associated with positive aesthetics and *design*. This highlights the importance of visual and cultural acceptance as crucial resources in sustainable construction. However, significant barriers also exist. The primary obstacles to the bio-based configuration in India is a *lack of widespread public acceptance* in the technological field and a *lack of skills* among construction and planning companies to work with bamboo as a construction material.

The second emerging socio-technical configuration in India which focuses on green conventional building materials enhanced by sustainable practices is strongly related to the goal of *profit maximization* and emphasizes the scarcity of bio-based materials (*ResourceLack*). *Certifications* such as LEED are considered central levers by the supporting actors for driving the sustainable transition of the field. Additionally, actors in this configuration strongly emphasize the goals of *energy efficiency* in buildings and the *recycling of construction waste*. In this incremental configuration, the predominant actors are large, powerful industry corporations and the government. These actor networks, recognize the critical role of potential new technologies (*TechFix*) in accelerating the transition through technological advancements, emphasizing this as the main pathway to achieve a greener construction sector. There are also minor, emerging configurations around other bio-based focal technologies. The use of *earth* and loam, for example, is particularly associated with *traditional knowledge* in this context, but remains largely unrelated to other configurations in the field. In contrast, the use of biomass in high-tech innovations (*HighTechBB*), such as 3D printing or agri-waste bricks, is related to the bio-based configuration around *Bamboo*, involving similar values and goals. The selective use of bio-based materials (*SelectiveBB*) is only loosely connected to the bamboo configuration, as the selective use of bamboo is becoming more common. However, it remains largely unrelated to other important goals or values in the socio-technical field. Overall, the STCA reveals a polycentric structure of the field consisting of the two main configurations and some smaller ones. There are some substantial overlaps between the incremental and the transformative configuration, such as shared goals relating to *waste recycling*, *energy efficiency* and the *circular economy paradigm*. There are, however, also substantial differences in terms of the remaining goals and requests for policy support. The incremental configuration aims to *maximize profits* through *technological fixes* and *certificates*, while the transformative configuration envisages the holistic integration of values such as the *ecologically balanced use* of construction materials through *frugality*, as well as the *design* of buildings.

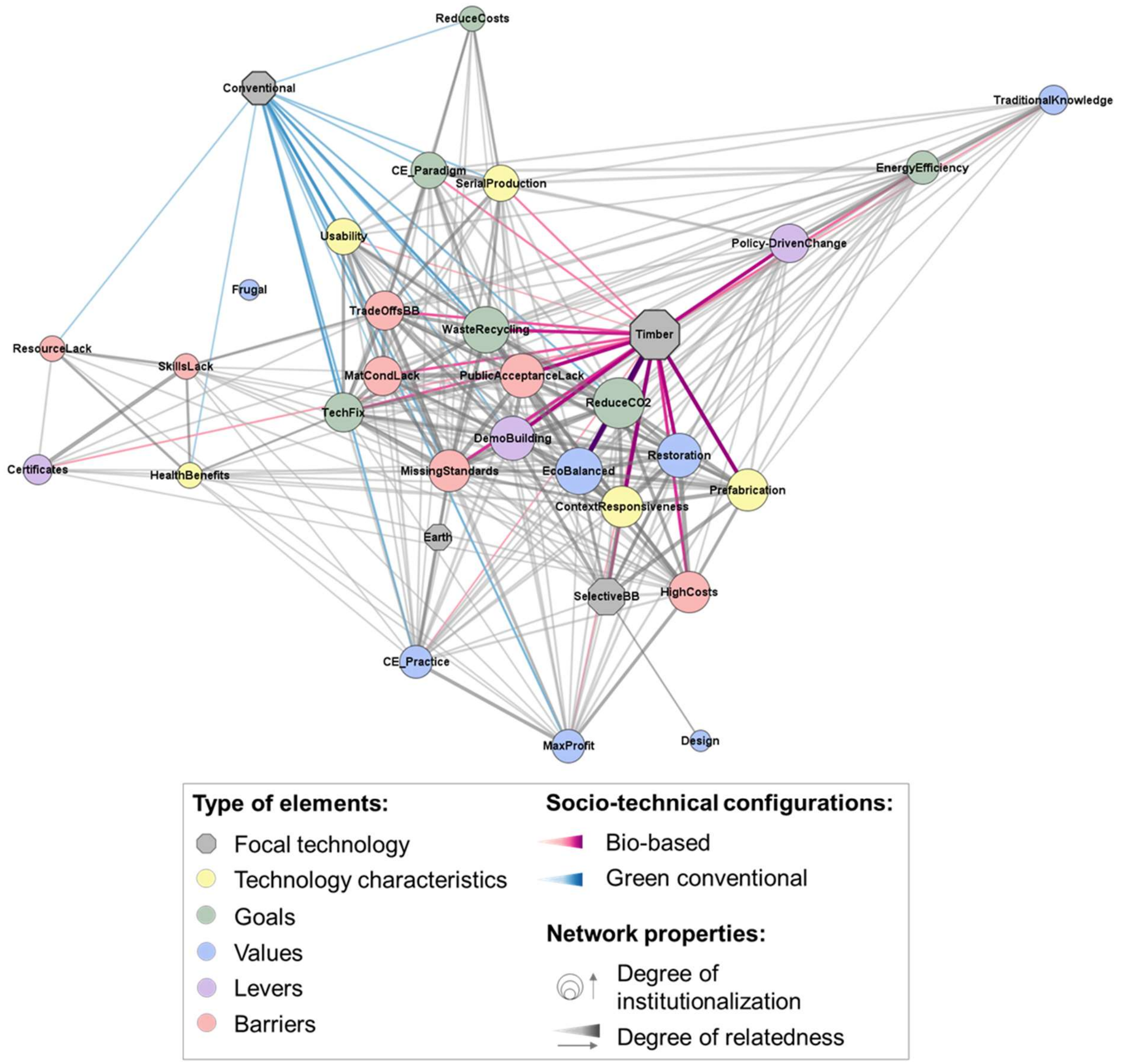

Figure 11: STCA – network (one-mode concept) in Germany

In contrast to India, the socio-technical field in Germany depicts a more clear-cut separation between the transformative and the incremental configuration (Figure 11). This becomes clear when we consider the comparatively weak links between the *conventional material* node and related institutional elements, as well as the lower number of overlapping elements of both socio-technical configurations. Compared to India, the German bio-based configuration is more institutionalized, centralized and coherently built around *timber*. This is further represented by the fact that although green conventional materials are linked to the idea that building practices should be simple and easy to implement (*Usability*), they are positioned at the periphery of the socio-technical field. Actor networks in Germany that are envisioning a bio-based transition pathway are confident about using timber. Unlike the transformative configuration in India, this one encompasses key actors in government and public procurement. Other relevant actors in the transformative configuration in Germany are engineers and researchers. This configuration around *timber* is strongly associated with similar overarching goals and technology characteristics to those identified in India for *bamboo*, primarily *CO_2 reduction* and acknowledging context-specific solutions (*ContextResponsiveness*). However, there are differences in the degree of relatedness of certain elements. Specifically, *prefabrication* principles, such as modular buildings and the *ecologically balanced* use of materials, are significantly more relevant in Germany than in India. In addition, timber is strongly related to renovation and *restoration* practices, emphasizing the renewal of existing building stock as a core approach for the sector's sustainability transition. This element is not considered relevant in the Indian context. Other emerging, albeit minor, configurations include the selective use of bio-based materials (*SelectiveBB*), which is more closely related to the bio-based configuration in Germany than in India. They share several technology characteristics and values, and therefore appear to be related. *Earth* and loam are also slightly associated with the timber configuration; however, they remain a minor part within the German socio-technical field.

Germany's transformative bio-based configuration has two crucial levers to advance its evolution. The first is an emphasis on *policy-driven change*, where policy frameworks like the EU Green Deal significantly influence the decisions and strategic orientations of stakeholders. Second, demonstration or lighthouse buildings (*DemoBuilding*) play a more substantial role than in India, accelerating the adoption of bio-based materials and practices. The goal to pursue *construction waste recycling* is important in Germany and plays a more significant role in the country's timber configuration than in India's bamboo configuration. Similar to India, Germany's bio-based configuration faces substantial barriers related to *public acceptance*, highlighting a common cross-national challenge in the (global) transition toward bio-based construction.

Although a number of large suppliers and research and development entities support the configuration of green conventional materials in Germany, it remains comparatively weaker and less integrated than the bio-based configuration. Key elements such as the role of potential innovations (*TechFix*) and *construction waste recycling* appear less prominently in Germany than in India's incremental configuration. Instead, the usability and comfort of established construction practices and technologies (*Usability*) emerges as the most related element, indicating that actors in Germany prioritize familiar techniques and established routines in their sustainability approaches. Other elements are mostly unrelated to this configuration, emphasizing its isolated role in the socio-technical field of sustainable construction materials in Germany.

In summary, we may say that across both countries, actors are pursuing the decarbonization of construction materials and emphasizing context-responsive solutions, yet clear differences are emerging. In India, initiatives focusing on bamboo draw on traditional knowledge and seek to increase production through standardization and serial production. In parallel, major industry firms are promoting 'greener' concrete and steel through developing new technologies and certification schemes aimed at expanding the market and increasing profitability. In Germany, the timber-oriented approach relies on prefabrication and modular methods, as well as policy initiatives and the renovation of existing buildings. Meanwhile, proponents of eco-friendly concrete and steel prioritize usability and maintaining established routines. Consequently, emerging socio-technical configurations in India tend to co-evolve and, at times, reinforce one another. In contrast, in Germany, the two emerging configurations remain weakly connected: timber is gaining institutional traction, while green conventional practices match better with established professional routines in the sector. While both trajectories aim for CO_2 reduction, they mobilize different resources and norms, such as design and tradition in India, and regulation, as well as demonstration projects in Germany. This yields distinct patterns of structural couplings and frictions within each field.

4.4.3 Modes of interaction between incremental and transformative socio-technical configurations

The two socio-technical fields presented above reveal that the incremental and the transformative configuration appear more interrelated in India and less in Germany. In the second step of our analysis, we examine the types of interaction across the core institutional elements in more detail: The relations to the focal technology are similar on the first sight, however, institutional connotations vary between the two countries related to the different stages of maturation. Different goals or barriers for example can represent different interaction or interdependency modes such as a *competition*, *symbiosis*, *commensalism* (etc.). In this section, we focus solely on the specific interactions between the key institutional elements and the focal technology of both configurations. To get a clear picture, we eliminated all other links from the networks and depicted the type of relationship based on the strength of the Jaccard values and qualitative observations from the interview data. Positive links are set in green, negative ones in red and neutral relationships in grey dotted lines. The details of all modes of interaction are listed in Table 11 in the appendix (Section 4.7).

For India, the predominant mode of interaction between the two configurations, incremental and transformative, i.e. bio-based (bamboo), is *symbiosis*, whereby both focal technologies benefit (see Figure 12 and Table 11). The analysis reveals that shared goals, such as *energy efficiency* of buildings, construction *waste recycling*, *reducing costs* and *reduction of CO_2 emissions*, are *symbiotic*. The latter is strongly associated with *bamboo* but only slightly with *conventional* materials. The qualitative examination of this interaction reveals a *symbiotic* relationship, as it helps both configurations to pursue this goal and advocate for their respective materials. More specifically, the argument of CO_2 reduction enables even actor groups pursuing an incremental pathway to justify the sustainability of their preferred solution.

> *"And we all know; the construction industry is largely responsible for all these carbon footprints. You have materials like concrete, the making of cement and steel, you require a lot of energy and that's all responsible for this. Ultimately, we have to reinvent steel, either some materials or technology which make buildings really cost effective. (...) Buildings have to be viewed in the larger context. It can't be limited to material" (India_1)*

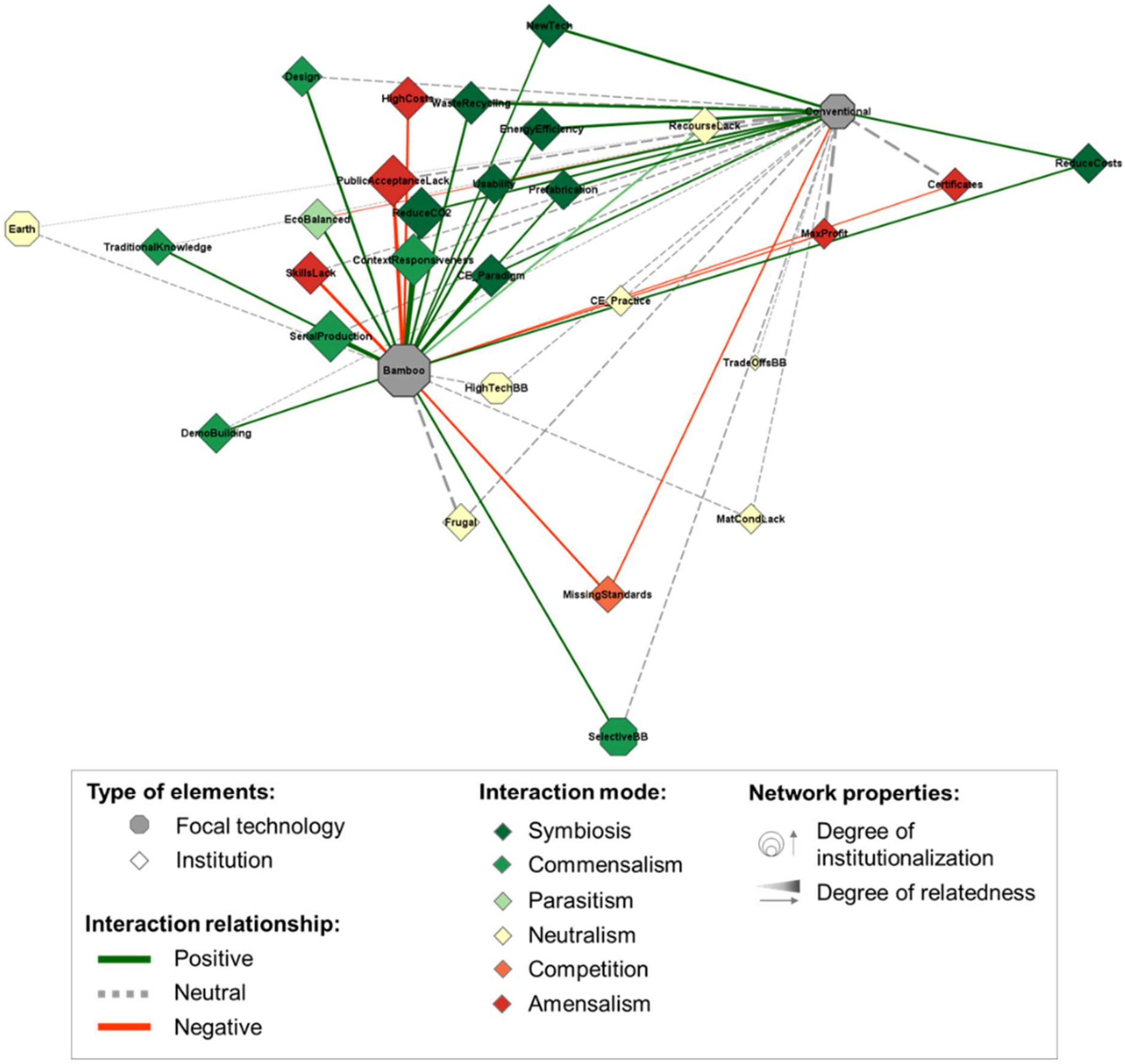

Figure 12: STCA – interaction modes in India

The second most common interaction mode between the two configurations is *neutralism*: both configurations remain unaffected because an institution in the socio-technical field is barely important in both configurations. Thus, they are not influencing the development potential of each of the two configurations. This applies particularly to some barriers. For example, there are issues with conditions of bio-based materials (*MatCondLack*), i.e. the incremental configuration claims that bio-based materials have weaker quality and are not as durable as steel and concrete. The STCA reveals that these two institutions are only weakly associated with both configurations.

We found one barrier that negatively influences both configurations and therefore functions as *competition*. The element of *missing standards* is slightly connected with both configurations. However, the qualitative analysis reveals that both configurations contest for the implementation of new national standards from which their technology would potentially benefit. Currently, both configurations are pursuing their own interests, while the absence of specific national standards is harming them both.

> *"Because we cannot consider this recycled concrete as concrete aggregate (…). Rather we have to treat it as a different material. So, some amendments have to be made in the codal provision before making its confident use in the field." (India_28)*

> *"Then in India we also have a policy which is called a 'Kutcha House', [which] means temporary house. So however good your house might be with mud and bamboo, it will still be called temporary. It's not called a permanent house." (India_25)*

There are a few cases of *commensalism* between the two socio-technical configurations in India, where the bio-based configuration benefits from an institutional element without affecting the incremental configuration. This is true, among other elements, for some of the value orientations that influence how actors use bio-based materials. This applies to *traditional knowledge* due to its low link to *conventional* and its beneficial nature for the transformative bio-based configuration. In this example, it represents an important institutional element within the bio-based configuration and is only weakly connected to the incremental configuration. Since traditional knowledge about bio-based building materials serves entirely different markets than those targeted by the green conventional logic, the latter is not negatively affected by the element's support for the former (*commensalism*).

> *"Instead of inventing things or reinventing the wheel, we believe in looking at traditional techniques and looking at innovations on them. (…) There's a lot of traditional knowhow that existed, which is getting lost, because we tend to look for new answers and mechanized solutions to everything, whereas sometimes the answer could already be there." (India_3)*

Another example of *commensalism* in India is the use of demonstration buildings to accelerate the transition. Almost all actors pursuing bamboo as the main material in the technological field of sustainable construction materials highlight the new airport terminal in Bengaluru, which is partially built with bamboo, as a lever for the configuration's evolution. In particular, they emphasize the material's symbolic value, as it showcases bamboo as a sustainable building material. This element (*DemoBuilding*) is not part of the incremental configuration. At the same time, our interviews show that it does not negatively influence the green conventional market, nor do they use it to advocate for their configuration (*commensalism*).

> *"It is known. Even the Bengaluru airport now they had a reconstituted bamboo with which they have made all the structures and all along with steel and other things. So, the application is known" (India_11)*

A few interactions between the two configurations are similar in Germany and India, particularly *amensalism* and *neutralism* (Figure 13). Some values such as implementing circular economy in practice (*CE_practice*) function neutrally in both countries because they are not strongly connected with either configuration. In cases of *amensalism*, established institutions created by the incremental configuration often act as a barrier to bio-based configurations that aim for transformative change. *High costs* and a *lack of public acceptance* for bio-based materials function as *amensalism* in both countries, negatively influencing the bio-based configuration without affecting the incremental configuration.

> *"So presently cost wise. Also, if you want to use bamboo, definitely it will involve more cost (...) Even though the material is cheaper, then connecting two pieces is difficult. Making it straight is difficult. (...) Your product is costlier than any other materials. (...) That is a real limitation right now." (India_24)*

> *"Britishers came here and they tried to tell that bamboo is a poor man's timber and only poor people use it. So, the social stigma of using your hemp, bagasse and all these kinds of things, materials, is also social stigma." (India_25)*

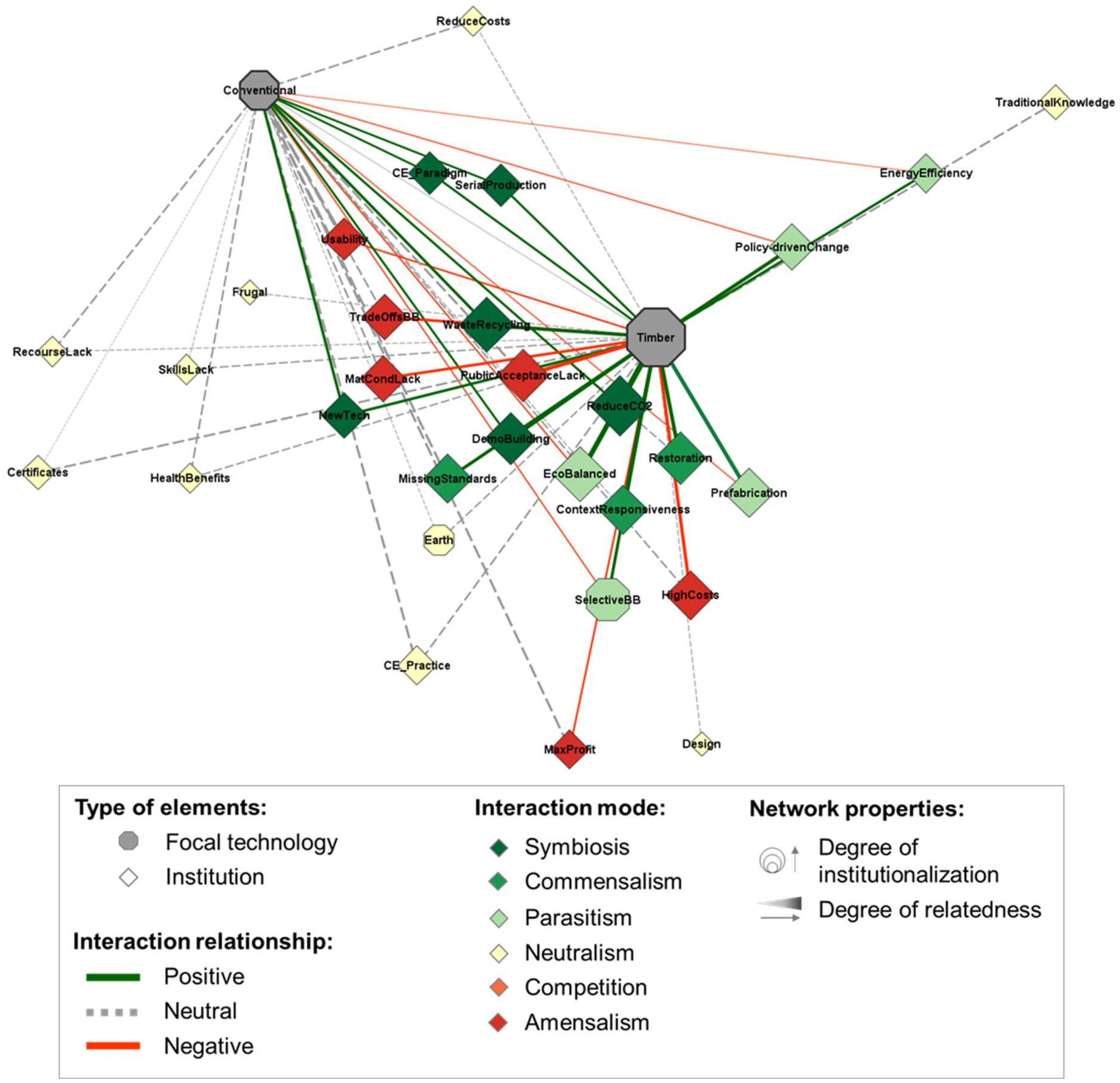

Figure 13: STCA - Interaction modes in Germany

Another element that supports the transformative bio-based configuration but hinders the continuous use of conventional materials (*parasitism*) is *policy-driven change*, building on new sustainability-oriented practices. There are two dimensions; first, specific timber-related construction initiatives in some German states drive this change and facilitate the bio-based configuration.

> *"Building regulation, that is of course a political issue (...) this has led to Baden-Württemberg becoming a pioneer in timber construction in Germany within just a few years. There are research projects behind this to create a regulatory basis to ensure that timber construction is of equal value." (Germany_7)*

The second dimension of *policy-driven change* in this regard relates to the EU taxonomy for new buildings. It is expected to favor those who have already developed the capabilities to meet the new requirements using bio-based materials. However, it poses significant challenges to the incremental configuration around the green production of conventional materials, thereby having a negative effect (*parasitism*).

> *"There's no getting around it anymore (...) due to the stricter regulation and stricter subsidies that the industry has faced with last year. (...) The new EU Buildings Directive will probably also be a tough one. In this respect, the real estate industry needs to build up a great deal of expertise in how to make this measurable. And then it has to deal with technologies, materials and building physics." (Germany_15)*

These examples of *parasitism* in Germany point in a similar direction as fewer interactions in *symbiosis* and *commensalism* compared to India. This indicates that the two configurations are less likely to be mutually beneficial. However, some institutional elements in Germany are strongly associated with *timber*, which benefits this configuration without negatively affecting conventional materials (*commensalism*). For example, the emphasis on *context responsiveness* required for the transition helps German actor networks advocate for the use of timber in construction. This allows them to show that their technology is suitable for sustainable construction in certain contexts.

> *"And that's why we find the approach (...) very exciting, which promotes locally adapted building culture. And it's also quite clear that different climatic influences must result in different building methods. This means that for us, timber construction is definitely the solution." (Germany_10)*

At the same time, they do not affect *green conventional materials* because they are not related (*commensalism*). Those involved in incremental configurations continue their construction practices but barely acknowledge this as an opportunity to integrate conventional materials with bio-based materials.

4.5 Discussion

Our results underscore significant differences in the types of interactions between emerging socio-technical configurations within India and Germany. We observed that different modes of interaction between incremental and transformative configurations lead to different gradients of synergistic versus antagonistic relationships affecting the evolution of the transformative configuration. The observed dominance of *commensal* interactions in India can be attributed to the early maturation stage in the socio-technical field, where bio-based materials (especially bamboo) can benefit from existing structures and practices without significantly challenging green conventional construction methods (Fischer and Losacker, 2025). This high gradient of synergistic relationships is represented by the mobilization of traditional knowledge to promote the benefits of bio-based construction without challenging the incremental configuration that pursues the green use of steel and concrete. This is in line with the perspective of Markard and Hoffmann (2016) who claim that the complementary nature of most interactions may accelerate a transition. In contrast, Germany's higher frequency of *parasitic* interactions in a more matured technological field leads to timber-based materials increasingly threatening conventional building practices. This high gradient in antagonistic relationships leads to the strong connection of timber construction with prefabrication and modular building principles that strengthens its market position, thereby actively displacing green conventional methods. Such interactions highlight the contested nature of sustainability transitions, as reflected through competing visions (Fischer and Losacker, 2024; Havinga et al., 2024) or contestation axes between interfaces in socio-technical configurations (Madsen et al., 2022). In a more mature technological field, such as that examined in the German case study, we find that the transformative configuration is primarily driven by public procurement and government actors. By contrast, in a less developed field, such as that in India, these same groups of actors are more strongly associated with the incremental configuration. Similarly, the identified levers, such as demonstration buildings and policy-driven change, seem to be mobilized more easily in a rather mature context, such as Germany. This is particularly true when it comes to overcoming barriers, which are also addressed by the incremental configuration in Germany, albeit less efficiently.

These divergent interaction patterns between the two countries also shed light on how policies and political frameworks influence configurations in different geographies (Hansen et al., 2024; Hansen and Coenen, 2015). New supportive policies, such as the EU Green Deal and national regulations such as building codes favoring timber, generate clear *parasitic* interactions in Germany. Such regulatory frameworks significantly strengthen timber-based construction materials at the expense of the incremental configuration by imposing stringent requirements that conventional materials struggle to fulfill. In contrast, in India, institutional elements related to regulatory frameworks and policies, although emerging, currently indicate rather neutral and complementary interactions. Here, the focus is on incentives, such as certification schemes and broader sustainability goals, including energy efficiency in buildings and construction waste recycling, neither of which inhibits either configuration. Our results indicate that policies should be tailored with a deep understanding of the material and institutional relationships between configurations in a given socio-technical field. In Germany, policymakers might leverage *parasitic* interactions intentionally, promoting bio-based solutions through stronger regulatory support, specific standards, and incentives explicitly disadvantaging carbon-intensive conventional materials. Meanwhile, India's current *symbiotic* context calls for policies that strengthen complementarities. This can include improving standards applicable to both green conventional and bio-based configurations, enhancing skills, and expanding public acceptance of bamboo through demonstration projects. Such context-sensitive policy strategies would enhance the effectiveness of sustainability transitions (Bergek et al., 2023; Hansen et al., 2024).

In addition, we find that the incremental configuration tends to draw on more broadly defined goals, while the transformative configuration is more value-oriented. These values are often tangible and easier to implement. Goals often function in *symbiosis*, as both configurations can easily claim to pursue them, which usually benefits both. Our results reveal that the mode of interaction for other types of elements, such as value orientations or levers, depends on the specific context of the socio-technical field and its stage of maturation. Another example of the influence of geographical contexts on sustainability transitions (Binz et al., 2025; Hansen and Coenen, 2015) is the way barriers affect transformative configurations. For instance, issues related to material conditions and sustainability trade-offs negatively affect bio-based materials (especially timber) in Germany more severely (*amensalism*), whereas they are less critical in India (*neutralism*). In the less mature technological field in India, greater urbanization pressure and different regulatory environments may explain this divergence. These contextual differences are crucial for understanding how similar elements may support or impede transitions differently in different geographical contexts. This is underlined by the role of spatial specificities in directing sustainability transitions (Schippl and Truffer, 2020; Yang et al., 2022).

At the level of the entire socio-technical field, sustainable construction materials in India seem to be a suitable instance demonstrating that a high degree of synergistic interactions can enable less mature fields to mobilize resources and grow. Thus, a homogeneous field structure may induce the mobilization of system resources. However, our results also indicate that, at higher stages of maturation, such as in the German socio-technical field, a high gradient of antagonistic relationships was identified. These results have significant implications for the debate around diversity and directionality within sustainability transitions (Bulah et al., 2024; Heiberg and Truffer, 2022a; Stirling, 2011), as this fragmented field structure raises questions about whether friction is necessary for a socio-technical field to evolve and develop clear directionalities (Bergek et al., 2023). As in the case of Germany, where the socio-technical field is more mature, directionality can be shaped through contested interactions. In this case, the bio-based configuration could benefit, as it is seemingly possible to separate from the incremental configuration by plausibly claiming to be the more 'sustainable' configuration. In contrast, the empirical case in India, which is at an earlier maturation stage, has shown that a high diversity of technological solutions and their overlap ensure the resilience of sustainability transitions. This is because they offer a larger range of potential solutions if one configuration fails to serve societal functions. In this sense, the broad, synergistic mobilization of system resources could indicate that diversity in early maturation stages is desirable in ongoing sustainability transition processes.

4.6 Conclusion

This paper aimed to explore the interactions between different emerging socio-technical configurations within a single socio-technical field. With a particular focus on their interactions, we compared two contexts of different stages of maturity and with distinct institutional and geographical conditions: India and Germany. We analyzed two distinct emerging configurations within each national context using Socio-Technical Configuration Analysis (STCA). In each country, one configuration focuses on the incremental change of greening conventional building materials, while the other focuses on the more transformative change of adopting bio-based construction materials. To conceptualize the interactions of socio-technical configurations, we draw on the literature on technology interactions (Havinga et al., 2024; Madsen et al., 2022; Sandén and Hillman, 2011), which we adapt and extend to encompass interactions between socio-technical configurations. Both countries exhibit a comparable twofold pattern but the degree and nature of interactions between the configurations differ.

In the case of an earlier stage of maturation of the socio-technical field in India, the emerging socio-technical configurations appear polycentric, while the more mature German field shows that the configuration centered on green conventional materials is somewhat isolated and less integrated with the bio-based configuration, indicating a higher degree of an antagonistic relationship. Furthermore, we find that only a few elements affect one configuration negatively in India when they are part of the other; most interactions are neutral. In Germany, however, more interactions benefit one configuration while simultaneously constraining the other. Besides that, several elements present in both countries exhibit markedly different interaction modes depending on the geographical context.

Beyond the specific insights we gained from the rather simple constellations of emerging socio-technical configurations, we argue that our proposals have a much broader application potential. Our basic approach is not limited to analyzing either incremental or more transformative configurations, nor is it limited to the interaction of two configurations. Rather, it enables the analysis of field-internal interdependencies among any number of configurations within a field, informing how their interactions may change as the field matures. This approach is equally well-suited to analyze bilateral potentials for competition or cooperation between actors promoting alternative approaches within a field, because it enables the assessment of the evolving structure of the field as a whole. It helps identify major strategic trade-offs for both individual innovating actors and policymakers. It also provides a systematic framework for comparing field structures in different contexts. An illustrative example would be the comparison of field dynamics in renewables in countries like Germany or Denmark, which have different innovation cultures and policy approaches to the energy transition. Therefore, we maintain that further elaborating on such multi-layered interdependencies in actor fields could overcome the somewhat dated dichotomies that still prevail in much of the transitions and broader innovation studies literature. Spelling this out as an encompassing research agenda requires more effort than what could be achieved in the present case study. The payoff of such a conceptual development strategy would be the ability to tackle more complex empirical phenomena that deviate from the clearly delineated classical cases of recent transitions in the energy and the transport sectors.

Finally, we would like to emphasize that the approach of identifying specific symbiotic or competitive interactions between the configurations by means of the STCA approach enabled the systematic mapping and assessment of these relationships. Application of this method to more complex field structures could provide some network-based indicators to assess the degrees of complementarity or competitiveness in a field in a more gradual way compared to what could be achieved in the rather dichotomous setting that we presented here. This potentially enables the bridging of qualitative coding with more quantitative measures of field structures and dynamics (Truffer et al., 2025).

4.7 Appendix

Table 9: Details on the interviews used for article 3

Interview name	Interviewee role	Organization Size	Organization details
Germany_1	Project Manager	Medium	Architectural firm focused on wood construction
Germany_2*	CEO	Medium	Architectural firm focused on wood construction
Germany_3*	CEO	Small	Architectural firm focused on repurposing/upgrading existing buildings with sustainable materials
Germany_4	CEO	Medium	Architectural firm focused on wood construction
Germany_5	CEO	Medium	Architectural firm focused on bio-based materials (mainly timber)
Germany_6	Founder	Medium	Planning and design of engineering structures focusing on sustainable projects
Germany_7*	Team Leader	Medium	Planning office in civil engineering with structural engineering projects using timber construction
Germany_8	Head of Sustainable Structures	Small	Engineering firm focused on wood construction
Germany_9	CEO	Medium	Planning firm focused on timber construction
Germany_10*	Project Coordinator	Medium	Timber construction campaign, initiated by a German state to promote climate-friendly construction with wood
Germany_11*	Director Network & Consulting	Medium	Network for sustainable buildings that develops sustainability certifications.
Germany_12	Project Manager	Small	Organization promoting timber construction in Saxony funded by the state
Germany_13	Head of Research	Big	Research on bio-based building materials (engineered bamboo and mycelium-bound)
Germany_14	Professor	Big	Research on timber construction and structural timber engineering
Germany_15*	CEO	Small	Supplier of low carbon and reusable concrete bricks based on geopolymers
Germany_16*	Head of Public Relations	Small	Supplier of timber and modular wooden building blocks
Germany_17*	R&D Program Manager	Big	Global R&D department of large cement supplier with focus on sustainability
Germany_18*	Head of Sustainability Strategy & Engagement	Big	Large cement supplier focused on clinker reduction
Germany_19	Key Account Manager	Big	Supplier of cross-laminated timber
Germany_20	Project Developer Modular Design	Medium	Project developer with investments wood construction projects
Germany_21*	Head of Sustainability Department (Person 1) & Engineer (Person 2)	Big	Large contractor, timber supply construction; turnkey buildings
India_1*	CEO; Professor; Director in government (Retired)	Big	Government (urban planning), University (sustainable construction), Large architectural firm
India_2	CEO (Person 1) & Project Manager (Person 2)	Medium	Non-profit organization for sustainable housing
India_3*	CEO	Small	Architectural firm focusing on bio-based materials (stabilized earth)
India_4	CEO (Person 1) & Architect (Person 2)	Medium	Architectural firm focusing on bio-based materials & intelligent water and sanitation designs
India_5*	General Manger	Big	Large contractor of industrial, infrastructure and public projects
India_6	CEO	Medium	Architecture consultancy focusing on bio-based resources such as waste or flash

Interview name	Interviewee role	Organization Size	Organization details
India_7	Managing Director (Person 1) & Associate Architect (Person 2)	Medium	Architectural firm focusing on passive and low energy architecture
India_8	CEO	Small	Architectural firm focusing on bio-based materials (e.g., poured earth concrete)
India_9	CEO	Medium	Architectural firm focusing on sustainable designs
India_10	Assistant Manager	Big	Large contractor of industrial, infrastructure and public projects
India_11	Managing Director	Medium	Supply and construction with various bio-based materials (bamboo, mud, recycled wood)
India_12	Senior Consultant	Big	Consultancy advising the government on the development of a bamboo-based supply chain
India_13	Assistant Professor; prior Industry Manager	Big	Research institute focusing on sustainable construction management
India_14	Consultant & former director of a research institute	Medium	Research institute for bamboo construction & advising an international interest group for bamboo
India_15	Executive Director	Medium	Research institute on earth construction and architecture
India_16*	Director	Medium	Government council for the promotion of construction materials and technologies
India_17	Director	Medium	Government institution for R&D in construction
India_18*	Regional Director	Big	International organization promoting bamboo
India_19	CEO	Small	Investor focusing on construction and agricultural bamboo projects
India_20	CEO	Small	Provider of a novel bio-based technology for constructing walls
India_21*	CEO	Small	Supplier of bio-based bricks
India_22	CEO	Small	R&D and supplier of waste-based sustainable concrete
India_23*	CEO	Small	Supplier of bricks based on recycled plastic waste and industrial waste
India_24*	CEO	Medium	Supplier of bamboo and planning & implementation of bamboo construction
India_25*	CEO	Big	Bamboo advocate: R&D, architecture, education & training
India_26	Postdoctoral Researcher	Medium	Research institute focusing on recycling of construction materials
India_27	Professor; Head of Department	Medium	Research on sustainable architecture focusing on waste materials
India_28*	Assistant Professor	Medium	Research on sustainable reinforced concrete

*Marked interviews were included in stratified subset

Table 10: Elements and actors in the technological field of sustainable construction materials

Label	Meaning	Categorization
	Element-codes:	
Timber	Timber is the preferred construction material in the transition	Focal technology
Bamboo	Bamboo is the preferred construction material in the transition	Focal technology
Earth	Earth, clay, or loam are the preferred construction materials in the transition	Focal technology
Conventional	Conventional materials are preferred in the transition, i.e. concrete and steel	Focal technology

Label	Meaning	Categorization
SelectiveBB	Selective use of bio-based materials in combination with conventional technologies	Focal technology
HighTechBB	High-tech bio-based materials or technologies are preferred. These can be agrocrete based on agricultural waste materials or 3D printed construction with bio-based materials	Focal technology
SerialProduction	A serial (mass) production aims to achieve economies of scale by standardizing processes that were previously unstructured or customized	Technology characteristics
Prefabrication	The construction sector would benefit from modular buildings and prefabrication in general. It involves the offsite production of building components, enabling faster onsite assembly and greater efficiency through modular construction	Technology characteristics
ContextResponsiveness	Different solutions are needed: In some (regional) contexts, some materials (e.g. timber) are needed and appropriate, while in other contexts, other materials and institutional logics are required for the transition	Technology characteristics
Usability	Usability and/or comfort of the building practices/technologies/materials	Technology characteristics
HealthBenefits	Bio-based buildings provide better conditions for physical and mental health, for example by improving indoor air quality, providing better moisture and thermal control, and reducing exposure to toxins	Technology characteristics
EcoBalanced	Actors pursue an ecological use of their construction materials	Values
CE_practice	Circular economy on the practice stage, where “metrics, tools, instruments and practical measures are central” (Korhonen et al., 2018, p. 550)	Values
Restoration	Views the preservation, improvement, and efficient use of the existing built environment as key for the transition. For this, renovation, insulation, and retrofitting are emphasized as the core strategies for achieving sustainability, highlighting care for existing structures, resource conservation, and the extension of building lifespans rather than replacement or new construction	Values
Design	The appearance and aesthetics of the material are perceived positively	Values
MaxProfit	Profit maximization	Values
Frugal	A frugal use of materials is desired: less processing and local resources with emphasis on sustainability	Values
TraditionalKnowledge	Actors seek to follow and advance existing (traditional) knowledge instead of following new (bio-based) innovations	Values
TechFix	Emphasizing the potential of emerging or not-yet-market-ready technologies as the primary pathway to sustainability transitions. They often downplay or dismiss the relevance of	Goals

Label	Meaning	Categorization
	sustainable solutions that are currently available, arguing that future innovations will deliver better results. This stance can delay or deflect immediate transitions by shifting the focus towards speculative technological breakthroughs	
ReduceCosts	Reducing costs/increasing affordability	Goals
ReduceCO2	Reduction of CO2 emissions	Goals
CE_paradigm	Circular economy on "the paradigm stage, [where] visions, concepts and norms are central" (Korhonen et al., 2018, p. 550)	Goals
WasteRecycling	The focus is on recycling construction and demolition waste, which can be from demolished buildings or from the production process	Goals
EnergyEfficiency	The focus is on the energy efficiency in the use of buildings and/or in the use of construction materials	Goals
Certificates	The use of certificates (e.g., LEED) is considered promising for the transition	Levers
DemoBuilding	Lighthouse projects/demonstration building is seen as a main driver to accelerate the transition and the diffusion of a certain material or technology	Levers
Policy-DrivenChange	Statements that policy frameworks addressing climate change (e.g., the EU Green Deal) influence or alter decisions	Levers
MatCondLack	Issue(s) with conditions of bio-based materials	Barriers
HighCosts	Too much costs of (certain) bio-based materials or technologies	Barriers
ResourceLack	Lacking Resource availability of bio-based materials	Barriers
MissingStandards	Missing standards	Barriers
TradeOffsBB	Sustainability trade-offs in the use of bio-based materials	Barriers
PublicAcceptanceLack	Lack of public acceptance	Barriers
SkillsLack	Lack of skills to pursue a certain technique/technology or to make use of a certain material	Barriers
	Actor-codes:	
StartUps	Start-ups	Upstream actors
RandD	Research & Development	Upstream actors
UpstreamResearcher	Basic research, e.g., in material sciences	Upstream actors
Supplier	Suppliers	Upstream actors
AppliedResearchers	Applied research, i.e., research in construction (architecture, planning, etc.)	Main actors
Industry	Industry players	Main actors
Engineers	Engineers	Main actors

Label	Meaning	Categorization
Planners	Planners	Main actors
Architects	Architects	Main actors
PublicProcureme nt	Public procurement	Other institutional actors
Investors	Investors	Other institutional actors
InterestGroups	Interest groups	Other institutional actors
Government	Government	Other institutional actors

Table 11: Modes of interaction between the incremental and the transformative configuration

Element	India	Germany	Type of element
Earth	Neutralism	Neutralism	Focal technology
HighTechBB	Neutralism	Neutralism	Focal technology
SelectiveBB	Commensalism	Parasitism	Focal technology
ContextResponsiveness	Commensalism	Commensalism	Technology characteristics
HealthBenefits	Neutralism	Neutralism	Technology characteristics
Prefabrication	Symbiosis	Parasitism	Technology characteristics
SerialProduction	Commensalism	Symbiosis	Technology characteristics
Usability	Symbiosis	Amensalism	Technology characteristics
CE_Practice	Neutralism	Neutralism	Values
Design	Commensalism	Neutralism	Values
EcoBalanced	Parasitism	Parasitism	Values
Frugal	Neutralism	Neutralism	Values
MaxProfit	Amensalism	Amensalism	Values
Restoration	Neutralism	Commensalism	Values
TraditionalKnowledge	Commensalism	Neutralism	Values
CE_Paradigm	Symbiosis	Symbiosis	Goals
EnergyEfficiency	Symbiosis	Parasitism	Goals

Element	India	Germany	Type of element
ReduceCO2	Symbiosis	Symbiosis	Goals
ReduceCosts	Symbiosis	Neutralism	Goals
TechFix	Symbiosis	Symbiosis	Goals
WasteRecycling	Symbiosis	Symbiosis	Goals
Certificates	Amensalism	Neutralism	Levers
DemoBuilding	Commensalism	Symbiosis	Levers
Policy-DrivenChange	Neutralism	Parasitism	Levers
HighCosts	Amensalism	Amensalism	Barriers
MatCondLack	Neutralism	Amensalism	Barriers
MissingStandards	Neutralism	Commensalism	Barriers
PublicAcceptanceLack	Amensalism	Amensalism	Barriers
ResourceLack	Competition	Neutralism	Barriers
SkillsLack	Amensalism	Neutralism	Barriers
TradeOffsBB	Neutralism	Amensalism	Barriers

Chapter Five

5 Why does transformative knowledge fail to transform? A multi-scalar (de-) legitimation perspective on the construction sector in Chennai, India

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Abstract

In this paper, asking why transformative knowledge might fail to transform, we develop a framework linking the concept of transformative knowledge (regions) to multi-scalar (de-) legitimation of a regional socio-technical configuration in Chennai's construction sector. We combine debates on transformative knowledge, legitimation and transition work and conceptualize how legitimation and de-legitimation interact in a multi-scalar setting. Using qualitative content analysis of a comprehensive set of expert interviews, we show that existing transformative capacities in Chennai's emerging bio-based construction sector are insufficient, as knowledge lock-ins and defensive work prevent disruption of the incumbent socio-technical configuration and hinder transformative change across spatial scales.

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5.1 Introduction

Transformative knowledge encompasses a normative, mission-oriented approach to driving transformative change, based on local interactions and practices, as e.g. fostered through experimentation (Suitner et al., 2023; Urmetzer et al., 2020). Moreover, transformative knowledge focuses on locally available resources, aiming for transformative regional development (Chlebna et al., 2024; Urmetzer et al., 2020). The goal of achieving fundamental change in current socio-technical systems raises the question of the extent to which transformative knowledge can facilitate actual change and why it might fail to do so. In particular, we argue that the inherently overly optimistic expectations of transformative knowledge should be called into question (Jeannerat et al., 2025; Urmetzer et al., 2020). In this context, transforming current socio-technical systems is intertwined with scaling and diffusing transformative solutions beyond grassroots levels (Hermans et al., 2016; Seyfang, 2010). However, the related barriers and how these might be overcome remain largely unexplored. Transformative lighthouse projects, for example, can have an effect on the development of transformative solutions (Bergek et al., 2023); however, they require a broader evaluation and legitimation to be successful. In this sense, we argue that the diffusion of transformative knowledge is subject to societal legitimation processes (Johnson et al., 2006). To date, scholars have mainly focused on legitimacy as an output that accelerates transitions, or lack of legitimacy as an inhibitor of transitions, while less research has focused on the interplay of different legitimation dynamics on the regional level (Binz et al., 2016a; Markard et al., 2016). We contend that shedding light on (de-)legitimation as a (social) process enables to understand these dynamics, and to capture a crucial function for regions to actually transform (MacKinnon et al., 2022). Furthermore, we follow the premise that processes of legitimation and related transition trajectories are multi-scalar in nature, i.e. they co-evolve and are interdependent across spatial scales (Heiberg et al., 2020; Marston, 2000; Miörner and Binz, 2021). Such trajectories are captured in what has been coined a socio-technical configuration in transition research, entailing the relationships and interconnections among actors, technologies, and institutions (Fuenfschilling and Truffer, 2016; Miörner et al., 2021).

In this paper, we provide a framework to analyze how a regional socio-technical configuration that aims for transformative change is subject to legitimation and de-legitimation processes across geographical scales. Building on the transition work framework (Löhr et al., 2022), we capture the extent to which actors contribute to transition-related processes (legitimation). To conceptualize de-legitimation we propose to differentiate between *implicit* and *explicit* de-legitimation by incumbents, drawing on literature on defensive work (Lehmann et al., 2022; Maguire and Hardy, 2009) and resistance to change (e.g. Geels, 2014). We employ a multi-scalar perspective to examine regional sustainability transitions, thereby building on and contributing to the literature on the (economic) geography of such regional transitions (Binz et al., 2025; Hansen and Coenen, 2015; Truffer and Coenen, 2012).

In the empirical part of the paper, we will examine the construction sector, which needs to transition to using bio-based materials to mitigate its negative climate impact (Zhong et al., 2021). This could potentially turn buildings into carbon sinks (Churkina et al., 2020). While emerging socio-technical configurations seek to advance such bio-based solutions (Mazzoni and Losacker, 2024), incumbents are hesitant to embrace this transition (Butzin and Rehfeld, 2013). Thus, a globally established socio-technical configuration exists around the use of cement and steel, while regional configurations that pursue the use of bio-based materials are emerging (Fischer and Losacker, 2024; Jayaweera et al., 2025). Both socio-technical configurations, the bio-based and the incumbent one, claim that their approach is suitable for decarbonizing the construction sector. However, they pursue diverging directions to achieving sustainability, i.e. different materials and practices, and thus both approaches are highly contested (Fischer and Losacker, 2025; Leeuw and Vogl, 2024).

Using the case of transformative knowledge in the construction sector in Chennai (India), we examine (de-)legitimation of an emerging socio-technical configuration pursuing bio-based materials in the region. Based on a rich set of interviews with actors in the regional and national construction sector, we use a qualitative content analysis approach to assess the multi-scalar (de-)legitimation of the regionally emerging socio-technical configuration. More specifically, we analyze along three prevailing dimensions: regional legitimation of the emerging socio-technical configuration, intra-regional de-legitimation by incumbents, and national de-legitimation by incumbents who aim to preserve their legitimacy (Heiberg et al., 2020; Suchman, 1995). This is complemented by further directions of multi-scalar (de-)legitimation such as influences from the global scale or other regions in India (Loorbach et al., 2020; Marston, 2000; Miörner and Binz, 2021). Based on the findings, we discuss why transformative knowledge about bio-based building materials in Chennai has not (yet) translated into transformative change in the socio-technical system.

The remainder of this paper is structured as follows: First, in the theory section, we elaborate on the concept of transformative knowledge from a transition studies perspective and delve into the literature on (de-)legitimation. Combining these literatures, we then propose a conceptual framework on the multi-scalar (de-)legitimation of transformative socio-technical configurations (Section 5.2). Next, we present the research design and methods (Section 5.3). In the subsequent results section, we provide insights into transformative knowledge and knowledge lock-ins in the construction sector. The section then elaborates on the multi-scalar (de-)legitimation of bio-based construction in Chennai (Section 5.4). Afterwards, we discuss these results, reflecting on the role of transformative knowledge in regional transition processes (Section 5.5). Finally, the paper concludes with a brief summary (Section 5.6).

5.2 A (de-)legitimation perspective on transformative knowledge

In Section 5.2.1, we first introduce the term "transformative knowledge regions" in the context of regional sustainability transitions. Next, we review the literature on legitimation of socio-technical configurations and derive a conceptual framework for studying the (de-)legitimation of transformative knowledge in Section 5.2.2. Lastly, in Section 5.2.3, we expand the framework to a multi-scalar perspective on (de-)legitimation processes.

5.2.1 Transformative knowledge and socio-technical configurations

Transformative knowledge bears an explicitly normative dimension (Jeannerat et al., 2025), with the overall goal to achieve transformative change which *"captures the idea that fundamental changes in our models for production and consumption are needed if either major threats to our societies are to be prevented or significant new opportunities to be seized"* (Weber and Rohracher, 2012, p. 1037). These fundamental changes can be understood as transformations of what the transition studies literature defines as socio-technical systems (Geels, 2004; Markard et al., 2012). Against this background, the normative goal of transforming such systems is constituted in transformative knowledge carried out within emerging socio-technical configurations that exist within larger socio-technical systems (Miörner et al., 2021). In this sense, certain technologies, institutions, and actors, all following the same institutional logic, are interrelated and constituted as coherent socio-technical configurations (Fuenfschilling and Truffer, 2016). They co-exist and interact with other configurations in socio-technical systems and can be either established and dominant (i.e. socio-technical regimes, see Fuenfschilling and Binz, 2018) or emerging (niche) configurations (Miörner et al., 2021). In order to achieve transformative change, emerging configurations must compete with established configurations, which often demonstrate resistance to such fundamental changes (Geels, 2004, 2014). In this regard, transformative knowledge, as encompassed in an emerging configuration, is increasingly recognized as a key component of achieving transformative change of socio-technical systems (Chlebna et al., 2023; Urmetzer et al., 2020). We refer to these emerging configurations as 'transformative configurations' in the following sections.

So far, the term transformative knowledge, despite lacking an established definition in the scholarly literature, has often been used in ecological economics to describe the type of knowledge used in parts of the bioeconomy (Bogner and Dahlke, 2022; Urmetzer et al., 2020). In this paper, we adopt this understanding but aim to develop it further from a spatial perspective, manifesting locally in so-called *transformative knowledge regions*, a term that has recently entered the academic debate (Jeannerat et al., 2025).

In the past, the regional development paradigm has viewed new technologies and knowledge-intensive regions as the primary vehicles for transformative change (Asheim, 2012). The focus on science, technology, and innovation, however, has often led to incremental improvements, rather than fundamental shifts toward sustainable modes of production and consumption (Schot and Steinmueller, 2018; Tödtling et al., 2022). In contrast, recent research instead focuses on *transformative* regional development aimed at addressing grand societal challenges (Chlebna et al., 2023; Suitner et al., 2023). Such perspectives emphasize ecological limits by prioritizing "*the content and direction of change*" (Chlebna et al., 2023, p. 223) as the center of regional transformative change. In this paradigm, we view transformative knowledge as a means of mobilizing resources in emerging socio-technical configurations, aiming to transform the socio-technical system (Jeannerat et al., 2025), rather than as a (conventional) form of knowledge generation.

Transformative knowledge regions shed light on this issue as "*arenas where knowledge is generated for, by, and as action in response to grand societal challenges*" (Jeannerat et al., 2025, p. 9). They foster a transformation-inducing context *for action* based on a few key aspects that will be introduced in the following. As indicated above, transformative knowledge is mission-oriented as an alternative to the goal of research and development (R&D) approaches that promote technological development only (Malecki, 1981). Rather than aiming for economic development as an overall goal (Schot and Steinmueller, 2018), a key aspect of transformative knowledge is the emphasis on local experimentation to generate the knowledge required for actual change (Jeannerat et al., 2025; Suitner et al., 2024). The idea is that the uncertainty and the challenge- and practice-based nature of experiments is a key leverage point for transforming socio-technical systems (*by action*) that are often resistant to change (Sengers et al., 2019). Following this logic, local societal challenges require a place-based approach through experimentation towards regional transformative change (Suitner et al., 2024). Within such approaches, transformative knowledge is often carried out in an inclusive and participative manner (Chilvers and Longhurst, 2016; Sengers et al., 2019), resulting in performative processes *as action* (Jeannerat et al., 2025). Another critical aspect is the multi-local and multi-scalar nature of transformative knowledge, recognizing that it does not necessarily emerge in isolated local niches but rather in more complex spatial settings (Butzin and Widmaier, 2016; Crevoisier and Jeannerat, 2009; Loorbach et al., 2020). In other words, while transformative knowledge might emerge place-based in a particular region, it is interrelated with developments in other regions and its diffusion is also dependent on processes at other (higher) geographical scales (Chlebna et al., 2023; Crevoisier and Jeannerat, 2009; Marston, 2000).

5.2.2 (De-)legitimation of socio-technical configurations

Although transformative knowledge might be successful on a small scale, research on niche innovations finds that they often fail to establish institutions that might be able to affect transformative change (Hermans et al., 2016; Seyfang, 2010). To understand such failures and how they might be overcome, we examine the (de-)legitimation of transformative socio-technical configurations. Legitimacy is considered as one of the corner stones in regional sustainability transitions (Gong et al., 2022; MacKinnon et al., 2022). In this paper, we follow Suchman's (1995) seminal definition: *"Legitimacy is a generalized perception or assumption that the actions of an entity are desirable, proper, or appropriate within some socially constructed system of norms, values, beliefs, and definitions"* (p. 574). Legitimacy is frequently cited as a critical aspect of technological change, particularly in the innovation systems literature (Bergek et al., 2008). We understand legitimation as the social process of legitimizing objects and de-legitimation as the process of resisting to change (Alsheimer et al., 2025; Johnson et al., 2006). There are two simultaneous directions of legitimation in this regard: while some actors seek legitimacy for certain (new) technologies or practices (Binz et al., 2016a; Harris-Lovett et al., 2015; Markard et al., 2016), there are also de-legitimation processes that slow down their diffusion (Miörner et al., 2022a). For example, discourse coalitions around a niche innovation can delegitimize conventional technologies, thereby driving transformative change (Markard et al., 2021). Conversely, incumbents also delegitimize emerging technologies to preserve their position, thus inhibiting change. We argue that these (de-)legitimation dynamics must be investigated in both directions: the decline of established socio-technical configurations and the potential diffusion of new ones (Miörner et al., 2022a; Schneider and Rinscheid, 2024).

Against this background, we expand Markard et al.'s (2016) and Binz et al.'s (2016a) conceptualization to study the legitimation or de-legitimation of entire socio-technical configurations centered around certain technologies. Building on Suchman's (1995) definition, we conceptualize the object of legitimacy as selected socio-technical configurations within a socially constructed system (Berger and Luckmann, 1966), that is the larger socio-technical system in which such configurations exist and evolve. The evaluators of certain actions (to be legitimized) in this system are actors that are part of the socio-technical system. We argue that perceived legitimacy is a key determinant of how successfully an emerging configuration (e.g., one driven by transformative knowledge) can mobilize resources and evolve. Moreover, we aim to uncover how this interrelates with and depends on the de-legitimation originating from established configurations that preserve their legitimacy, continue their practices, and remain powerful in the socio-technical system. In this context, we modify previous perspectives on technology legitimacy (Binz et al., 2016a; Markard et al., 2016) by integrating a 'transition work' perspective (Löhr et al., 2022). While emerging configurations draw on transition work to gain legitimacy, incumbents aim to preserve and repair their legitimacy by conducting 'defensive work', (Kainiemi et al., 2020; Maguire and Hardy, 2009) which delegitimizes the transformative configuration. To conceptualize de-legitimation, we further distinguish *implicit* and *explicit de-legitimation*. Our conceptual framework combines both legitimation and de-legitimation of emerging socio-technical configurations that aim to transform the socio-technical system (see Table 12).

Table 12: Forms of (de-)legitimation of emerging socio-technical configurations (partly based on Löhr et al. (2022) and Maguire and Hardy (2009))

Forms of (de-) legitimation		**Definition**
Legitimation	*Creating*	Developing new transition-related processes such as rules, narratives, and practices that render an emerging socio-technical configuration appropriate and desirable within a given socio-technical system
	Maintaining	Reinforcement and reproduction of previously developed transition-related processes by stabilizing norms, beliefs, practices, and actor networks to ensure persistence and continuity of a socio-technical configuration
	Disrupting	Active challenge and destabilization of established institutions, incumbents and technologies that sustain dominant configurations, thereby opening space for alternative, emerging socio-technical configurations
De-legitimation	*Implicit*	Indirect undermining of an emerging configuration by incumbents through the preservation and repair of their own legitimacy (e.g., framing their practices as superior or inevitable), which implicitly marginalizes alternatives
	Explicit	Direct contestation of an emerging configuration by associating it with negative narratives, questioning its credibility, or actively resisting its diffusion through political, discursive, or institutional strategies

For the legitimation of an emerging socio-technical configuration, actors rely on transition work (Löhr et al., 2022). Their goal is to contribute to the transition of the socio-technical system towards "*more sustainable modes of production and consumption*" (Markard et al., 2012, p. 956). The transition work framework by Löhr et al. (2022) incorporates related processes towards such a transition that involve three dimensions or parts thereof: institutions and rules, actors and organizations, as well as materiality and technology. According to their framework, actors in emerging configurations pursue three forms of transition work to gain legitimacy for a socio-technical configuration. If they *create* transition-related processes through actions such as advocacy, political work, or by framing and defining rules, they can legitimize the transformative configuration within a socio-technical system. Moreover, transition work involves *maintaining* these previously established transition-related processes and, finally, *disrupting* established institutions, incumbents or technologies (Löhr et al., 2022). The further along in the transition process, the more institutionalized and legitimized the emerging socio-technical configuration becomes (Binz et al., 2016a; Harris-Lovett et al., 2015).

At the same time, established socio-technical configurations delegitimize emerging ones, often based on legitimation strategies of the former. These strategies primarily aim to preserve and repair legitimacy (Suchman, 1995). This is achieved either by fostering their own technology and related institutions to preserve the status quo within the socio-technical system or by conducting 'defensive work' aiming to prevent emerging socio-technical configurations (Kainiemi et al., 2020; Lehmann et al., 2022; Maguire and Hardy, 2009). Here, we propose to distinguish between *implicit* and *explicit de-legitimation* of the emerging socio-technical configuration. *Implicit de-legitimation* occurs when an approach focuses on advancing its own socio-technical configuration, e.g. by preserving the legitimacy of its institutions, actor networks and technology (Binz et al., 2016a; Harris-Lovett et al., 2015). This involves institutional work, including actions such as solution framing and mimicry (Binz et al., 2016a; Lawrence and Suddaby, 2011; Suchman, 1995). *Explicit de-legitimation* is in place if the 'arenas' of legitimation actively involve another socio-technical configuration or parts thereof, which might relate to their institutions, actors or technologies (Lehmann et al., 2022). This is usually the case when an established configuration resists and counters actions relying on transition work of an emerging configuration (Kainiemi et al., 2020; Maguire and Hardy, 2009). Such defensive work may include any activity that uses aspects of an emerging configuration (e.g., rules or characteristics of a technology) to associate it with negatively perceived narratives. In other words, new technologies and their associated norms and values are subject to *explicit de-legitimation* (Lehmann et al., 2022).

5.2.3 Multi-scalarity in (de-)legitimation

Finally, to derive our conceptual framework, we will first briefly outline how the development and (de-)legitimation of configurations are viewed in recent contributions to the regional studies and sustainability transitions literature. Therefore, we will use the simple example of an emerging configuration at the regional level and an established configuration at the national level to characterize the theoretical foundations of multi-scalar (de-)legitimation, which will be conceptualized in detail afterwards. We argue that a newly emerging socio-technical configuration carries transformative knowledge but needs to compete with other (established) configurations in order to gain influence. Thus, a crucial function of emerging socio-technical configurations is to develop a coherent counter-narrative to the established configuration (Jolly and Hansen, 2022; MacKinnon et al., 2022). In an emerging transformative configuration, this counter-narrative is likely to be held by only a few actors in a region, while it may be held in other places as well ('multi-location milieus', see Crevoisier and Jeannerat, 2009). Thus, this configuration seeks to gain legitimacy by selecting and conforming to an environment and to persuade networks of actors from other configurations (Suchman, 1995). Forrer et al. (2022) refer to this as a bottom-up legitimization trajectory of a socio-technical configuration, which aims to legitimize its logics and modes of operation. At the same time, the established socio-technical configuration employs a top-down legitimization trajectory backed by e.g., the government and other powerful actors or institutions. In this sense, large actor networks suffer from a 'knowledge lock-in' (Stassart and Jamar, 2008), meaning they often resist changes (Geels, 2014). To this end, the established configuration has produced knowledge in the past and perpetuates it, making it seem inevitable – a situation that can be described as a cognitive lock-in (Grabher, 1993; Stassart and Jamar, 2008). The dominant narrative enables the established configuration to preserve and sometimes repair its legitimacy by protecting its accomplishments, propriety, and overall assumptions when continuing to use a technology in a certain way (MacKinnon et al., 2022; Suchman, 1995). These opposing narratives fundamentally reject alternative solutions and seek to delegitimize other configurations within a socio-technical system (Ertelt and Hawxwell, 2025; Simoens et al., 2022).

We expand on this perspective regarding the legitimation and de-legitimation of socio-technical configurations through bottom-up and top-down trajectories. To this end, we adopt a multi-scalar approach to regional sustainability transitions (Miörner and Binz, 2021; Truffer and Coenen, 2012). Building on previous work, we examine the spatial influence on legitimacy in sustainability transitions, including regional differences, multi-scalarity, and diffusion across space (Ayrapetyan et al., 2025; Hansen et al., 2024; Heiberg et al., 2020; Miörner et al., 2022a; Rohe and Chlebna, 2021). Furthermore, due to the multi-scalar nature of transformative knowledge, capturing these dynamics is essential (Chlebna et al., 2023;

Crevoisier and Jeannerat, 2009; Loorbach et al., 2020). The (de-)legitimation of an emerging socio-technical configuration evolves in various scalar directions (Figure 14). Thus, the legitimation of a focal emerging configuration may derive from the same geographical scale, i.e., the same region. However, it may also be mobilized from other regions (Butzin and Widmaier, 2016; Loorbach et al., 2020). Similarly, actors from an established configuration within the region (intra-regional) or from other regions ('multi-location milieus', see Crevoisier and Jeannerat, 2009) can delegitimize the emerging socio-technical configuration.

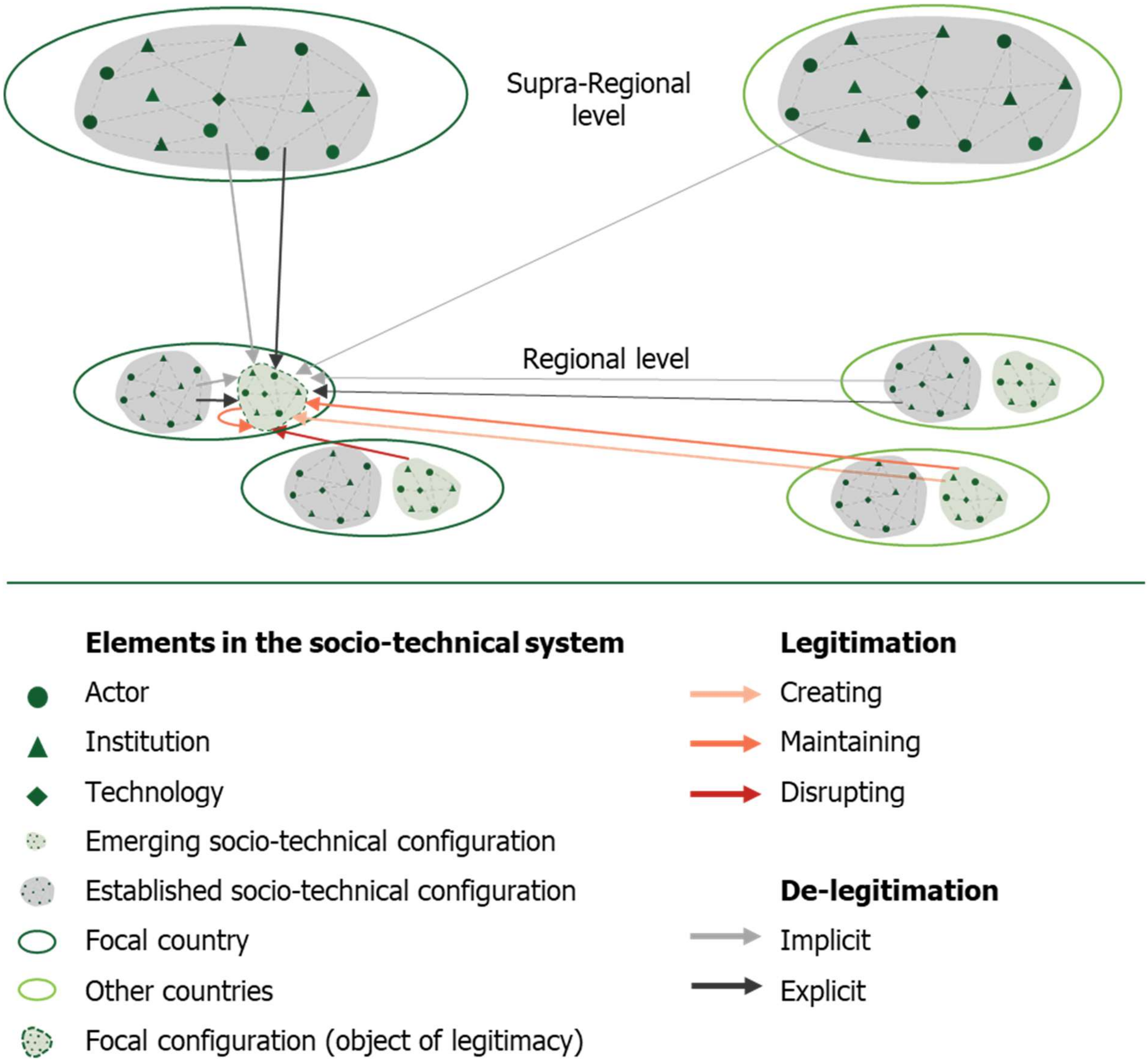

Figure 14: Multi-scalar (de-)legitimation of an emerging socio-technical configuration

Along these multi-scalar directions, the focal emerging socio-technical configuration relies on transition work to gain legitimacy (Löhr et al., 2022). Actors *create* transition-related processes by building new institutions, organizations and technologies, *maintaining* them to sustain persistence, and ideally *disrupting* established institutions, incumbents and technologies that reinforce the dominant socio-technical configuration. Established configurations delegitimize the focal emerging configuration either *explicitly* or *implicitly*.

Explicit de-legitimation occurs when incumbents actively frame the emerging configuration through negative narratives (defensive work). *Implicit de-legitimation* arises when incumbents primarily focus on preserving or repairing their own legitimacy, thereby passively undermining the emerging configuration.

5.3 Research design

The regional construction sector in Chennai, India, is an appropriate case study for applying the presented framework, given the transformative knowledge for bio-based construction in the greater Chennai area. The region hosts a few nationally recognized key players that promote the use of bio-based materials, such as earth, loam, and bamboo. India is also a highly relevant case in the construction sector due to the rapid growth of its cities (including Chennai) and the continuous growth of mineral-based materials in the sector (Zhong et al., 2021). In this paper, we aim to understand how the emerging bio-based configuration draws on transition work across geographical scales as well as how the established socio-technical configuration delegitimizes the emerging transformative configuration in Chennai. Empirically, we utilize a large set of semi-structured expert interviews conducted in 2023 and 2024. These interviews cover diverse geographical scales to capture the inherent multi-scalarity of (de-)legitimation. See the detailed table 13 in the appendix (Section 5.7) for more information, listing all interviews used in the analysis.

A broad variety of stakeholders were interviewed, including architects, planners, engineers, suppliers, and start-ups. These were supplemented with interviews with government officials and industry association representatives. Through a purposive sampling approach, we selected interviewees based on their relevance and influence on the respective socio-technical configuration. Initially, we identified these interviewees through desk research on influential and successful bio-based construction projects and powerful incumbent organizations. We supplemented the desk research with snowball sampling methods, ensuring theoretical saturation. The first round of interviews was conducted online with actors in India, complemented with interviews in other countries, namely China and Germany, providing insights on the global scale. The second round was conducted in person, primarily in Chennai, and supplemented by interviews at a concrete trade fair in Mumbai. The semi-structured interviews followed a consistent guideline and were slightly tailored to each specific interviewee. The interviews focused on socio-technical systems and innovation in the construction sector and enabled us to identify two socio-technical configurations: an emerging transformative configuration that pursues bio-based materials and an established configuration that uses cement and steel. The guidelines included questions about the (de-)

legitimation of socio-technical configurations including all related processes (e.g., transition and defensive work) and transformative knowledge as well as knowledge lock-in.

This substantial set of interviews allows us to identify the dynamics of (de-)legitimation between established and emerging socio-technical configurations from a multi-scalar perspective through a qualitative content analysis approach (Kuckartz, 2019). In essence, we analyzed the interview data based on different geographical scales where certain configurations are territorially embedded. From there, we identified the legitimation and de-legitimation of the regional socio-technical configuration that pursues the use of bio-based materials in Chennai.

We defined a specific coding scheme, including subcodes for each legitimation and de-legitimation process, based on the framework developed in the theory section. We then employed a deductive coding process involving triangulation and intercoder reliability testing with four colleagues from our research project to ensure validity and robustness of the codes and results. A first set of codes maps transformative knowledge in Chennai. This includes aspects such as experimentation, a mission-orientation toward transformative change, and an emphasis on inclusion and participation, among others. Next, we coded 'knowledge lock-in' by incumbents, which involves resistance to change and cognitive lock-in, rendering the established socio-technical configuration as inevitable. For (de-)legitimation processes, we coded along the aforementioned multi-scalar directions. For each multi-scalar direction that legitimizes the emerging socio-technical configuration, we coded the subdimensions of transition work: *creating*, *maintaining* and *disrupting* (Löhr et al., 2022). In cases of de-legitimation of the transformative configuration, we distinguished between the various multi-scalar directions and included subcodes on *implicit* and *explicit de-legitimation*. In cases where the primary message is to advance incumbent institutions and technologies, we coded *implicit de-legitimation*. If defensive work is carried out, i.e., if established configurations actively malign an transformative configuration or aligned institutions, organizations and technologies, we coded *explicit de-legitimation* (Lehmann et al., 2022; Maguire and Hardy, 2009). Based on this coding scheme, we were able to assess various directions of multi-scalarity and the related legitimation and de-legitimation processes of the emerging socio-technical configuration in detail. This, in turn, enables us to analyze the extent to which transformative knowledge actually advances a regional sustainability transition in the construction sector. More importantly, it allows us to identify the interdependent and multi-scalar dynamics of (de-)legitimation that hinder or foster regional transformative change.

5.4 Results

5.4.1 Transformative knowledge and knowledge lock-in in the construction sector

First, we analyze how transformative knowledge in the emerging configuration and knowledge lock-in in the established configuration provide reasoning *for, by and as action* in the construction sector. Next, we demonstrate the results based on the proposed framework for multi-scalar legitimation and de-legitimation of the transformative configuration pursuing bio-based construction.

The greater Chennai area can be viewed as an arena *for action* driven by transformative knowledge around bio-based materials. It provides a 'tool *for action*' (Jeannerat et al., 2025) that fosters goal- and mission-oriented approaches and can be leveraged by the emerging socio-technical configuration. These approaches emphasize and acknowledge the urgency of addressing the negative environmental impact of the construction sector, while highlighting the need for a fundamental shift in education and practices (Q1-Chennai_1)[22]. This mission-oriented approach to the more ecologically sensible and balanced use of construction materials also serves to shift client expectations towards longevity. This introduces a normative directionality that supports the framing of the transformative configuration. Chennai's ecosystem and networks of actors pursuing bio-based construction facilitate the development of transformative knowledge surrounding the use of bio-based materials (Q2-Chennai_6). Nevertheless, transformative knowledge is multi-local; in other words, important knowledge is also carried by actors in transformative configurations in other places. Such transformative knowledge is also generated in other Indian regions and in regions abroad. For example, experimentation with bamboo construction creates situated knowledge that could benefit actors in Chennai. Such experiments are central to transformative knowledge *by action* (Q3-India_25). In this sense, the greater Chennai area can be seen as an arena for experimentation of bio-based materials, with several demonstration projects generating practical know-how *by action*. This includes developing new applications of bio-based materials, adapting traditional techniques and enhancing existing ones. These pilot projects of bio-based construction are also implemented in other places, thereby building transformative knowledge *by action* (Q4-Germany_12). Lastly, certain behaviors or practices *as action* situate what to do. This applies to skills development across the value chain, which encompasses knowledge in practice (Q5-

[22] All quotes can be found in Table 14 in the appendix (Section 5.7). We link to the interview quotes in the following style: Quote number and interview name.

India_14, Q6-India_29). Further actions in this context include training formats, conferences and advisory services in the greater Chennai area and beyond that institutionalize practices.

While actors in the emerging configuration draw on transformative knowledge, as described above, actors in the established configuration rely on knowledge lock-in. In this context, both configurations fundamentally reject opposing views on which construction materials should be used. As such, the inherent knowledge is interdependent with the action employed and generates a contested understanding of other materials. For example, the transformative configuration views conventional materials as contradicting the stated mission orientation. Conversely, the established configuration based on the continuous use of cement and steel actively views bio-based materials as unable to meet the demands of India's growing construction sector. The underlying reasons can be identified by examining knowledge lock-in *for*, *by* and *as action*. These cognitive lock-ins are an instrument of the established socio-technical configuration *for action*, catering to the vision of India as a rapidly growing economy with developed infrastructure. Consequently, there is a significant and ongoing reliance on cement and steel (Q7-India_TF_7). Another powerful tool is codified knowledge *for action*, which is rooted in the lock-in in established codes or certification schemes. Knowledge lock-in can be mobilized to enable incumbent actions, constituting growth and development speed frames *for action* that help the established configuration but portray alternative solutions as impractical given Chennai's development trajectory (Q8-Chennai_16).

There is also knowledge lock-in *by action* (i.e., certain existing resources or assets), as represented by the built environment and ongoing mineral-based construction projects. These projects are mainly large-scale national programs that materialize and normalize actions by the established configuration. Such assets or rules result in incumbent lock-in, leading to a significant knowledge gap regarding bio-based materials due to a lack of awareness among consumers, contractors, architects, and engineers. Thus, the advantages and value of bio-based materials cannot be adequately addressed *by (established) actions* within the current socio-technical system of the construction sector (Q9-Chennai_11, Q10-Chennai_11, Q11-India_21). The same applies to the vested interests of incumbents who want to preserve the status quo, which is established *as action*. As such, they often create significant barriers to change, such as contractors' reluctance to adopt new materials and the influence of the cement lobby. This has led to concrete being associated with modernity and status, which has ultimately contributed to its widespread adoption despite its environmental impact (Q12-Chennai_11). The perceived need for "quality products" which are assumed to be achievable only through the use of cement and steel, constitutes knowledge lock-in *as action*. This feeds the main mission of providing quality products to society instead of addressing the negative environmental effects that these products have on society. In this sense, incumbents are 'locked in' to the conventional framing of quality (mineral-based materials) for the growth and well-being of society in India. Furthermore, incumbents habitually compare everything to cement. This is a cognitive routine that narrows the search to concrete or steel alternatives, thus locking in the search directions. Through this, they situate knowledge lock-in *as an action* in everyday life and as a widely held belief (Q13-Chennai_10).

5.4.2 (De-)legitimation of the bio-based configuration in Chennai, India

5.4.2.1 Multi-scalar legitimation

In this section, we explore how the transformative configuration in Chennai is subject to multi-scalar legitimation. Overall, we analyze the three forms of transition work: *creating*, *maintaining* and *disrupting*. For each of these, we demonstrate our framework by following the sub-forms of transition work (Löhr et al., 2022) and differentiating these transition-related processes depending on their territorial embedding at different geographical scales. Actors in Chennai conduct transition work, thereby contributing to the intra-regional legitimation of the emerging (bio-based) socio-technical configuration. These actors are centered around architectural and design practices that experiment with bio-based and frugal construction. They collaborate with entrepreneurial material producers and builders who develop, supply, and assemble bamboo- and earth-based components. Often, these collaborations take the form of visible pilot projects that demonstrate technical viability and aesthetic appeal to local clients. Knowledge intermediaries in universities, consultancies, and training initiatives translate these experiments into formal design rules, courses, and advisory formats, thereby making bio-based solutions more intelligible within Chennai's professional field. Together, these actors generate situated expertise, demonstrate the feasibility of concrete projects, and gradually inscribe bio-based construction into the area's repertoire of legitimate construction options. Driven by these regional actors, processes of *creating transition* are ongoing, as most of the actions identified by Löhr et al. (2022) are being implemented in the region. Indeed, actors often emphasize the importance of *educating and learning*[23] in fostering a shift towards sustainable construction practices. This includes training local masons and construction workers in bio-based materials and techniques, educating clients about the long-term cost savings of sustainable construction practices, and developing diploma programs in bamboo construction, for example (Q14-Chennai_7). Similar actions promoting *educating and learning* can be seen in other Indian regions. These initiatives build capabilities across the

[23] We use *italics* for sub-forms of transition work to emphasize specific actions relating to legitimation of the emerging socio-technical configuration. These sub-forms are based on the framework of Löhr et al. (2022) and we refer to their paper for a more detailed explanation of each sub-form.

supply chain of bio-based materials, ultimately creating the skills and know-how that the transformative configuration in Chennai could benefit from (Q5-India_14).

A crucial aspect is *inventing and experimenting* with existing bio-based materials. For example, new combinations or techniques are tried out locally (Q15-Chennai_6). The focal bio-based configuration in Chennai can also draw on inter-regional legitimation from other regions in India, particularly Mumbai and Bangalore. Actors in these transformative configurations range from research institutes and university labs working on sustainable construction management to award-winning material start-ups and architectural and engineering firms experimenting with bamboo and other bio-based materials in visible projects. Non-governmental organizations (NGOs), task forces, and multi-local city networks (e.g., climate-oriented municipal alliances) complement this field by advocating for new standards, training formats, and targets that are referenced in Chennai. Together, these actors constitute a multi-local epistemic community that generates transformative knowledge, codifies practical design rules, and provides reference projects that the emerging configuration in Chennai can use to institutionalize bio-based construction. As is seemingly typical in cases of transformative knowledge, *inventing and experimenting* plays a crucial role in a multi-local manner through award-winning materials and system experiments with bio-based materials. These experiments produce tangible results that can be showcased, thereby providing legitimacy for the transformative configuration in Chennai (Q3-India_25, Q16-India_25). Figure 15 shows the most important actions related to the legitimation of the bio-based configuration in Chennai for each direction of multi-scalar legitimation.

These specific efforts and accomplishments also contribute to *defining rules and setting targets*, as is done in Mumbai and Bangalore, for example. In these cities, actors establish specific targets and codified rules, such as references to European fire standards and treatment standards of the Bureau of Indian Standards. These rules could help the transformative configuration in Chennai articulate clear criteria for approvals and procurement in public and private projects (Q17-India_29). In this context, actor networks in other regions abroad substantially contribute to the legitimation of the transformative configuration in Chennai. In some regions in Germany, for example a dense network of timber-oriented architecture firms, structural engineering offices, municipal developers, and regional timber initiatives plays a central role. These entities deliver emblematic multi-story timber projects, lobby for changes in building classifications, and establish networks and alliances that present wood construction as a credible, policy-backed climate solution. In some Chinese region, the transformative configuration is driven by a network of bamboo-focused architectural firms, provincial standardization institutes, and research laboratories in regions such as Zhejiang and Fujian. These laboratories often collaborate with international organizations that promote bamboo as a sustainable material. The transformative configurations in some regions abroad provide actors in Chennai with legitimation through building codes, narratives, and demonstration projects that they can strategically reference. More specifically, Zhejiang and Bavaria, among others, have successfully integrated bio-based materials into their regional construction sectors. Standards and codes introduced from these places contribute to a lower perceived risk of bio-based materials by providing norms and rules that actors in Chennai can refer to. For example, building codes and bamboo standards in China have been promoted by actor networks in Zhejiang and Fujian (Q18-China_14). However, this also applies to timber in some regions of Germany where changes to the building code permitted the use of timber in higher building classes. Thus, actor networks in Chennai can use these rule changes to justify amending their building codes, which is a major issue in the transition towards bio-based construction materials (Q19-Germany_2).

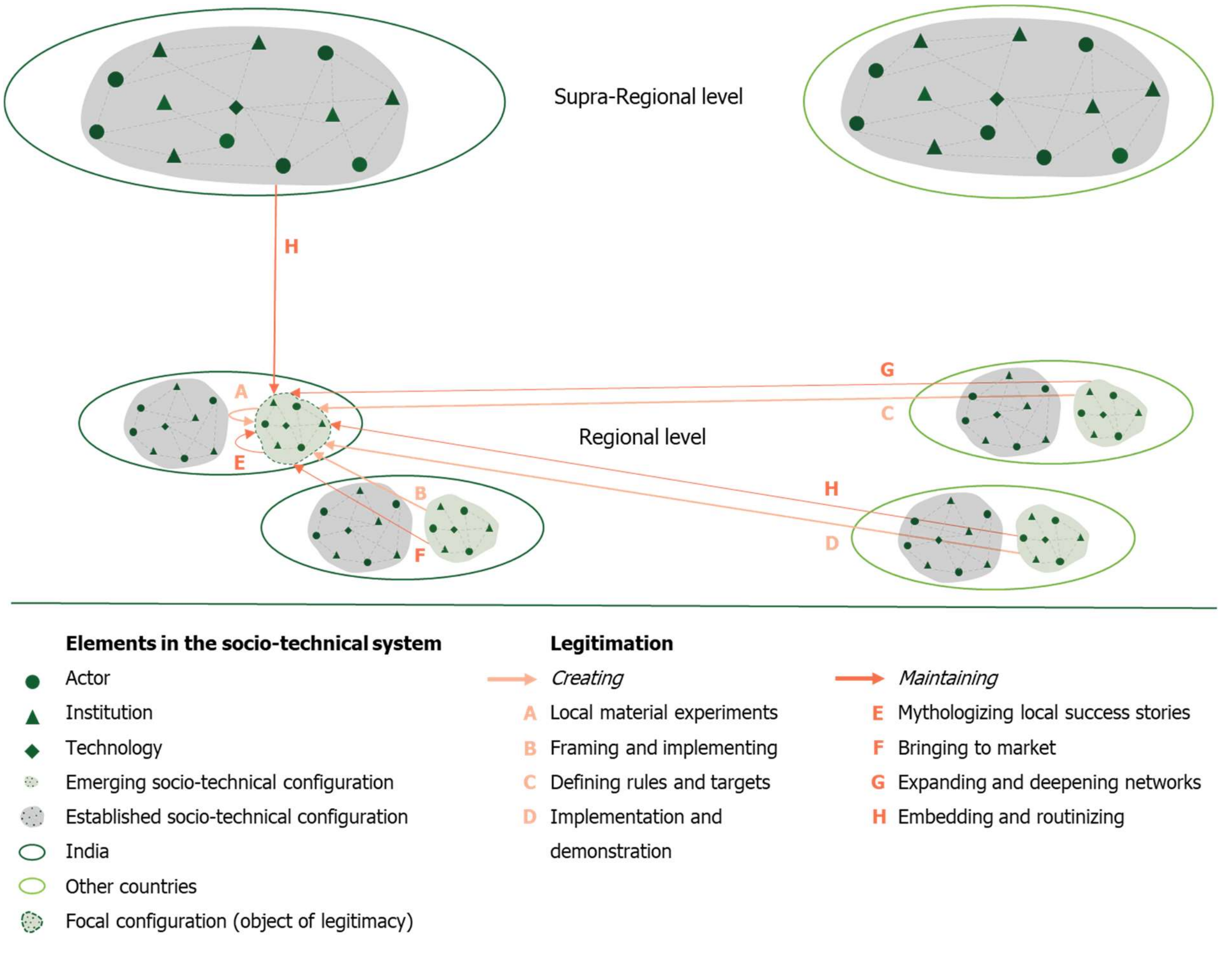

Figure 15: Multi-scalar legitimation of the emerging configuration in Chennai

Other crucial processes of creating transitions in Chennai include *narrative work, framing and constructing of identities*. The use of bio-based materials, such as bamboo, evokes passion among other actors in Chennai working on construction projects (Q20-Chennai_6). Similarly, regionally *framing* and theorizing an alternative configuration that considers traditional materials and durability contributes to legitimizing the transformative configuration of bio-based materials in Chennai. Actors actively depict bio-based materials as climate-suitable, long-lasting, and professional (Q21-Chennai_11). Actors in other Indian regions contribute to this *narrative work and framing* through the use of bamboo in pre-engineered buildings, for example. This enables the alignment of bio-based materials with familiar product categories, which lowers adoption costs and associates bio-based materials with existing, taken-for-granted practices (*mimicry*). Aesthetic reframing redefines the identity of bio-based materials, transforming bamboo from ”poor man’s timber“ into a premium, design-forward material, for example. This provides the transformative configuration in Chennai with legitimacy and identity to build on (Q22-India_25, Q23-India_29). Regions abroad also provide scripts that might help actor networks in Chennai to *construct identities*. For example, state-led timber initiatives in other countries frame bio-based construction as a climate instrument involving substitution, carbon storage, and refurbishment (Q24-Germany_10). These actions relate to *advocacy and political work* in other regions of India and abroad that legitimize the transformative configuration in Chennai. This involves advocating for new policies, such as contesting the ‘Kutcha House’ status of bamboo and proposing a target share of bio-based materials for new buildings. These efforts provide legitimacy for actor networks in Chennai that primarily struggle with the lack of regulatory institutions (Q25-India_25, Q26-India_25).

Actors in Chennai also draw on *creating transitions* through *implementation* and local demonstrations that materialize the transformative configuration. This builds legitimacy through taken-for-grantedness and new valuation scripts (Q27-Chennai_8). The same applies to actor networks in other Indian regions since they also *implement* projects based on bio-based materials. These high-visibility demonstrations (e.g., temple banquet halls and large corporate interiors) create a reservoir of reference cases that actors in Chennai use to promote the use and procurement of bio-based materials, thus receiving inter-regional legitimation (Q28-India_24). Similarly, demonstration projects abroad provide legitimacy for the transformative configuration in Chennai. In Germany, municipal pilots (e.g., a 57-meter timber high-rise) and early multi-story timber projects are normalizing bio-based construction (Q29-Germany_7, Q4-Germany_12). In China, the government commissions bamboo construction, converting the R&D of engineered bamboo into regional standards and actual construction (Q30-China_9).

The transformative configuration in Chennai draws on the creation of *networks, coalitions, and organizations* through the formation of a peer group for bio-based materials. This involves building teams and training programs, as well as institutionalizing routines and capabilities around the configuration, thus enabling its legitimization (Q31-Chennai_6). To some extent, these actions are also substantiated in interregional networks in India. Throughout the country, we observe the *formation and deepening of coalitions*, such as NGOs, task forces, the C40 program, and university labs. These coalitions create multi-local arenas whose resources, such as norms, training, and policy drafts, can be adapted by the transformative configuration in Chennai. We can also see these coalitions expanding to some extent, which accounts for *maintaining transition* processes as networks strengthen their interdependence (Q32-India_25, Q33-India_25). Somewhat unexpectedly, incumbents at the national scale from the established configuration in India may unintentionally draw on transition work, such as by selectively including bio-based materials. The new terminal at Bangalore Airport, for instance, used bamboo alongside conventional materials, achieving significant public attention. Actors of the transformative configuration in Chennai often use this case to mobilize legitimacy for their practices. It enables them to argue that bamboo was *implemented* on a larger scale and facilitates their *narrative work* by associating bio-based materials with established technologies and rules, *creating transitions*. Furthermore, it contributes to *embedding and routinizing* by pushing bio-based materials into mainstream projects and embedding them as almost ordinary choices (*maintaining transition*) (Q34-India_11).

We also observe *maintaining transition* processes through *mythologizing*, as actor networks in Chennai speak positively about the initial successes of bio-based materials. Overall, however, transformative configurations in Chennai have not yet done sufficient work to *maintain transition* processes. Nevertheless, they have accomplished to *sustain* some actions, which preserve institutions or technologies beyond their initial scope. Their bio-based materials have *sustained* for a long time, longer than initially thought. Some peer communities in other Indian regions have managed to preserve and extend their activities in *education and research*. This helps *maintain transition* processes through long-term learning loops and also helps legitimize the focal transformative configuration in Chennai (Q35-India_25). It shows where and how the bio-based configuration is being legitimized elsewhere in India and which actions contribute to the legitimization of Chennai's transformative configuration. These include *implementing* and *mimicry* to lower adoption barriers, *defining rules and targets* to address cost and insurance or trust issues, and *creating* and *expanding networks* to supply skilled labor and credible reference cases. There are two more examples that represent only a small amount of effort to *maintain transition* processes. In Chennai, actors draw on the *upscaling* of their technology by bringing bamboo to new markets, making multi-story houses possible. Nevertheless, it will take time for diffusion to occur and for the configuration to gain further legitimacy. The transformative *configuration expands networks and organizations* by establishing bamboo as a subject in architecture schools in India. However, further work is required to *maintain* the transition process and gain further legitimacy. Globally, coalitions around bio-based materials are expanding, as in some German regions where networks and investors use emblematic projects and lobbying to institutionalize timber-based options. Their public claims reinforce the configuration's legitimacy as a standard practice and *maintain the transition* (Q36-Germany_20).

In contrast, some actors in Chennai are almost refusing to *maintain transition* processes. These actors are reluctant to establish rules, standards, or practices that other actor networks (outside the transformative configuration) can build on and embed. This is a good example of why transformative knowledge often lacks legitimacy, as it does not primarily aim to conform with the larger socio-technical system. As such, they refuse to align with certain system rules or norms (e.g., the treatment of material), which would be required for scaling (Q37-Chennai_6). While *maintaining transition* processes in other regions of India often fail due to the lack of regulatory institutions, some Indian actors manage to upscale bio-based materials (*bringing to market*). This is evident in Mumbai and Bangalore, where actor networks stabilize demand in segments willing to pay for quality and narrative, such as eco-tourism, clubhouses, and corporate lounges. These sales channels are deliberately routinized and practices are normalized, which the transformative configuration in Chennai can build on (Q23-India_29).

So far, the transformative configuration in Chennai has failed to *disrupt* established institutions, incumbents and technologies which constitutes a lack of legitimacy. This can be attributed to a lack of regulatory institutions that could facilitate the development of the bio-based configuration. Actors are unable to establish policies that treat bamboo as a material for permanent buildings (Q25-India_25). Another implication is that, although the transformative configuration in Chennai frequently refers to pilot projects, it nevertheless seems to struggle to leverage such demonstration projects to *disrupt* the established configuration (e.g., through norms and rules) (Q38-Chennai_2).

The transformative configuration in Chennai that pursues bio-based materials has gained legitimacy by drawing on various forms of transition work (in particular *creating*). It is further legitimized by similar actions in other Indian regions and abroad. However, the focal configuration in Chennai lacks sufficient regulatory institutions (e.g., building codes) to *maintain transition*-related processes. Furthermore, the cognitive stigma and dominant narratives frame bio-based materials as temporary and as materials for the poor. This delegitimizes the bio-based configuration and prevents it from successfully drawing on transition work.

5.4.2.2 Multi-scalar de-legitimation

Structured similarly to the previous section, this section provides insights into the multi-scalar de-legitimation of the transformative configuration driven by the established configuration. First, we analyze *implicit* de-legitimation, followed by *explicit* de-legitimation. We demonstrate how such defensive work differs across geographical scales for both types.

Within Chennai, de-legitimation is mainly driven by incumbent actors embedded in the established configuration that pursues a conventional use of cement and steel: large contractors and developers, established engineering firms, and client groups whose expectations are anchored in durability, speed, and 'modern' concrete aesthetics. These actors are supported by local professionals who are socialized in mineral-based architecture and who reproduce design standards in which concrete is the unquestioned quality benchmark. Everyday procurement routines, cost heuristics, and status-laden imaginaries of concrete as the material of progress are powerful vehicles of knowledge lock-in. This pushes bio-based options to the margins of what is perceived as technically and socially acceptable.

As part of intra-regional de-legitimation, incumbents preserve their own legitimacy by anchoring client expectations in durability and validation of technologies by naturalizing cement as the benchmark. This comparison *implicitly* delegitimizes the bio-based configuration by protecting the accomplishments of incumbent technologies and rendering bio-based materials divergent (Q13-Chennai_10). These narratives, both regionally and nationally in India, emphasize the importance of supplying high-quality cement for the society and national growth. In doing so, they *implicitly* delegitimize bio-based materials (Q39-India_TF_7). The focus on making incremental improvements to established materials and the emphasis on established technologies *implicitly* reinforce the dominance of the current socio-technical configuration. Powerful lobbies, particularly at the national level, further hinder the adoption of sustainable alternatives and thus *implicitly* delegitimize the transformative configuration in Chennai around bio-based materials (Q11-India_21). Related to this are lower costs and the 'green premium' framing, which is observed in Chennai, as well as on national and international scales. Incumbents aim to preserve their legitimacy by emphasizing costs first and foremost in their framing, thereby *implicitly* delegitimizing bio-based materials as nice-to-have but unaffordable (Q40-Chennai_16). Similarly, incumbents' narratives primarily focus on the durability and safety of conventional materials. By highlighting the quality and perceived excellence of their materials, they repair their own (moral) legitimacy while *implicitly* depicting bio-based materials as potentially short-lived or risky in Chennai's climate. This de-legitimation is further substantiated by international influences that also declare concrete the default construction material (Q41-Chennai_16, Q42-China_6). Figure 16 illustrates some of the most significant actions associated with the de-legitimation of the bio-based configuration in Chennai, considering each direction of multi-scalar de-legitimation. An important factor in this regard is the prevalence of cement in Chennai's existing material structures, which contributes to the de-legitimation of bio-based materials. Various forms of concrete are considered the default material for Chennai's built environment. This *implicitly* sidelines bio-based materials, making them appear non-standard, risky, or simply out of scope (Q43-Chennai_13).

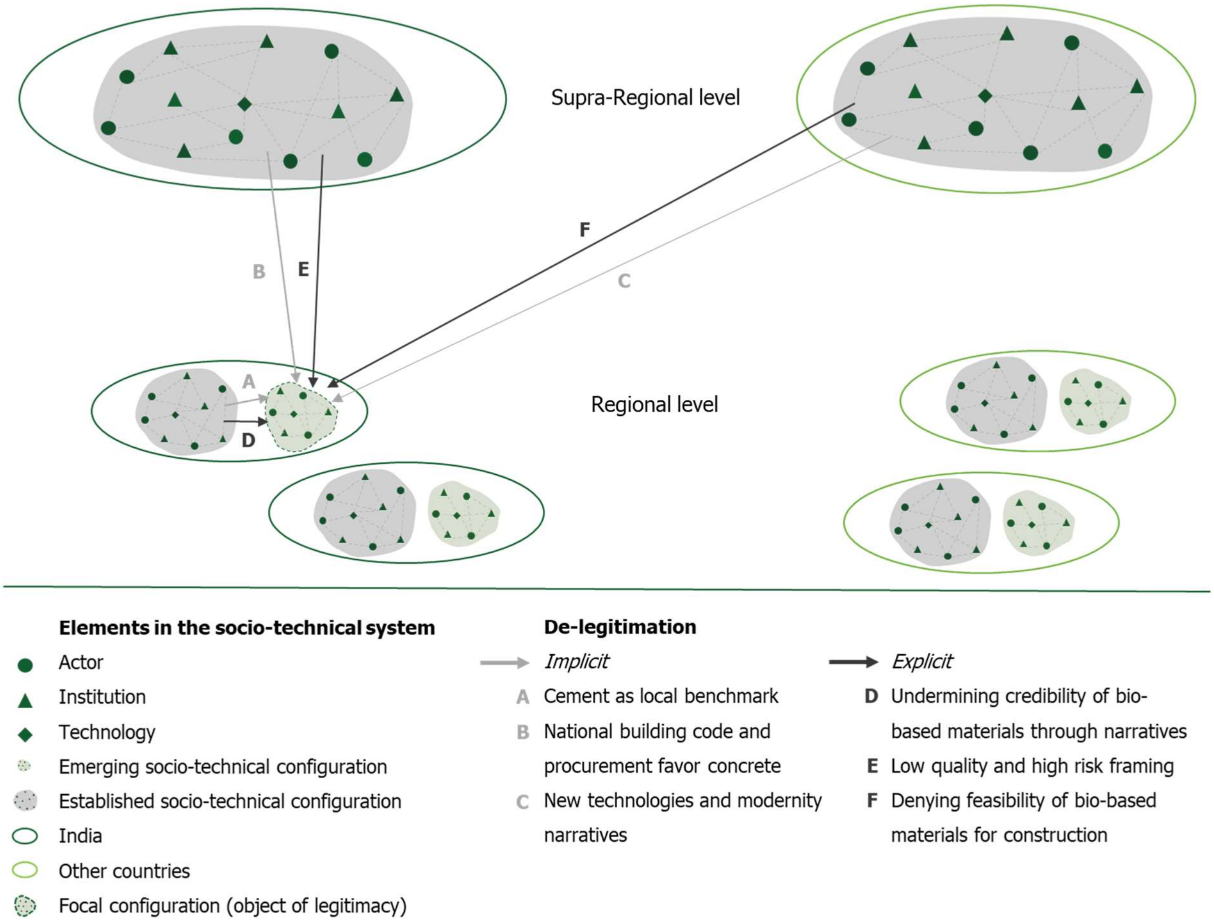

Figure 16: Multi-scalar de-legitimation of the emerging configuration in Chennai

At the national scale, de-legitimation is driven by a tightly coupled configuration of large cement producers, industry associations, and central government bodies responsible for infrastructure, housing, and standard-setting. Through their influence on the national building code, public procurement rules, and rating schemes, these actors establish a development narrative in which rapid urban growth is intertwined with cement and steel. This renders bio-based materials 'out of scope.' Certification organizations and rating providers reinforce this by prioritizing operational efficiency indicators over embodied carbon and keeping material criteria aligned with established solutions. This allows national mineral-based suppliers to preserve their legitimacy while sidelining bio-based alternatives as technically immature or unsuitable for India's growth ambitions. In this context, their main strategy for preserving cognitive legitimacy involves various certification heuristics (LEED, GRIHA), rather than reducing the embodied carbon of materials. This allows incumbents to adhere to established rating systems and still provide clients with a 'sustainable' label, which *implicitly* delegitimizes other materials (Q44-Chennai_16). In other words, by framing their products as sustainable, they are *implicitly* undermining bio-based alternatives, which are objectively less CO2-intensive and can therefore be considered more sustainable (Q45-India_TF_7).

De-legitimation also stems from the globally established socio-technical configuration around cement and steel. However, the constellations of actors differ between Europe and China. In China, powerful, state-linked general contractors, global industrial suppliers, and export-oriented construction companies perpetuate the idea that growth is essential. In this narrative, concrete is the material of choice for large-scale modern development, while bio-based materials are seen as niche, risky, or incompatible with high-rise urbanization. In Germany, large multinational cement producers and related engineering groups dominate. Their R&D and sustainability departments promote decarbonization strategies centered on carbon capture and storage (CCS), incremental clinker reduction, and 'green' concrete. This repairs their legitimacy while limiting the perceived scope for material substitution and *implicitly* portraying bio-based alternatives as inferior. In both contexts, international rating schemes, conservative building codes, and global professional networks act as amplifiers of this established configuration. They stabilize knowledge lock-in and reinforce the idea that cement- and steel-based solutions are the default path for climate-compatible construction. Thus, new 'green' technologies and materials from abroad undermine bio-based solutions in Chennai. For example, upstream European incumbents repair their legitimacy by equating decarbonization with CCS and incremental clinker reduction. This defensive strategy narrows the perceived space for material substitution and *implicitly* delegitimizes the bio-based configuration (Q46-Germany_17). Similarly, institutional conformity to the established configuration that promotes continuous use of cement and steel enables incumbents to preserve their legitimacy. More specifically, incumbents advocate for conventional building codes and durability standards, which *implicitly* delegitimize bio-based materials by hindering their development. This regulatory exclusion of bio-based materials is evident globally, as they are barely mentioned in building codes, hindering their adoption and *implicitly* contributing to their de-legitimation regionally, such as in Chennai. Although there may be initial global standards, as previously mentioned, they have yet to be translated into (national) building codes (Q47-India_13).

Against this background, the national building code of India constitutes a large resistance to change, as it is not adapted to the opportunities of bio-based materials (*implicit de-legitimation*). India has one national building code for its six climate zones, each of which requires different materials and regulations. Some areas, such as Chennai, are suitable for and would benefit from bio-based materials. However, the national government does not reflect this, as it focuses on a general development initiative that targets the use of cement and steel (Q48-Chennai_5). The national government establishes standards and public procurement guidelines that contractors of large projects adhere to. In other words, the general development initiative and any other mineral-based projects significantly impact the *implicit de-legitimation* of bio-based configurations (Q49-India_13). The national development initiative also helps incumbents throughout the country to develop the dominant narrative of rapid growth, which preserves legitimacy of the established configuration in the construction sector. However, this focus *implicitly* delegitimizes transformative configurations around bio-based materials and shifts the focus to overall development in the country using conventional materials (Q7-India_TF_7).

Regional and national government policies and regulations play a crucial role in either *implicitly* favoring established materials through building codes and certification processes or failing to provide sufficient incentives for adopting bio-based alternatives. The lowest-bidder system for government contracts exacerbates this issue further (Q50-Chennai_5). In addition to these actions, the national government contributes to the de-legitimation of regional transformative configurations through its own certification schemes. These help to preserve the legitimacy of technologies related to the established configuration that are already embedded in certification pipelines. Meanwhile, "green" certifications are often optional (Q51-India_16). This may be related to India's rating system practices, which prioritize operational themes such as energy or water efficiency while excluding materials. This, of course, inhibits transformative configurations built around alternative materials (Q52-India_10).

Beyond these cases of *implicit de-legitimation*, actors in Chennai also *explicitly* delegitimize the bio-based configuration. This occurs when regional incumbents emphasize the inevitability of conventional materials and actively counter initiatives to change by declaring cement to be non-substitutable and alternatives to be impossible. This narrative often emerges in the context of India's need to expand housing and infrastructure. It claims that the bio-based configuration cannot provide these critical societal functions. This is particularly true for established configurations in major cities like Chennai, which must meet the demands of rapid urbanization (Q8-Chennai_16). Similarly, our results show defensive work being carried out, which leads to the *explicit de-legitimation* of parts of the bio-based configuration. In this context, the regional use of bamboo in Chennai, for example, is framed as unsustainable within real-world supply chains. Thus, it undermines one of the most common technological options of the bio-based configuration while simultaneously asserting the necessity of concrete (Q53-Chennai_13).

We also find *explicit de-legitimation* of bio-based materials at the national scale in India, where they are framed as low in durability and quality. This is partly due to a lack of awareness and understanding of bio-based materials, as well as the active sabotage of these materials. Ultimately, this leads to offensive anti-bio-based narratives that deny the materials' suitability and ignore implemented bio-based construction projects. These narratives are also present in other growth markets for construction, such as China (Q54-India_TF_7, Q55-China_7). Similarly, narratives with negative connotations often involve a lack of know-how and immature supply chains, which are frequently associated with bio-based materials (Q56-India_13). The established configuration undermines the credibility of transformative configurations of bio-based materials by raising questions about their equivalence in testing compared to conventional materials (Q57-India_10).

5.5 Discussion

Our case study indicates that transformative knowledge is unable to effect change not because it is absent, but rather because it is continually delegitimized from various scales. First, incumbent's *implicit de-legitimation*, articulated through cost, speed and durability heuristics, conformity to certification routines, and building codes risk aversion, keeps bio-based materials outside the default directions of search. This occurs by reproducing benchmarks against which novelty appears exceptional rather than appropriate. Second, the emerging bio-based configuration faces defensive work by incumbents that *explicitly* delegitimizes it by claiming its inevitability which weakens its momentum. In our framework, this is the established configuration's top-down response to bottom-up transition work effort, which we consider a constitutive part of the multi-scalar (de-)legitimation process. Third, these dynamics are not merely cognitive but enacted: knowledge lock-in is performed *as* and produced *by* routine *actions* (e.g., procurement via certifications and building code constraints) while being instrumentalized *for action* through growth and speed narratives. These de-legitimation efforts by the established configuration across scales unfold specific dynamics that hinder the scaling and diffusion of a transformative configuration. Thus, our framework offers initial insights into why transformative knowledge may fail to actually transform.

Nevertheless, the transformative configuration of bio-based materials in Chennai is somewhat successful since it is legitimized to some extent. However, it lacks a broad, positive evaluation by actors in the socio-technical system. One way to identify what is lacking to facilitate transformative knowledge in such cases in the future is to recognize the missing transformative capacities of local actors in Chennai (Hofstad et al., 2026). While ideational and experimental capacities seem high, our results show that institutional and adaptive capacities are lacking. Thus, we conclude that actors embracing transformative knowledge may not yet be able to establish sufficient structures or create institutional arrangements for collaboration across scales (missing institutional capacity). More importantly, our results reveal that *disrupting* activities, based on Löhr et al. (2022), do not (yet) exist. In other words, actors in the emerging transformative configuration have not managed to *disrupt* existing socio-technical structures, primarily due to the absence of adoption and adjustment of established institutions (missing adaptive capacity). These missing local capacities may hinder the design and implementation of suitable policies (Hofstad et al., 2026). In this regard, our framework helps to identify barriers related to transformative knowledge's inability to transform. It also provides initial directions for overcoming these barriers by identifying the transformative local capacities that are missing.

Furthermore, our results partially unpack the transfer of legitimacy between the emerging and established configurations (Wesche and Skjølsvold, 2025). This provides further insight into how transformative knowledge has failed and which leverage points might be used in the future to gain legitimacy. Some of the *explicit de-legitimation* can be described as legitimacy capture, whereby the established configuration exploits actions of the emerging configuration in Chennai to 'capture' legitimacy for their own development, often to repair their own legitimacy. In addition, if incumbents unintentionally draw on transition work, as in the bio-based demonstration project at Bangalore Airport, it becomes apparent that incumbents sometimes share legitimacy with the emerging configuration when it benefits both. Therefore, an approach for an emerging configuration pursuing transformative knowledge could be to leverage the exchange of legitimacy with incumbents, ideally driving actions that *maintain* and *disrupt* transitions. In other words, the transformative configuration could aim to 're-capture' the legitimacy that their materials are associated with.

5.6 Conclusion

In this paper, we explore whether transformative knowledge translates into transformative change. By bringing together the emerging debate on transformative knowledge (Jeannerat et al., 2025) with the literature on socio-technical configurations and legitimacy (Binz et al., 2016a; Miörner et al., 2021; Miörner et al., 2022a), we developed a conceptual framework that emphasizes (de-)legitimation as an inherently multi-scalar phenomenon (Heiberg et al., 2020; Miörner and Binz, 2021). Building on the framework of transition work (Löhr et al., 2022), we demonstrated how emerging transformative socio-technical configurations draw on *creating*, *maintaining*, and *disrupting* transition-related processes to gain legitimacy, while established configurations engage in *implicit* and *explicit de-legitimation* through defensive work. Thus, our framework shifts the focus from legitimacy as an outcome to (de-)legitimation as a set of contested socio-technical processes that determine whether and how transformative knowledge can reconfigure socio-technical systems.

Empirically, we examined the use of bio-based construction materials in Chennai, which illustrates the presence and productivity of transformative knowledge, though it remains constrained by multi-scalar (de-)legitimation dynamics. Actors in the emerging configuration around bio-based materials develop and disseminate transformative knowledge through experimentation with earth- and bamboo-based construction materials, construction of demonstration projects, coalition formation, and selective reference to inter-regional and international cases. These activities primarily contribute to *creating* transition-related processes and, to a lesser extent, *maintaining* them. However, the transformative configuration fails to *disrupt* established institutions, incumbents and technologies. At the same time, they are confronted by pervasive knowledge lock-ins *for, by,* and *as action* in the established configuration by incumbents centered on cement and steel. This configuration is reinforced through building codes, certification practices, narratives of growth, speed, and quality, and the materiality of the existing built environment. Through *implicit* and *explicit de-legitimation* across regional, national, and global scales, incumbents keep bio-based materials at the margins and prevent the emerging configuration from *disrupting* established configurations. Our analysis suggests that, although ideational and experimental local transformative capacities (Hofstad et al., 2026) in Chennai are relatively strong, institutional and adaptive capacities are weak. This helps explain why transformative knowledge has not yet been able to reconfigure the socio-technical system, both regionally and beyond. Although the transformative configuration is not yet ready for diffusion and scaling up, a finding supported by similar studies on grassroots innovation (Hermans et al., 2016; Seyfang, 2010), our results demonstrate the relevance of transformative knowledge for local development and future local government policies. In Chennai, weak institutional and adaptive capacities limit the diffusion of bio-based construction. This suggests that regional innovation policy should not only support experimentation, but purposefully strengthen existing capacities, as well as create new ones where necessary.

These findings have three main implications. First, they address overly optimistic expectations about transformative knowledge by showing that its diffusion depends on multi-scalar (de-) legitimation. In other words, the goal of achieving transformative change through a mission-oriented approach may often be unrealistic in emerging configurations (Hermans et al., 2016; Seyfang, 2010). This may be due in part to the second implication: emerging configurations pursuing transformative knowledge must balance ambitious goals with limited influence over established institutions and markets. To gain access, credibility, and resources, these configurations must align with incumbents and established standards. However, this often comes with conditions that narrow or reframe their radical aims. This illustrates a tension between accumulating legitimacy and preserving the transformative goal (Hermans et al., 2016; van Summeren et al., 2023). Third, our results highlight the importance of strengthening local transformative capacities beyond experimentation. Building regulatory and organizational arrangements that embed transformative knowledge, as with alternative construction materials in building codes, rating systems, and procurement practices, is essential for emerging configurations that pursue and build on transformative knowledge to gain broader legitimacy. Thus, assuming transformative knowledge inherently aims to transform socio-technical systems, transformative capacities (including institutional and adaptive capacities) are required for diffusion and scaling. Future research could examine these dynamics in other sectors and regions and explore how combinations of transition work, defensive work, and transformative capacities affect the trajectories of transformative knowledge regions.

5.7 Appendix

Table 13: Details on the interviews used for article 4

Interview name	Interviewee role	Organization details
Chennai_1	Architect	Architectural firm focused on sustainable practices
Chennai_2	Architect, Professor, Policy advisor	Architectural firm focused on bio-based solutions and frugality; involved in the Chennai development master plan
Chennai_3	CEO	Software provider for construction companies (prop-tech) & platform for sustainable solutions in construction
Chennai_4	Regional director	Bilateral business chamber promoting trade and industry between India and another country
Chennai_5	Principal architect	Architectural firm focused on locally available and bio-based building materials
Chennai_6	CEO	R&D for bamboo construction with experimental approach
Chennai_7	CEO	Architectural firm focused on traditional natural building materials (e.g., earth, stone)
Chennai_8	Lead planner	Planner of eco cottages using bio-based materials
Chennai_9	CEO & Procurement engineer (2 interviewees)	Supplier of materials and machinery for 3D printing using concrete, fly ash and industrial waste
Chennai_10	CEO	Provider offering affordable, fast and sustainable construction through on-site concrete 3D printing using sustainable concrete and geopolymers
Chennai_11	CEO	Architectural firm focused on sustainable materials including waste timber, earth and construction waste.
Chennai_12	Sustainability manager	Supplier of building materials (mainly glass)
Chennai_13	CEO	Sustainable concrete developed based on waste (industrial, agricultural and C&D waste)
Chennai_14	Partner	Green building consulting firm providing certifications and advice
Chennai_15	Executive head	Central planning development authority
Chennai_16	Professor and Chair	University department for construction materials research
Chennai_17	CEO	Supplier of bio-based building materials (waste wood)
Chennai_18	Managing director	Supplier of tunnel boring machinery for large scale projects
India_TF_1	Engineer	Supplier of sprayed concrete, admixture chemicals and machinery; provides implementation services for construction projects
India_TF_2	Director	Developer and supplier of innovative green concrete solutions
India_TF_3	Area Manager	Machinery supplier; technology for bricks based on concrete and fly ash
India_TF_4	Manager	Supplier of chemical technologies for the construction industry (adhesives & admixtures for concrete)
India_TF_5	Engineer	Supplier of large machinery for concrete 3D printing in the construction industry
India_TF_6	Sales Manager	Supplier of specialized fibers for tensile reinforcement and crack prevention in concrete
India_TF_7	PR Manager	Large cement manufacturer and supplier
India_TF_8	Quality Control Manager	Large ready-mix concrete (RMC) manufacturer
India_TF_9	General Manager Sales	Manufacturer and supplier of conventional construction materials (concrete, AAC blocks & steel)

Interview name	Interviewee role	Organization details
India_1	CEO; Professor; Director in government (Retired)	Government (urban planning), University (sustainable construction), Large architectural firm
India_2	CEO (Person 1) & Project Manager (Person 2)	Non-profit organization for sustainable housing
India_3	CEO	Architectural firm focusing on bio-based materials (stabilized earth)
India_4	CEO (Person 1) & Architect (Person 2)	Architectural firm focusing on bio-based materials & intelligent water and sanitation designs
India_5	General Manger	Large contractor of industrial, infrastructure and public projects
India_6	CEO	Architecture consultancy focusing on bio-based resources such as waste or fly ash
India_7	Managing Director (Person 1) & Associate Architect (Person 2)	Architectural firm focusing on passive and low energy architecture
India_8	CEO	Architectural firm focusing on bio-based materials (e.g. poured earth concrete)
India_9	CEO	Architectural firm focusing on sustainable designs
India_10	Assistant Manager	Large contractor of industrial, infrastructure and public projects
India_11	Managing Director	Supply and construction with various bio-based materials (bamboo, mud, recycled wood)
India_12	Senior Consultant	Consultancy advising the government on the development of a bamboo-based supply chain
India_13	Assistant Professor; prior Industry Manager	Research institute focusing on sustainable construction management
India_14	Consultant & former director of a research institute	Research institute for bamboo construction & advising an international interest group for bamboo
India_15	Executive Director	Research institute on earth construction and architecture
India_16	Director	Government council for the promotion of construction materials and technologies
India_17	Director	Government institution for R&D in construction
India_18	Regional Director	International organization promoting bamboo
India_19	CEO	Investor focusing on construction and agricultural bamboo projects
India_20	CEO	Provider of a novel biobased technology for constructing walls
India_21	CEO	Supplier of bio-based bricks
India_22	CEO	R&D and supplier of waste-based sustainable concrete
India_23	CEO	Supplier of bricks based on recycled plastic waste and industrial waste
India_24	CEO	Supplier of bamboo and planning & implementation of bamboo construction
India_25	CEO	Bamboo advocate: R&D, architecture, education & training
India_26	Postdoctoral Researcher	Research institute focusing on recycling of construction materials
India_27	Professor; Head of Department	Research on sustainable architecture focusing on waste materials
India_28	Assistant Professor	Research on sustainable reinforced concrete
India_29	CEO	Supplier of bamboo and planning & implementation of bamboo construction
China_1	CEO	Construction project management consulting company
China_2	CEO	Architectural office focused on sustainable, bio-based construction
China_3	Director	Bamboo design center
China_4	Managing Director	Architectural firm focused on sustainable building solutions
China_5	CEO; Professor	Architecture firm; Research on sustainable architecture

Interview name	Interviewee role	Organization details
China_6	Head of Global Construction	Industrial company with international industrial construction projects
China_7	Managing Director	General contractor specialized on international (sustainable oriented) clients
China_8	Senior Engineer	Planning, engineering and design of sustainability-oriented construction projects
China_9	CEO	Architectural firm focused on bamboo architecture
China_10	General Manager	Engineering consulting company for sustainable engineering solutions
China_11	Professor	Research on bio-based architecture
China_12	Associate Professor	Research on energy efficiency & green building materials
China_13	Professor	Research on bio-based architecture
China_14	Programme Coordinator	International organization promoting bamboo
China_15	Professor	Research on bio-based construction materials
China_16	Professor	Research on bio-based construction materials
China_17	Professor	Research on engineered bamboo and timber
China_18	CEO	Engineered bamboo supplier
China_19	CEO	Bamboo construction material supplier
China_20	Sales Director	Bamboo construction material supplier
Germany_1	Project Manager	Architectural firm focused on wood construction
Germany_2	CEO	Architectural firm focused on wood construction
Germany_3	CEO	Architectural firm focused on repurposing/upgrading existing buildings with sustainable materials
Germany_4	CEO	Architectural firm focused on wood construction
Germany_5	CEO	Architectural firm focused on bio-based materials (mainly timber)
Germany_6	Founder	Planning and design of engineering structures focusing on sustainable projects
Germany_7	Team Leader	Planning office in civil engineering with structural engineering projects using timber construction
Germany_8	Head of Sustainable Structures	Engineering firm focused on wood construction
Germany_9	CEO	Planning firm focused on timber construction
Germany_10	Project Coordinator	Timber construction campaign, initiated by a German state to promote climate-friendly construction with wood
Germany_11	Director Network & Consulting	Network for sustainable buildings that develops sustainability certifications.
Germany_12	Project Manager	Organization promoting timber construction in Saxony funded by the state
Germany_13	Head of Research	Research on bio-based building materials (engineered bamboo and mycelium-bound)
Germany_14	Professor	Research on timber construction and structural timber engineering
Germany_15	CEO	Supplier of low carbon and reusable concrete bricks based on geopolymers
Germany_16	Head of Public Relations	Supplier of timber and modular wooden building blocks
Germany_17	R&D Program Manager	Global R&D department of large cement supplier with focus on sustainability
Germany_18	Head of Sustainability Strategy & Engagement	Large cement supplier focused on clinker reduction
Germany_19	Key Account Manager	Supplier of cross-laminated timber
Germany_20	Project Developer Modular Design	Project developer with investments wood construction projects
Germany_21	Head of Sustainability Department (Person 1) & Engineer (Person 2)	Large contractor, timber supply construction; turnkey buildings

Table 14: Interview quotes used for article 4 referred to in the results section (5.4)

Quote ID	**Interview quote**
Q1-Chennai_1	*"I'm really concerned that we are the ones who actually drive the construction sector, and we are the one who ruined it also. (...) The earlier architects have taken very less responsibility. And it's not a blame game, but (...) I think education has to be more concerned about environment and sustainability now." (Chennai_1)*
Q2-Chennai_6	*"Auroville is all about education research. So, we draw volunteers and students like they saying for yearly 3,000 to 5,000. (...) Not only bamboo. Earth, bamboo and other natural materials. (...) Whatever you see here, this is all done by students. It's all experimented by the students and with the students." (Chennai_6)*
Q3-India_25	*"So, I have been trying to do bamboo reinforced slabs, concrete slabs, and I have developed several variants of that in that I also use the bamboo waste, which is a very fine fiber waste, and put it in my concrete mix to eliminate the cracks and for better bonding, because then you have bamboo as reinforcement, and you also have these bamboo fibers which are there in the concrete, it bonds better. And this is one solution for which my office, which is called bamboo symphony, has got more than eight to ten national and international awards for that innovation." (India_25)*
Q4-Germany_12	*"We initiate pilot projects because we think that it is very important to show that building with wood is also possible on a large scale and that we might also look at problems in such projects, such as fire protection and moisture protection. These are issues that perhaps still hinder others in their decision to implement the entire project with timber construction. That's why we have initiated two large pilot projects, a timber high-rise in Leipzig (...) A 57-metre-high timber house in Leipzig. These will not be luxury apartments, as one would otherwise expect, but actually social housing." (Germany_12)*
Q5-India_14	*"So, I'm* involved in educating *them about the different primary processes; the chemical treatment and then sizing, grading so that they don't have too much of waste and how to utilize the waste that kind of improves the value chain so that the benefits come to the farmers themselves. And bamboo has several uses." (India_14)*
Q6-India_29	*"We could be able to convince the farmer that will pay a better price. And then the farmer adopts better farming practices of growing bamboo. Then we start using it. Then we have set up a facility where bamboo needs to be treated for durability. Then you need to have trained manpower to make it straight to do joinery. Then you need engineers and architects who know bamboo construction techniques. And then you need a success story to show the people that, yes, this is all that which we have created." (India_29)*
Q7-India_TF_7	*"We want to see India as a very developed nation. So, we are providing such good services to the society." (India_TF_7)*
Q8-Chennai_16	*"If you want completely to change, things may never happen. Will cement be stopped to use in construction in India? Never. I don't think I will ever see it. Or it will not happen for many years because we don't have an alternative. We cannot stop construction because we need houses, we need infrastructure. So, we cannot say, let us wait for a sustainable material to come. It will not happen." (Chennai_16)*
Q9-Chennai_11	*"See, generally it has never become a kind of buzzword or anything. I mean, most of the construction which happens is in a conventional way. Sustainability is never a priority. (...) What I will say mostly it is greenwashing, which is happening" (Chennai_11)*
Q10-Chennai_11	*"They are taught only about concrete and steel, which is a major contributor to the global warming and climate change" (Chennai_11)*

Quote ID	Interview quote
Q11-India_21	*"The biggest barrier is definitely the mafia, the cement and the sand 'mafia'. They would never ever allow sustainable materials to become mainstream unless there is a systemic implementation of sustainable materials. Right? And yet again, we do have significantly large lobbies, fueled by billions and almost a trillion dollars in profits, which again significantly hinder any efforts that are made towards sustainability." (India_21)*
Q12-Chennai_11	*"The thing is that you are having a modern building or a new building. General public belief is that concrete is more durable, more expensive to do, which is true. (...) So, trying to own a concrete house has become an aspiration among the people. And they thought that gives them a better status, social status, because it's not." (Chennai_11)*
Q13-Chennai_10	*"When you get introduced to a new technology and its environmental aspects, they always look in comparison with cement. So that is like the major benchmark that they have. And as such because of the economy people are not looking into environmental factors. (...) When it comes to a general customer, they look into what is good for them and how they can get a validated system which is already there and how well it can withstand for years." (Chennai_10)*
Q14-Chennai_7	*"We have trained, we spent a lot of time on training with them or getting them trained and improving upon them." (Chennai_7)*
Q15-Chennai_6	*"We used no steel just cement bamboo inside. So, we tested it. You see, we get volunteer very fresh first year students. But they're sitting on a computer. They don't have any idea. We try to teach more practical. Theory, you can get anywhere." (Chennai_6)*
Q16-India_25	*"Now we have a 'bamboo-crete' wall that we do (...) and they use cement mortar to plaster. It (...) has the strength of a nine-inch wall, like a brick wall, but it takes only two inches. (...) So, the space is saved, but it has the strength and it has got the horizontal loading. It can take up to 500 kg." (India_25)*
Q17-India_29	*"In our preservative treatment process, we have a fire-retardant chemical introduced (...) as per the European standards norms as per standard codes. Second thing is about durability (...) [where] we have a proper treatment process defined by forest residents in diagonal by bamboo and we have a proper code of Bureau of Indian Standard. So that helps us to convince people that yes as per standard it's a durable [material]." (India_29)*
Q18-China_14	*"We also carrying out and influencing international standards. I am in a working group since 2013 for structural use of bamboo in construction and we produced international bamboo standardization." (China_14)*
Q19-Germany_2	*"This has also manifested itself in the introduction of the paragraph. (...) So [wood] was also allowed to be used in building classes 4 and 5." (Germany_2)*
Q20-Chennai_6	*"It's becoming a passion bamboo. Because you see bamboo becoming very passion and a brand." (Chennai_6)*
Q21-Chennai_11	*"We have been using timber for more than 30 years. (...) We use recycled materials in our projects for more than 30 years. And that has become very critical for bringing in the sustainability because timber is very sustainable, it can be reused and all those things. (...) You have to have a long-term durability for the buildings. It should reduce the repair cost of the building" (Chennai_11)*
Q22-India_25	*"Britishers came here and they tried to tell that bamboo is a poor man's timber and only poor people use it. So, the social stigma of using your hemp, bagasse and all these kinds of things, materials, is also social stigma." (India_25)*

Quote ID	Interview quote
Q23-India_29	*"So, what we thought was the best way is to convince rich people first to use this method. The moment rich people start using this method public consumption will automatically change. But if you try to convince suppose mediocre or middle-income people and then try to go up it's very difficult. So, what we did is we concentrated on a premium buyer and try to create a product and services for them of that class. So, we found that somebody is paying more. He should get value for money. And that can happen only if you are doing project for say maybe tourism industry where people expect things to be ecofriendly and ready to pay more or maybe places like a clubhouse of villa project or welcome lounge where developer builder want to show up and want to spend money to do that. So, these are our initial clients, tourism industry and this type of cafeteria, welcome lounge." (India_29)*
Q24-Germany_10	*"Generally speaking, the (…) timber construction campaign is a state initiative, i.e. a political project of the state government (…) to achieve various goals. Above all, however, the focus is on climate protection, the creation of a kind of CO2 storage in the buildings. And at the same time, of course, the substitution of CO2-intensive materials such as cement or structural steel." (Germany_10)*
Q25-India_25	*"In India we also have a policy which is called a 'Kutcha House', [which] means temporary house. So however good your house might be with mud and bamboo, it will still be called temporary. It's not called a permanent house. (…) So, in the government also, I'm trying to change that policy. I've been pushing it for last 20 years, still not been able to, because that's a very huge thing." (India_25)*
Q26-India_25	*"And I am proposing to use 30% of bamboo and other fiber-based materials in the building. I'm trying to put that into the national building code, in the PWD [Public Works Department], in the government. So, it's like trying to close the loop. And the waste from this whole thing can actually go to make pellets for energy, ethanol, and whatever they want to do." (India_25)*
Q27-Chennai_8	*"The first property from India to be featured on the social media platform of Airbnb. (…) So that's when we get a lot of bookings and reservations and I guess started liking this kind of you know, natural and eco-friendly houses which you don't see anywhere in southern part of India or anywhere in India." (Chennai_8)*
Q28-India_24	*"What we tried to do is bamboo construction. Just like a pre-engineered building (…) is done. All components made in factory and on site. You don't have to do much as (…) it is just assembling with the nut boards. (…) So, this is a banquet hall and having 24 meters of a span, 500 people sitting capacity. And if you see how, it is constructed now, all these components are made in a factory like this. And then these components are then transported to site." (India_24)*
Q29-Germany_7	*"And the tradition in southern Germany, the timber construction tradition, is different. Timber construction is generally more accepted there than in northern Germany. But it is possible, taking Berlin as an example, the first seven-storey timber construction was in Berlin, which actually has no tradition of timber construction and offers an extremely urban environment. But a very open-minded building code has made it possible for the first lighthouse projects to be implemented there." (Germany_7)*
Q30-China_9	*"The largest project I've done in China is a 32 meters span arches with a green roof, doesn't have concrete. The concrete was used only for the support of the arches, but there is no concrete slab. And the roof is all made of soil and plants, and it uses natural light and natural ventilation the most. So, it's very well studied from sustainable point of view and it works very nicely." (China_9)*

Quote ID	Interview quote
Q31-Chennai_6	*"People building three storey, four storey, five storey now. You know, using full culm bamboo, you know. Yeah. So again, this is simple, you know. But there is more possibility. There is a real need (...). Also, the training program is now part of every architectural school in India. There is one subject where they study bamboo now. So, it has the value. Definitely can work with combined material." (Chennai_6)*
Q32-India_25	*"So, I'm also trying to do skilling through my NGO. I do advocacy, but I am also building this second row of people behind me who will take things forward. (...) Now what I have done now is that in the c 40 women for climate program I was a cohort for Bangalore, I've done a very overarching concept now of climate action plan using bamboo. I'm calling it the bamboo city where bamboo is planted in the city and bamboo is used in the city. So, I am proposing to plant one bamboo per citizen to provide him oxygen." (India_25)*
Q33-India_25	*"When I started working in 1999 with bamboo, I was the only Indian architect practicing and trying to push it into the private market. And now there are more than 100 architects here who use bamboo in their building." (India_25)*
Q34-India_11	*"It is a substitute (...) for steel and wood. It is known. Even the Bengaluru airport now they had a reconstituted bamboo with which they have made all the structures and all along with steel and other things. So, the application is known." (India_11)*
Q35-India_25	*"A lot of thermal studies have been done, a lot of sound insulation studies have been done and things like that. How to really improve and things like that. And yeah, I still get a lot of research requests and dissertation and all these kind of things from across the world, from all the students from across the world." (India_25)*
Q36-Germany_20	*"We also try to lobby through the Coalition for Timber Construction. (...) So of course, it's also important to do positive advertising for timber construction." (Germany_20)*
Q37-Chennai_6	*"We have done this with our basic resource. (...) I'm not like 'where [is the] support for money? There have been other things we just did like more as a traditional method. But there is a lot of opportunity there. Whatever you see on this building, these are 12 years, 15 years not treated bamboo. They're not treated. You see the way I tested so. But I'm not the like a big engineer. They want to take my report or something, you understand? But for me, my living experiment, my living report. This is 15 years. The 15 year whatever you see the construction this is not treated. So, if you treat the bamboo with a different model, you work with the engineer, this can be sustainable more." (Chennai_6)*
Q38-Chennai_2	*"So, all that is happening, but for it to come into mainstream construction practice. They did try out a housing project with those prefabricated walls. But to the best of my understanding, it did not become a norm. It did not happen in other projects. It happened as one pilot project. It. So we have to analyze why. Because it was a wonderful idea. It brought in a new quality. So, I'm wondering why. It could just be that the construction companies need training and capacity. So, when they don't have the training, so new technology is suddenly brought into Chennai to absorb it. I think that there is a gap there. There is a gap and so (...) there's research, there's one pilot project, but doesn't percolate. So, I have. I know quite a few times this has happened." (Chennai_2)*
Q39-India_TF_7	*"So, we are contributing a lot to the Indian economy in terms of providing quality material in the construction industry. And we (...) educate people about the quality work we are doing for the society." (India_TF_7)*
Q40-Chennai_16	*"It will happen. The question is at what cost? If it is going to be much more expensive, people will not use it." (Chennai_16)*

Quote ID	Interview quote
Q41-Chennai_16	*"We work a lot on durability because something that is often said to be sustainable may not last. But we believe that durability is very important. Otherwise, you can have something green, but it doesn't last more than few years. Then what is the whole point of using?" (Chennai_16)*
Q42-China_6	*"Concrete is still the number one building material. And that puts you on the safe side in all cases. And that basically puts the brakes on this development." (China_6)*
Q43-Chennai_13	*"People are very conservative in terms of structural engineering. They don't like to have new solutions coming in. They don't want new solutions to hit in. They are very well settled with the old systems been running for the last 30 years, 40 years. They don't want change so early. Same with architects." (Chennai_13)*
Q44-Chennai_16	*"Very rarely we have a client saying that this has to have so much of carbon footprint. That will not happen. They will say we want (…) platinum LEED rating. But the granularity of how much they go into will not be there." (Chennai_16)*
Q45-India_TF_7	*"Our company, stack line itself speaks about sustainability. And we are, you know, dedicated to providing sustainable products to the customers. So, all our products, which we are, you know, showcasing here are all sustainable products, green products. And we are focusing on green energy, zero carbon emissions and all such types of products, that we are talking about." (India_TF_7)*
Q46-Germany_17	*"We will have the very first cement plant with CO2 capture next year. We will produce CO2-free cement. Half a million tons per year, with even bigger projects following every year." (Germany_17)*
Q47-India_13	*"Our building codes do not support this use of these kind of materials. That's one restriction and until that gets changed, it is not going to be used by mainstream." (India_13)*
Q48-Chennai_5	*"The other one is a national building code, which is an oxymoronic thing. (…) India is a vast country with six climatic zones. And to have a national building code that certifies only certain technology and material is counterproductive, both in terms of carbon footprint, but in terms of skill development. There are a lot of local building materials that have local skills that over the three generations have completely died out, because the national building code does not recognize these as certified building technologies and have safety regulations for that." (Chennai_5)*
Q49-India_13	*"So, for all these large infrastructure projects primary client is the government of India. Right so, (…) they are the one who can develop you know standards, technical specifications which can come in the tender documents and document which ultimately will be followed by the contractors who will implement, who will execute those products." (India_13)*
Q50-Chennai_5	*"The downside of it is that these skills are only serving the market of people with cash flow. It is not actually influencing the market of low-income group housing and mass housing and other things that is still under the control of the government, which is still following the national building code and the system of tendering that is basically says lowest bidder." (Chennai_5)*
Q51-India_16	*"First of all, government of India has authorized my organization to evaluate and certify these innovations. Certification is very important. So, we certify innovative products and materials. (…) The moment we certify these materials and technologies, that gives confidence to the users: (…) 'the government has certified these materials. So, these materials are good, these materials can be used'." (India_16)*
Q52-India_10	*"In India, the material side is pretty much lacking when you compare it to energy efficiency or water efficiency. So, on material side, nobody focuses." (India_10)*

Quote ID	Interview quote
Q53-Chennai_13	*"Bamboo is now being transported from northeast to central part, western part of the country. But then again it becomes (...) unsustainable after some time and the volume is going to increase. So, each specific area has its own merits and demerits. So, it has its own material that we have to use it. That's why we say that concrete has to be constant." (Chennai_13)*
Q54-India_TF_7	*"Bamboo and timber constructions? See, basically, we would not like to take products which are, you know, damaging the environment, because mass use of such products will certainly, you know, raise out the environment, greenness and all those things. So, we will not support such things." (India_TF_7)*
Q55-China_7	*"I would say that bamboo is perhaps used in interior fittings, as a replacement for wooden floors, for example. You see it very often, perhaps also as ceiling elements. It exists, but I don't think it will be used on a large scale, for example in shell construction. It won't be feasible so quickly." (China_7)*
Q56-India_13	*"But negative influence would be (...) the high cost and lack of availability of technical knowhow on the market whether it is designers or people who would work at site so that is one challenge." (India_13)*
Q57-India_10	*"The problem with bio-based solutions in India is that it is not being scientifically tested, if I'm not wrong. So, if the manufacturer will maybe force themselves, initiate themselves, to bring up some bio-based solutions to the construction industry, maybe the contractors like us (...) can take up based on the second quarters on the economic side. So, they have to be affordable. (...) So that the (...) the bio-based material is equal to the conventional material. They have to prove that. Right?" (India_10)*

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