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What hinders the transition towards a bio-based construction sector? A global innovation system perspective on its value chain

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ABSTRACT

The construction sector is heavily polluting and an actual threat to the natural environment, therefore its transition towards becoming bio-based is imperative. This transition is currently unfolding and it is driven in particular by innovation activities taking place along the sector's value chain. In the upstream segment, bio-based materials are being improved, while novel building techniques in the core segment enable the use of these materials. In this paper, we utilize the global innovation systems (GIS) framework to examine these innovation activities and their valuation dynamics. In particular, we investigate how the GIS of the bio-based construction sector is organized along its value chain, providing insights into the barriers to the sector's sustainability transition. Our empirical analysis, based on a rich set of expert interviews, demonstrates that the GIS configuration changes along the value chain, driven by profound differences in the innovation mode. This situation creates a bottleneck that hinders the sector's transition, where knowledge about bio-based materials developed upstream fails to translate down the value chain. However, we also find that several niche firms cover and integrate multiple value chain segments and overcome this knowledge gap, suggesting that the transition towards a bio-based construction sector could accelerate with further innovation system reconfigurations.

1. Introduction

The construction sector severely impacts the natural environment. From resource depletion and waste generation to energy consumption and greenhouse gas emissions, its environmental footprint is substantial and far-reaching. The construction sector relies heavily on various materials that necessitate energy-intensive extraction and production processes, resulting in adverse impacts on biodiversity, water scarcity and, especially, greenhouse gas emissions. Steel and cement production alone account for about 7.2 % and 3 % of the total global CO_2 emissions, respectively. Moreover, the mismanagement of materials during the construction and the demolition phases further exacerbates environmental challenges, with the majority of construction waste being disposed in landfills (Cabeza et al., 2022; Churkina et al., 2020; United Nations Environment Programme, 2022). Therefore, a transition of the sector is crucial for addressing its substantial environmental impact.

In this transition, the bioeconomy plays a key role. For example, bio-based construction materials, including wood, bamboo, and agricultural by-products, unlike conventional ones, are often biodegradable or recyclable at the end of their lifespan, offering the potential to decrease material extraction and landfill waste. Moreover, bio-based construction materials can significantly lower greenhouse gas emissions by replacing carbon-intensive ones, such as steel and cement, and through carbon sequestration, even lead to negative emissions in the long run. This suggests that buildings and cities could potentially act as carbon sinks if the construction sector shifts towards a bioeconomy (Amiri et al., 2020; Churkina et al., 2020; Mishra et al., 2022).

However, the transition towards a bio-based construction sector is a complex process, reliant on different innovation activities taking place throughout the entire value chain. In the upstream segment of the value chain, which is mostly concerned with the development and supply of building materials, the focus is mainly on product innovations, characterized by the creation of new bio-based materials or the refinement of traditional ones. The core segment of the value chain, instead, which is concerned with the planning and engineering of buildings, is focused more on developing new building techniques and process innovations, and on adapting them to the specificities and peculiarities of each construction project (Butzin & Rehfeld, 2013). In order to facilitate the

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bio-based transition of the sector, it is fundamental to understand the underlying system resources and mechanisms driving these different types of innovations along the different segments of its value chain.

The paper therefore aims to understand how a bio-based transition of the construction sector can take place and be promoted. Specifically, it seeks to answer the following research question: How is the multi-scalar configuration of the global innovation system of the bio-based construction sector organized along its value chain, and what does this imply for the sector's sustainability transition?

Against this background, the paper aims to analyze (multi-scalar) resource formations in the innovation system of the bio-based construction sector along the value chain, thus enabling a comprehensive understanding of the sector's transition dynamics.

In order to do so, the paper builds on the global innovation system (GIS) framework, allowing us to examine not only the emergence of innovations but also their diffusion and valuation, by considering global and multi-scalar dynamics. This framework facilitates a thorough analysis of how knowledge is generated (innovation mode) and how markets are formed and legitimacy for innovations is established (valuation mode). Both the innovation mode and the valuation mode incorporate a spatial dimension, indicating that resource formation processes can be either regional or global. This involves the integration of resources from various levels within the innovation system, leading to a multi-scalar configuration of the system (Binz & Truffer, 2017). Since the value chain position of the actors active in the sector influences the innovation process and the spatial configuration of resource formation, we analyze GIS configurations for different value chain segments, following Rohe (2020). Empirically, the paper draws on a rich set of expert interviews with stakeholders along the value chain in the bio-based construction sector, from four different countries: Germany, Italy, China and India.

Previous studies have utilized this framework to explore the spatial aspects of resource formation along the value chain for different sectors, such as wind energy (Rohe, 2020), sanitation (van Welie et al., 2019), and solar PV (Hipp & Binz, 2020). Our study, however, extends the existing literature on global innovation systems by analyzing not only different segments of the value chain but also different types of innovation within a single sector. Moreover, it does so for the bio-based construction sector, therefore exploring how the configuration of innovation systems can evolve during ongoing transition processes. Our findings highlight a pronounced knowledge gap between the value chain segments, with upstream knowledge about novel bio-based materials not effectively flowing downstream. This knowledge gap can be attributed to a shift in the configuration of the innovation system, with changes in the innovation mode. We describe this phenomenon as the *innovation gap 2.0*, building upon the notion of the innovation gap proposed by Butzin and Rehfeld (2013), which consists in the potential knowledge waste arising from the project-based nature of the construction sector that can hinder the transferability of innovations across different projects and that has been identified as a barrier to innovation within the sector (Butzin & Rehfeld, 2013; Dreher & Thiel, 2022; Dubois & Gadde, 2002). However, our research also indicates that the transition towards a bio-based construction sector is altering the sector's regime logic, as new actors in the bio-based domain are integrating multiple segments of the value chain. These transition dynamics not only reshape the organization of the value chain but also help to bridge the knowledge gap we have identified. Thus, the paper contributes to the growing body of literature on the geography of innovation and transitions, facilitating an understanding of the interplay between multi-scalar innovation systems and socio-technical regime logics in the context of the bioeconomy (in line with Binz et al., 2020; Fuenfschilling & Binz, 2018; Miörner & Binz, 2021).

The remainder of the paper is organized as follows: the second section focuses on relevant background literature and the theoretical framework; the third section presents the data and the methodological approach; the fourth section describes and discusses the main findings of the paper, while the fifth summarizes and concludes.

2. Background literature and theoretical framework

2.1. Multi-scalar configurations of innovation systems

In the field of innovation studies, there has long been a consensus that innovation does not follow a linear path, but instead arises from complex interactions among various actors possessing different yet complementary competencies, including technological, managerial, financial and regulatory skills (Dosi, 1988; Kline & Rosenberg, 1986; Lundvall, 1992). For this reason, it is essential to approach the emergence and diffusion of innovations from a systemic perspective. This recognition has led to the development of numerous conceptual approaches aimed at studying and defining innovation systems. These variants include national (NIS; Lundvall, 1992), regional (RIS; Cooke et al., 1997), and technological (TIS; Carlsson & Stankiewicz, 1991) approaches. The main difference among them lies in the way system boundaries are set, i.e. in determining which elements are considered contributors that generate positive externalities related to innovation and which are not (Bergek et al., 2015).

The recent conceptualization of a multi-scalar, global innovation system (GIS) is an approach that, unlike the abovementioned innovation system approaches, takes into account both the industry specificity and the spatiality of innovation systems, and that views innovation systems through a multi-scalar and global lens (Binz & Truffer, 2017; Heiberg & Truffer, 2022; Rohe, 2020). GIS conceptually consist of subsystems where different types of system resources are created – knowledge generation, investment mobilization, market formation, and technology legitimacy – which support (or hinder) innovation. These subsystems are not defined and delimited based on space, but based on the actor networks and the institutional contexts that are involved in the formation of system resources. Subsystem boundaries can correspond to national or regional borders, but they can as well develop in networks that transcend national and regional borders. GIS development fundamentally depends on whether and how the resource formation processes in the subsystems is coupled to each other. This happens through so-called structural couplings, which are the connections among the subsystems implemented by the different actors, networks and institutions involved in the system resource creation in the different subsystems (Tsouri et al., 2021). GIS structures and development depend also on the type of technology or industry and their characteristics (Agutu et al., 2024). These characteristics, in fact, impact the spatiality of system resources. The innovation's characteristics taken into account by the GIS framework are the innovation mode and the valuation mode.

Innovation mode refers to the dominant way in which knowledge is generated, and can be categorized into two distinct types: STI (science-technology and innovation) or DUI (doing, using, and interacting) (Binz & Truffer, 2017; Jensen et al., 2007). STI involves knowledge derived from scientific research and development, predominantly conducted in laboratories or academic institutions, while DUI encompasses knowledge generated mainly through face-to-face interactions among producers, users and consumers. In terms of spatiality, innovations that mainly rely on STI tend to be characterized by more globally footloose knowledge networks, facilitated by multi-scalar and scale-transcending collaborations. Innovations relying mainly on DUI, instead, are often characterized by locally sticky knowledge rooted in specific regional institutional contexts. This spatial stickiness arises from the need for close proximity and continuous face-to-face interactions to facilitate knowledge exchange (Alhusen et al., 2021; Binz & Truffer, 2017; Jensen et al., 2007).

Innovation valuation, instead, refers to the way an innovation or technology becomes a valued product for their users (Carvalho & van Winden, 2018; Jeannerat & Kebir, 2016). It is based on the other three system resources: markets, investments and legitimacy, and it can be distinguished between standardized valuation and customized valuation. Standardized valuation applies to relatively homogeneous and standardized products for mass markets, such as fast-moving consumer goods. These operate within a global market influenced by price signals, and user preferences tend to be relatively homogeneous and aligned across various places and institutional contexts. Customized valuation, instead, is applicable to innovations that are tailored to customer demands in specific territorial contexts and that depend on symbolic valuation in local markets (Binz & Truffer, 2017; Jeannerat & Kebir, 2016; Rohe & Chlebna, 2021).

The combination of these dimensions gives rise to four generic GIS configurations (see Fig. 1). *Production-Anchored GIS:* this configuration is associated with standardized valuation and the DUI innovation mode. An example of this configuration is the early wind energy industry, which relied on localized knowledge and a standardized approach to valuation. *Footloose GIS:* in this configuration, innovation is linked to standardized valuation and the STI mode. An example is the solar photovoltaic industry, with innovations emerging globally and addressing mass markets. *Spatially sticky GIS:* in this configuration, innovation is associated with customized valuation and the DUI innovation mode. Industries such as specialized machine tools or luxury watchmaking exemplify this GIS, where specialized products are tailored to local demands. *Market-anchored GIS:* this configuration is associated with customized valuation and the STI innovation mode. Complex products and systems, like consulting services or biogas plants, fall into this category, as they require adaptation to specific local contexts (Binz & Truffer, 2017).

Each GIS configuration exhibits distinct spatial resource formation patterns, which, in turn, have different policy and governance implications. Within this framework, it is also possible to compare innovations and their development over time. Photovoltaics, for example, has shifted from a customized technology to a standardized mass product (Dewald & Fromhold-Eisebith, 2015).

A few recent studies have employed this approach to comprehend the spatial aspects of resource formation along the value chain in specific sectors, with empirical applications to wind energy (Rohe, 2020), sanitation (van Welie et al., 2019), and solar PV (Hipp & Binz, 2020). These studies demonstrate that the spatial organization of resource formation, and thus the GIS configuration, may vary among different segments of the value chain (see also Malhotra et al., 2019). This variation has important implications for the geography of these sectors and for the transition dynamics within them. We follow this approach of applying a value chain perspective to the multi-scalar resource formation in innovation systems, focusing on innovation in the bio-based construction sector. The (bio-based) construction sector is a particularly interesting case for GIS research, especially for value chain-sensitive GIS research, for reasons that we will elaborate on in the next section.

2.2. Innovation in the construction sector

The construction sector is often labeled as traditional and non-innovative, and not as a knowledge-intensive domain, which is perhaps also a reason why the sector seems to escape the radar of many scholars in the (geography of) innovation community (Dreher & Thiel, 2022; Losacker & Fastenrath, 2023). However, the construction sector has a lot of peculiarities that make it interesting for innovation research. The main peculiarity relates to how the value chain of the construction sector is organized and how innovation activities differ along the value chain (see e.g., Butzin & Rehfeld, 2013; Harty, 2008; Segerstedt & Olofsson, 2010; Slaughter, 1998).

In a stylized and simplified typology, we can distinguish three value chain segments (see Fig. 2). Firstly, the upstream part of the value chain covers mainly the development and supply of building materials. This part of the value chain thus typically features product innovations, with novel building materials being developed and traditional ones being improved. Although these innovations might be viewed as incremental, there is indeed a lot of innovation activity in recent years that relates to novel bio-based building materials, for example, engineered bamboo, cross-laminated timber, insulation materials made from typha, or other biomass feedstocks such as hemp or straw, among many other examples (Amiri et al., 2020; Churkina et al., 2020; Mishra et al., 2022; Wilde & Hermans, 2024). Secondly, the core part of the value chain involves the processes of designing and planning buildings, tasks typically undertaken by architects and engineers. This stage is mainly concerned with integrating various building materials, devising new building techniques, and navigating the unique aspects of each construction project. As such, innovation within this segment of the value chain is project-specific, relying on knowledge that is often unique to each project, and involves several organizational and process innovations (Dubois & Gadde, 2002; Harty, 2008; Slaughter, 1998). Closely related to this segment is the downstream part of the value chain, which pertains to the actual construction work, where these innovations are applied on-site.[1]

Previous research on innovation in the construction sector has particularly focused on the core segment of the value chain, namely the planning of construction projects. Such research indicates that construction, being inherently project-based, relies on the development of practical knowledge tailored to each unique project. This process is influenced by various factors, including location, ownership, environmental conditions, and legal frameworks, necessitating customized solutions as standard approaches are often inadequate. Innovations often arise in response to unexpected challenges encountered during planning and construction, drawing significantly on tacit knowledge and experience (Dreher & Thiel, 2022; Dubois & Gadde, 2002; Harty, 2008).

This focus on project-specific solutions presents a major challenge for innovation in the sector: the risk of knowledge waste due to the difficulty in transferring insights and innovations across different projects, thereby hindering the scalability of innovations and the transfer of knowledge. Butzin and Rehfeld (2013) describe this phenomenon as an *innovation gap*, a distinctive feature of the construction sector. They attribute the innovation gap to four key factors, all of which are also supported by empirical research on innovation and transitions in the construction sector.

(1) *Complexity*: Construction projects are characterized by high levels of uncertainty and interdependency. This complexity arises from the unique, one-off nature of each project, involving unfamiliar local environments, new and unknown actors, and unpredictable conditions (Bygballe & Ingemansson, 2014; Dreher & Thiel, 2022; Gidado, 1996). (2) *Local Boundedness*: Unlike industrial value chains with fixed production locations, the construction sector operates as "moving factories," where each project is tailored to specific local conditions. This local dependence limits economies of scale and results in a spatially dispersed sectoral structure, affecting knowledge creation and diffusion (Butzin & Rehfeld, 2013; Dubois & Gadde, 2002). (3) *Loose Coupling*: The project-based nature of the construction industry leads to loosely coupled relationships among actors. This flexibility in assembling trade and competence constellations tailored to specific projects can hinder the development of efficient working routines and trustful, synergetic communities of practice (Dreher & Thiel, 2022; Harty, 2008; Svartefoss & Klitkou, 2024). (4) *Strong Institutionalization*: The construction sector is heavily institutionalized, with formal and informal rules, norms, and regulations providing stability in a high-risk environment. However, this strong institutionalization can mediate against change and innovation, as existing structures are deeply entrenched (Fastenrath & Braun, 2018; Gibbs & O'Neill, 2015; Jayaweera et al., 2023; Losacker & Fastenrath, 2023; Nykamp, 2017).

These factors combine to create an environment where knowledge

[1] Our analysis focuses on the upstream and the core segments of the value chain of the bio-based construction sector, since innovation takes place especially in these segments of the sector's value chain, while the downstream one is more concerned with implementing the innovations developed in the upper ones.

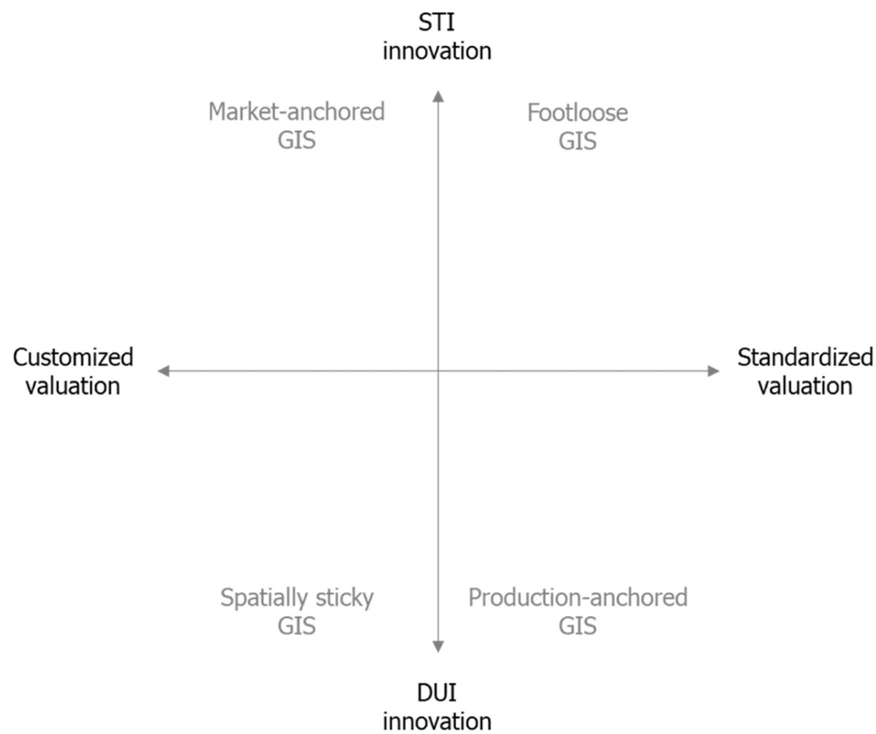

Fig. 1. Different generic GIS configurations (based on Binz & Truffer, 2017: 7).

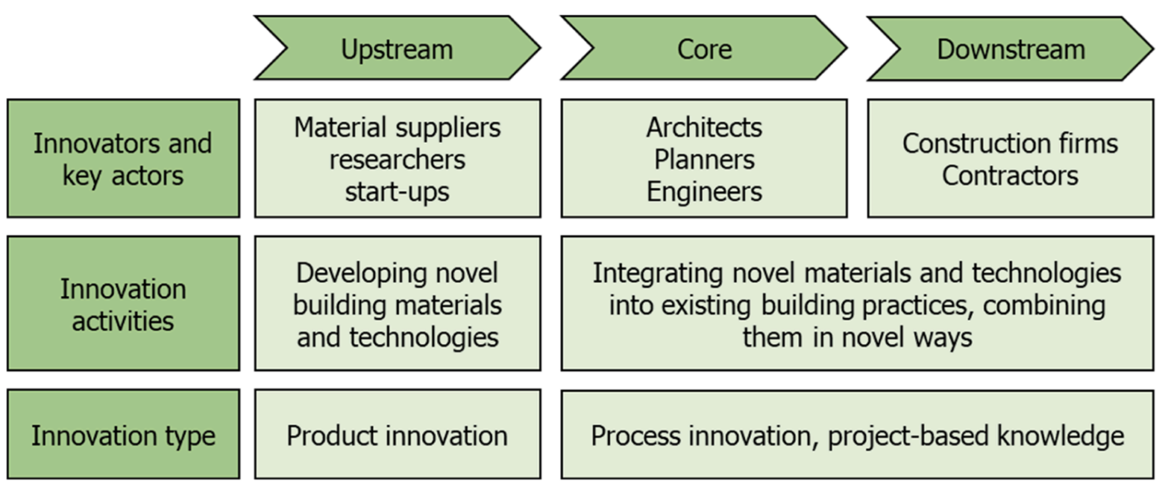

Fig. 2. Stylized value chain in the (bio-based) construction sector.

transfer across projects is challenging, leading to potential knowledge waste and hindering the adoption of innovations.

However, the above research on innovation in the construction sector has left several issues unresolved. Primarily, studies have focused predominantly on the modes of learning and knowledge development within the sector (innovation mode), while overlooking other critical resources of the innovation system like market formation and legitimacy (valuation mode). In essence, the aspect of valuation has been largely ignored. Still, the literature allows us to elucidate the GIS configuration of the conventional construction sector. Based on the aforementioned attributes, the conventional construction sector appears to be characterized by a predominantly production-anchored GIS configuration in its core value chain segment. Due to its project-based nature and local boundedness, its innovation mode seems to be mainly DUI. In contrast, its innovation valuation mode appears to be predominantly standardized, as the core segment of the conventional construction sector primarily relies on the use of standardized materials and building techniques.

As previously discussed, the majority of innovation research has concentrated on the core segment of the construction sector, with less attention given to the upstream segment where innovative building materials are developed. This oversight can also be attributed to the fact that traditional building materials such as steel and cement have historically undergone only incremental changes. We argue, based on the literature and insights on the conventional construction sector, that its upstream segment of the value chain is characterized by a footloose GIS configuration, with global STI learning and global markets for conventional building materials such as steel and cement (Dewald & Achternbosch, 2016).

However, with the shift towards bio-based and sustainable materials, the upstream sector has experienced increased innovation, attracting new players to the field (Wilde & Hermans, 2024). In the empirical part of the paper, we bridge the aforementioned research gaps by examining innovation activities throughout the value chain of the emerging bio-based construction sector and integrating both the innovation mode and the valuation mode in the global innovation systems framework.

3. Data and methods

The empirical section of the paper derives insights from a cross-national case study on the bio-based construction sector, involving two European countries, Germany and Italy, as well as two Asian countries, China and India. The rationale for the case study design and the selection of countries was to represent diverse local conditions including income levels, natural and climate conditions, institutional frameworks, and the varying market demands and conditions of the built environment. Comparing these diverse countries can contribute to the identification of common challenges and opportunities, as well as unique problems and solutions that can be adapted to the different contexts, therefore providing a comprehensive overview on the global transition to a bio-based construction sector.

Moreover, our empirical analysis encompasses a variety of bio-based materials derived from numerous renewable resources like timber, bamboo, typha, or hemp, found upstream, as well as diverse building practices in the core, including timber framing or modular construction, and the use of bio-based materials for insulation and drywalling.

Within the scope of a larger research project, (online) expert interviews were conducted across all four countries, engaging stakeholders active in their respective construction sectors. Specifically, experts from both the upstream and core segments of the value chain in the bio-based construction sector were involved. Upstream professionals included researchers and personnel from supplier firms, encompassing both established suppliers and startups providing novel bio-based materials. Core segment professionals comprised architects, engineers, and planners with considerable experience in bio-based and sustainable building practices. Some interviewed stakeholders have roles that span multiple value chain segments, including downstream contractors.

The selection of experts was guided by a purposive sampling method, particularly focusing on their reputation and engagement within the bio-based construction sector of each country. Purposive sampling was chosen to ensure that participants possess deep insights and expertise relevant to key aspects of sustainable and bio-based construction. Participants were selected based on the relevance of their roles and contributions within their respective national contexts. This approach ensures that the study captures diverse perspectives and experiences crucial for getting a comprehensive and nuanced overview on the transition towards a bio-based construction sector. Additional experts were pinpointed through snowball sampling techniques. For triangulation purposes, these interviews were complemented by additional ones conducted with actors active in the conventional construction sector. Additionally, for each country, further interviews were conducted with stakeholders from industry associations, governmental authorities, and related entities with intermediary functions. The bulk of the interviews took place between August and December 2023, with a handful of additional interviews conducted up to February 2024 to achieve theoretical saturation (Saunders et al., 2018). The final dataset includes 20 interviews for Germany, 19 for Italy, 17 for China, and 28 for India (84 in total). On average, interviews lasted 50 minutes, with durations ranging from 30 to 90 minutes. The paper focuses specifically on 55 interviews conducted with suppliers of bio-based materials and core actors working with bio-based constructions (see Table A3 in the appendix). The remaining 29 interviews have not been used to map the GIS configuration in the bio-based construction sector but have been utilized to gain an overall understanding of the innovation and transition dynamics occurring in the sector.

As mentioned above, the interviews conducted are part of a broader research project examining the transition towards a bio-based construction sector. The first author of this paper conducted all interviews in Italy, while the remaining interviews were carried out by other research associates involved in the project. All interviews were guided by a semi-structured interview guideline, which was slightly modified to accommodate the specific country context and stakeholder type. For instance, the questions posed to upstream actors were slightly different from those asked to core actors. The interview guideline was structured around two primary sets of questions: one set focused on the socio-technical regime and the transition dynamics relevant to the sector, while the other set was more concerned with how novel bio-based materials and building techniques are developed (innovation mode) and how they are diffusing in the market (valuation mode). The analysis in this paper particularly draws from responses to the latter set of questions (see Table A1 in the appendix).

The interviews were recorded, then transcribed and translated in English and finally coded with MAXQDA. The methodology we used in order to analyze the collected data is a qualitative content analysis, following the principles by Kuckartz (2019). The first step in the analysis was conducted using a deductive approach, we thus relied on the GIS framework in order to build the initial coding system. This pre-determined set of codes included innovation mode, innovation valuation, and the system resources influencing them, therefore knowledge, markets, investment and legitimacy. Once the interviews were coded according to this structured set of codes, we performed an inductive analysis, which allowed us to identify relevant emerging patterns and concepts. During this second step of the analysis, new categories were identified and added to the coding system, including codes on the knowledge gap, on skills and education.

During the first step of the analysis, it was possible to identify the GIS configurations for the different value chain segments, while during the second step of the analysis, the knowledge gap and the strategies different actors are using in attempt to close it were detected (about which we will provide further information in the results section).

In order to ensure the validity and the robustness of our findings, different steps were taken. We employed both triangulation among interviewees, in order to reduce 'single source bias', and triangulation among the researchers involved in the interview and coding process, so to ensure consistency and reliability in the data interpretation (Flick, 2004). Inter-coder reliability tests have been employed to test the validity of the coding system and the robustness of our findings (O'Connor & Joffe, 2020). We discussed the findings among all the members of our research group and together with other research groups working on similar topics.

4. Results

4.1. GIS configurations along the bio-based construction sector's value chain

Our analysis reveals that the configuration of the innovation system in the emerging bio-based construction sector differs from the configuration of the conventional carbon-intensive construction sector. While the conventional construction sector is characterized by a more footloose GIS configuration in the upstream part (Dewald & Achternbosch, 2016) and a more production-anchored GIS configuration in the core part of the value chain, the bio-based construction sector follows different logics and configurations. In particular, the upstream segment is characterized by a predominantly STI innovation mode and a customized innovation valuation mode, resulting in a market-anchored GIS configuration, while the core segment is characterized by a DUI innovation mode and a customized valuation, resulting in a spatially sticky GIS configuration (see Fig. 3).

Our analysis indicates that despite the heterogeneity of the bio-based materials and building practices examined, the innovation modes and valuation modes observed are strikingly homogenous. This is likely attributable to the shared characteristic among all studied building materials and techniques: they are all bio-based. This means they are

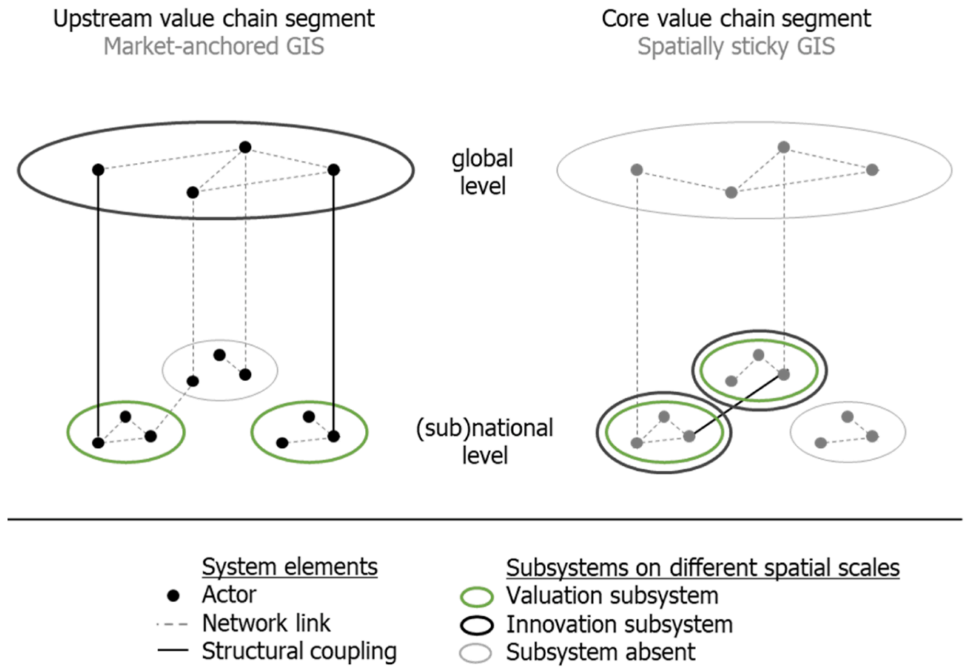

Fig. 3. GIS subsystems along the value chain of the bio-based construction sector (template based on Binz & Truffer, 2017: 8).

renewable, organic, and often closely tied to local natural conditions. We observed only minor differences in the innovation and valuation modes among various bio-innovations, leading us to consider them as a homogeneous group.

Similarly, this applies to cross-country variations. Indeed, we observe that the bio-based construction sector exhibits significant differences among countries, especially concerning preferred bio-based materials and building techniques, as well as in aspects such as rules and regulations, industry structures, and scientific capabilities. There are also variations in the appearance of the built environment among the countries studied, to highlight just a few of the differences between the countries' construction sectors. However, the process through which bio-based innovations emerge and diffuse exhibits striking similarities across countries, despite the aforementioned heterogeneity.

4.1.1. *GIS configuration of the upstream value chain segment*

In the upstream segment of the construction sector's value chain, innovation depends mainly on knowledge that is generated through research and by following scientific methods and principles. This knowledge creation process takes place mostly in universities, research-intensive startups and R&D departments of material suppliers. Research involving experts and scientists from different fields, collaborations with inventors, partnerships with universities and research institutions are all very important elements for the innovation process in this segment.

> *"I think multidisciplinary research is the key answer to solve some of the main challenges we are facing. […] We need the knowledge and science and technology from material scientists, biotechnology, from a bio engineers, or even from the business development guy who has insights of the market. So that's how we are basically able to solve different issues, to come up with new solutions." (Germany_Researcher_1)*

At the same time, also industrial partnerships play a fundamental role for the development of new solutions and innovations, because they can provide important feedbacks, e.g. on current issues that are arising with the use of specific products or materials, which could then be addressed by the scientific partner. In addition, due to their knowledge of the market, industrial partners can also provide suggestions or come up with requests for new products or solutions, which again could be addressed by the scientific counterpart. Therefore, the upstream segment is characterized by strong science-industry linkages. While innovation is developed scientifically and formally, thus following a STI process, also more informal interactions with industrial partners seem to be important for the innovation process, which is a characteristic element of the DUI innovation mode (Alhusen et al., 2021).

Often partnerships transcend regional and national boundaries. Many upstream actors collaborate with international partners in order to develop new sustainable solutions. In general, the location of their partners does not seem to be a determinant factor in deciding which actors to collaborate with. However, the importance of the partners' location fluctuates based on the type of research that is being carried out. In case of research involving just knowledge or data exchanges, partners' location is irrelevant, in case of research involving physical exchanges e.g. of material samples, geographical proximity becomes more important. Knowledge exchange in internationalized networks, e.g. in scientific communities or international professional networks also plays an important role.

> *"We have partners globally, we are already working with [name of partner from UK], we have a couple of partners in Africa, in Ethiopia also, in Germany as well, we went to Constance and also with the University we have collaborated." (India_Startup_1)*

> *"For us in research I would say location is not important, as long as we can work together remotely, also we can work so much together and maybe once or twice a year or three times a year you can meet in a workshop somewhere in Europe or somewhere in Asia. That's fine." (Germany_Researcher_1)*

Innovation valuation in the upstream segment of the value chain, instead, is mainly customized and local. Bio-based materials and solutions for construction purposes are researched and supplied unevenly across different countries and local contexts. There is no global homogenous market, nor global homogeneous technology legitimacy levels for these products. Their market is highly dependent on territorial context and local conditions, first and foremost on the locations where the natural materials necessary for the development and production of bio-based solutions grow in nature. Climatic conditions also have a major impact on what materials can be used and how they can be used in different locations, with local materials often responding better to local climatic conditions, so there is a strong emphasis on sourcing and using local materials, or at least adapting them to different climatic conditions.

"[Product] thickness and the size can also vary and depending on the local conditions and climate we can change the face material. Let's say if you're going to an extreme cold climate, we can change the thickness of the face material and then sandwich the panel, so that will suit the local conditions and also gives the users the kind of comfort which is needed for the inside." (India_Startup_1)

Moreover, since these materials naturally grow in these territories, and are therefore well known and have been used for centuries, there are greater acceptance and legitimacy levels for their use in these areas. It needs to be mentioned that legitimacy-building processes for bio-based solutions are still ongoing and a work in progress. Oftentimes, natural materials were more accepted and widely used centuries ago. When cement and other modern materials entered the game, natural alternatives were increasingly abandoned as deemed outdated, obsolete, and inferior. This shift was evident not only on construction sites but also in academic settings, where traditional construction techniques based on the use of natural materials were gradually phased out and no longer taught. We are now experiencing a slow rediscovery and a renewed interest in them, however globally diversified and still highly dependent on the location where these materials naturally grow.

"Just to give you an example, in Italian universities there was almost a century-long blackout in teaching wood as a construction technique. That is, wood was taught until World War I and World War II. Then with the advent of steel and concrete, wood was no longer taught in any Italian university. To this day this has changed, in Italian faculties there are some professors who now teach a bit about wood on a voluntary basis." (Italy_Supplier_3)

In addition, customers from different countries tend to have differentiated demands, requirements and standards, both from an aesthetical and a practical point of view. Investments and efforts in research and development seem to be focused on those materials for which a local market already exists and for which legitimacy is already (at least partially) built. In addition, national governments norm, set out standards and provide incentives mainly for the use of those materials for which a market already exists or for which there seem to be potential for a market to be created.

"We have partnerships with European and non-European, but mostly European manufacturers who develop products based on what are the demands of the different areas of Europe and North America. And so this comparison becomes very interesting because it allows us to put together a little bit of different expertise and decline it so that we get to have a product that is easier to then not only put on the market, but to last on the market, to create a market." (Italy_Supplier_1)

As the upstream segment is characterized by a predominantly STI innovation mode and a customized innovation valuation, its GIS configuration is found to be mainly market-anchored.

4.1.2. GIS configuration of the core value chain segment

For what concerns the core segment of the bio-based construction sector's value chain, the innovation mode is mainly DUI. Knowledge is, in fact, generated mainly through partnerships and collaborations, with other professionals, with suppliers, with artisans, technicians and planners, who exchange ideas, knowledge and information. Since innovation in this segment mainly consists in new project-based processes, therefore highly project- and context-specific types of innovation, they require the engagement of all the different partners in order to come up with novel solutions specific for the project at stake.

"At the professional level we tend to have [partnerships with] professionals with whom we work all the time. Thermotechnicians, engineers, sometimes geologists. On the other hand, as far as collaboration with businesses and artisans is concerned, it is a more complex thing because there is a lot of exchange of information, there is a lot of improving, that is, I also do training, I give a lot, however I also learn a lot each time. And I leave a lot of room for proposals. And that's throughout the whole process." (Italy_Architect_2)

The partners involved in the realization of the project are normally co-located in the same area, which facilitate face-to-face interaction and knowledge circulation.[2] Proximity and informal knowledge exchange seem to be relevant and to happen especially during the implementation phase of the project.

"We try to work with firms located in Northern Italy, because it is important for us to occasionally meet in person, to see each other, talk to each other and like each other. In our industry the dialogue part is still very important, despite the fact that everything is very computerized. In the sustainability sector especially, the human side has a lot of relevance." (Italy_Engineer_1)

Also, in the case of the core segment, the innovation valuation mode is predominantly customized and local. The implementation of bio-based construction projects is in fact highly place specific and context dependent. Markets do not appear globally homogeneous, and neither do legitimacy levels. As in the case of the upstream segment, market formation is influenced by the location where the natural materials that are necessary for the implementation of the bio-based construction project can be found in nature, as well as by the climatic conditions. Most planners and architects, in fact, try to use mainly locally sourced materials for their construction projects.

"We possibly take the wood from the forest next door, the straw from the farmer who is there, the sand from the local river, also because then the house when it is made with the local earth, with local wood, from my point of view, it has a much better environmental response than a house made with non local materials, both at an aesthetic level, so in terms of shapes, colors, etc., and at the level of just responding to environmental parameters, humidity, heat, etc." (Italy_Architect_2)

Legitimacy does not seem to be standardized for specific materials, nor for bio-based materials in general. Some countries, in fact, seem to accept more the use of natural materials for construction projects than others.

"The problem is getting these good examples that we have here [in Germany] to be accepted by Chinese companies. [...] The Chinese look at it very carefully. And the Germans do it more for, I don't want to say ideological reasons, but for sensible reasons, and they're prepared to spend a lot of money on it." (China_Planner_1)

There are also geographic variations in terms of regulations. There are no quality standards that harmonize market entry barriers in various parts of the world, nor equally favorable regional institutional contexts.

"Some of them [Chinese construction companies] build all over the world, but the focus is clearly on China. If they build in other countries, for example in the US, Mexico and so on, they have to follow these higher local standards." (China_Planner_1)

Differently from the upstream segment, the core segment, which is characterized by a DUI innovation mode and a customized valuation mode, has a spatially sticky GIS configuration. There is therefore a GIS configuration shift along the value chain of the bio-based construction sector, mostly due to the change in the innovation mode between the upstream and the core segment (see Fig. 4). Additional quotes illustrating the GIS dimensions along the value chain are provided in

[2] This might be different in some special cases, for example in star architecture projects (Dreher & Thiel, 2022).

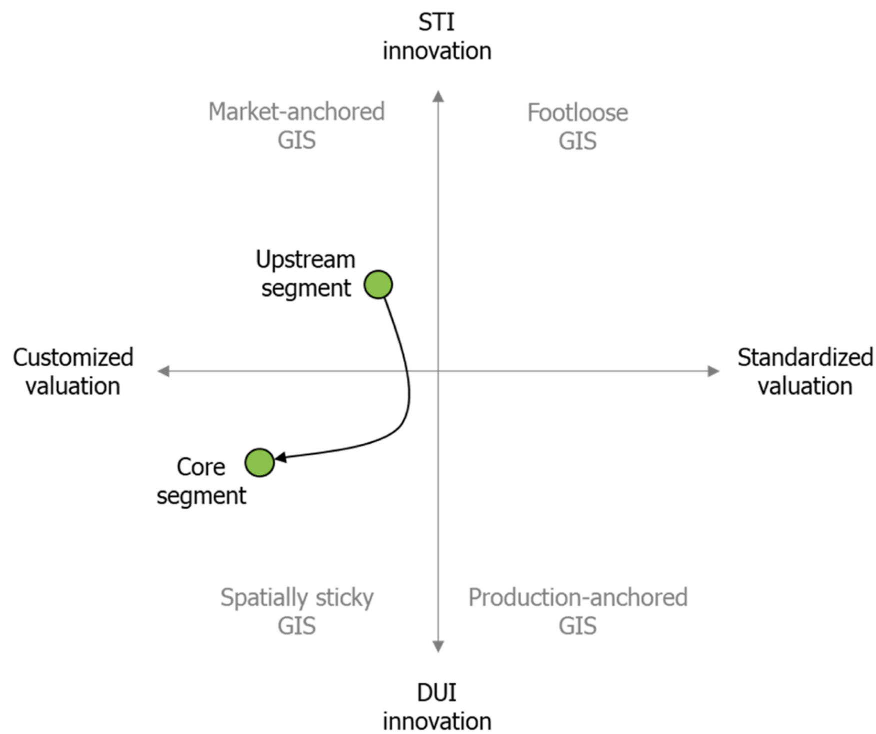

Fig. 4. Shift in GIS configuration between upstream and core segments of the value chain in the bio-based construction sector (template based on Binz & Truffer, 2017: 7).

Table A2 in the appendix.

4.2. The innovation gap 2.0 in the bio-based construction sector

Our results point to the fact that the GIS shift acts as a bottleneck for the sustainability transition of the sector, causing the extensive scientific knowledge developed upstream and built internationally on bio-based construction materials and solutions to not be easily translated and implemented at the core. This bottleneck lies precisely in the translation of the product innovation developed upstream into the project-based process innovation implemented at the core, and therefore causes a slowdown in the diffusion and the scalability of bio-based product innovations. This is mainly due to the shallow contacts and linkages that take place between upstream actors on one side, and core and downstream actors on the other side.

> *"For us there are two key partners: the planning office and the construction company. And from the scientific side, there are relatively few or no points of contact." (China_Architect_1)*

We refer to this bottleneck as an *innovation gap 2.0*. It is particularly pronounced in the bio-based construction sector and compounds the already existing innovation gap identified by Butzin and Rehfeld (2013). Knowledge diffusion and innovation transferability in the construction sector is, in fact, already hindered by the sector's project-based nature, which added to the identified innovation gap 2.0 typical of the bio-based construction sector, makes knowledge and innovation diffusion and therefore the transition towards a bioeconomy in the construction sector even more complicated (Butzin & Rehfeld, 2013; Dreher & Thiel, 2022; Dubois & Gadde, 2002). The innovation gap 2.0 is amplified by a lack of specialized knowledge in the use of bio-based materials for construction projects that we observe especially in the core and the downstream segments of the value chain, and which is mostly due to a scarcity of formal education and training programs taking place in universities and technical schools. Formal education is in fact mostly focused on training technicians, construction workers and planners to deal with conventional construction materials.

> *"In Italian faculties there are some professors who teach a bit about wood on a voluntary basis, but it is not something that is normed at the state level and so it is clear that all the designers who are out there don't know wood very well, they have to do the training afterwards. Also in high school almost all Italian professors don't even talk about wood and bio-based materials in general." (Italy_Supplier_3)*

The knowledge gap is being increasingly acknowledged by actors active in the sector, who are adopting different strategies in order to close it. First of all, more and more actors are starting to provide educational and training programs on how to use bio-based materials, in order to compensate for the lack of formal education, as well as to make bio-based constructions more widely understood and accepted. This is being done both for economic reasons, in fact they need it in order to survive on the market and expand their market; as well as ethical reasons, the vast majority of actors involved in the sector strongly believes in the need for the bio-based transition of the construction sector to take place, and is committed to play an active role in order to make it possible. Core actors appear to be mainly focused on educating and training downstream actors, artisans and construction workers in particular. That is because in order to implement their construction projects they need specialized workers who are familiar with the necessary techniques required to build with bio-based materials. For what concerns upstream actors, instead, they tend to educate and train both core and downstream actors, so to make sure their bio-based products will be included in the planning of the construction projects and proficiently utilized by construction workers.

> *"We had to create the demand. How? Through education and training. So in the early years we invested, and we continue to invest a lot, in training. We tried to make technicians understand that there were new materials. Through courses, through discussions, organised events, we presented our opportunities and started to create movement." (Italy_Supplier_4)*

Moreover, in an attempt to address the identified knowledge gap, upstream actors are increasingly expanding their role in the construction sector, positioning themselves along the entire value chain, therefore providing multiple services and acting not only as suppliers and educators but also as construction firms and, in some cases, planners as well (see Fig. 5). We define these actors as *integrated bio-based construction firms*, as they integrate different services that would normally be provided by other actors.

The value chain of the integrated bio-based construction sector, instead of having a standard structure, as represented in Fig. 2, will tend to have a more integrated structure, as represented in Fig. 5. This is due to the fact that the innovation gap 2.0, which is also caused by a lack of skilled workforce that can implement the knowledge produced upstream, leads upstream actors, suppliers in particular, to provide also services that normally core and downstream actors would provide, consequently leading to a more integrated value chain.

These *integrated bio-based construction firms* typically start their business as bio-based materials' suppliers. However, they often find that there is no market for their products due to a general lack of knowledge about how to use these materials, coupled with strong skepticism and resistance towards adopting products and construction techniques that deviate from conventional norms. In response to these challenges, these firms begin to diversify, integrating additional activities and services into their business operations. Thus, they expand along the value chain and evolve into integrated construction firms specialized in the use of the bio-based products they supply. Sometimes, they provide also planning services, therefore employing architects or engineers that are specialized in the planning of bio-based construction projects.

> *"Yes, we are suppliers, manufacturers and builders. We had to become builders because nobody was paying attention, we were not taken seriously by anyone [since they were supplying bio-based materials]" (Italy_Supplier_7)*

An alternative but closely related tendency of upstream actors is the one to not integrate all these different services within one single firm, but to closely and continuously collaborate with planners and construction workers that they trained through the educational programs they provided. The result is the same obtained by the integrated bio-based construction firms: they manage to overcome the scarcity of specialized construction workers and professionals interested and able to handle alternative bio-based materials.

While the identified innovation gap 2.0 seems to be a distinctive feature of the bio-based construction sector, as highly impacted by some of its distinctive characteristics, it is possible that a similar innovation gap might arise also in other bio-based industries due to a likely shortage of skilled workforce capable of handling 'new' bio-based materials, which remain niche in many sectors. However, we leave this matter to be explored in future research.

4.3. A (global) transition towards a bio-based construction sector?

The existing literature on barriers to the transition of the construction sector towards more sustainable modes of production has primarily emphasized supply-side factors, such as the availability of (bio-based) materials, and demand-side factors such as consumer preferences, costs, as well as regulations and norms that might hinder an increased use of bio-based construction materials (Kylkilahti et al., 2020; Riala & Ilola, 2014; Winder & Bobar, 2018). The findings of these studies align closely with the core concepts of the sustainability transitions literature. They demonstrate that the socio-technical configurations of a sector manifest across various dimensions, including technology, material supply, and socio-institutional aspects. This results in a rigid regime logic that is difficult to transform (Köhler et al., 2019; Markard et al., 2012).

While many of such studies bear only an implicit geographical perspective, our research instead advances these insights by informing how innovation activities that enable transitions are spatially organized in both the upstream segment of the sector and the core segment.

Our results demonstrate that the transition towards a more sustainable and bio-based construction sector has profound implications not only on the innovation system configuration of the sector, but also on the organization of its value chain, which we expect to become more integrated the more the sector transitions towards a bioeconomy (see also Mast, 2022). We expect this transition to be easier for countries where the construction sector's value chain is not excessively fragmented and more complex for countries where the value chain is more disaggregated. The Chinese construction sector, for instance, is characterized by a more fragmented value chain that involves the work of many different actors in order to implement a construction project. Therefore, we expect they might go through more complex challenges in integrating different activities within one single organization and therefore in moving towards a bio-based transition of the sector. For Germany, on the other hand, we find that the innovation gap is less pronounced between material suppliers (upstream) and architects or engineers (core), but rather strong further down the value chain, with a lack of knowledge and skills in construction firms and craftsmen (downstream), preventing the realization of the bio-based building projects as designed. We attribute this to the fact that the transition to a bio-based construction sector is more advanced in Germany than in the other countries studied.

We expect that the future transition towards a bio-based construction sector will vary considerably between countries, both in terms of pace and in terms of preferred materials and building techniques. Currently, China and India mostly focus on bamboo for their bio-based construction projects, while Germany and Italy emphasize the use of wood. However, each country tends to approach these materials differently and to prioritize different construction techniques. In China, the emphasis is

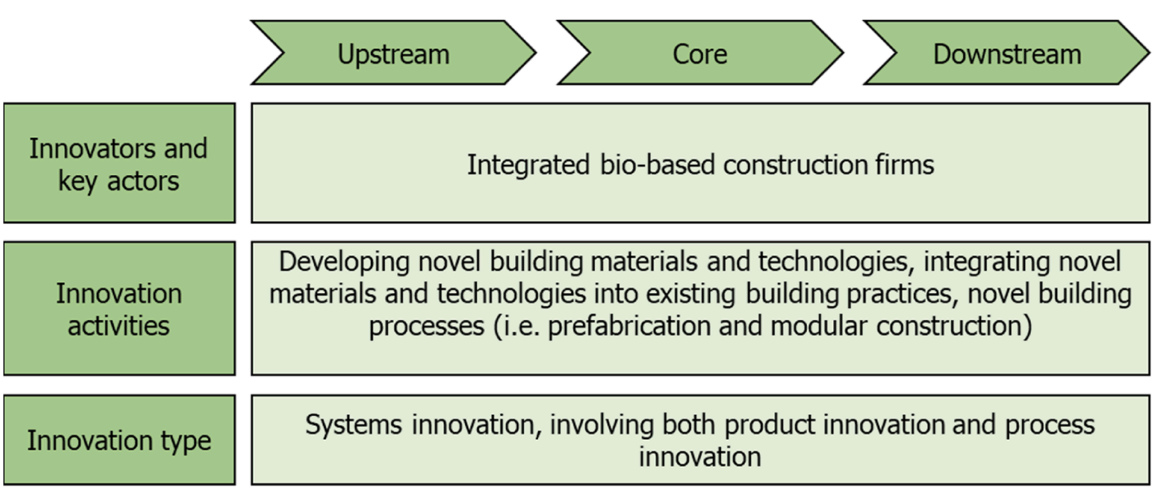

Fig. 5. Stylized value chain in the integrated bio-based construction sector.

on the use of engineered bamboo, while India, on the other hand, adopts a more frugal approach to the use of bamboo. In Italy, instead, wood is still used in more traditional ways, while Germany prioritizes modular and serial timber constructions. Looking ahead, the pace of the transition towards a bio-based construction sector and the transformative potential will differ significantly among these countries. As rapidly developing and growing countries, we expect China and India to possess high transformational potential and to advance swiftly in the sector. Germany and Italy are also making notable strides towards a bio-based construction sector, with Germany being in a leading position as benefiting from a strong industrial base, innovative construction techniques, and comprehensive sustainability policies.

This divergence may also manifest at the regional level, with some regions leading the way while others follow suit (on which see Fastenrath, 2018; Jayaweera et al., 2023). This is consistent with previous research on the geography of sustainability transitions, which demonstrates that transition processes unfold heterogeneously across different areas, with some regions or countries leading globally (Hansen & Coenen, 2015; Losacker & Liefner, 2020).

Although (regional) transition pathways might differ, we argue it is interesting to acknowledge that, at the same time, the innovation mode and valuation mode in the bio-based construction sectors are found to be very similar across countries and across different bio-based innovations. This includes a highly localized and customized valuation dimension taking shape in local legitimation processes and local market formation processes, which has also been observed in transition studies for other sectors (Dewald & Truffer, 2012; Rohe, 2020).

Against this background, it is questionable to what extent the global regime in the construction sector, currently mainly organized around the use of cement and steel, might be disrupted by a new (bio-based) socio-technical configuration, as is imagined by several researchers (Churkina et al., 2020; Mishra et al., 2022). Given the heterogeneity and local specificity in the valuation of bio-based construction materials and techniques observed in our study, it is likely that there will not be a new global regime in the future, but rather a multitude of localized socio-technical configurations, providing an interesting case for further research on the geography of transitions in the (bio-based) construction sector (following e.g., Binz et al., 2020; Fuenfschilling & Binz, 2018; Miörner & Binz, 2021). However, we leave this issue for future researchers to explore.

5. Conclusion

In light of the ongoing transition towards a bioeconomy in the construction sector, this paper aimed to answer the following research question: How is the multi-scalar configuration of the global innovation system of the bio-based construction sector organized along its value chain, and what does this imply for the sector's sustainability transition? For this purpose, the paper utilized the global innovation systems framework to understand the spatial configuration of both the upstream and core segments of the value chain, emerging from the predominant modes of innovation and valuation. The paper aligns with the line of reasoning that has recently emerged in the literature on GIS, highlighting the significance of a value chain perspective on innovation activities (Hipp & Binz, 2020; Malhotra et al., 2019; Rohe, 2020; van Welie et al., 2019).

The results suggest that innovation activities in the upstream part of the value chain, primarily concerning novel bio-based materials, are characterized by a market-anchored GIS configuration. Conversely, innovation in the core part, which primarily involves novel building techniques and process innovation, is distinguished by a spatially sticky GIS configuration. Accordingly, we observe a shift in the mode of innovation along the value chain. Our empirical findings suggest that this shift may act as a bottleneck for the sustainability transition of the sector. This is because the extensive scientific knowledge developed upstream, which is built internationally on bio-based construction materials and solutions, may not be easily translated and implemented at the core. This bottleneck primarily lies in the translation of product innovations developed upstream into the project-based process innovations implemented at the core.

Our findings carry significant implications for policymakers and stakeholders in the construction sector who are striving to advance the bioeconomy transition within the sector. Firstly, our research underscores that transitioning to a bioeconomy involves more than just substituting carbon-intensive building materials (such as steel and cement) with bio-based alternatives (like engineered bamboo and cross-laminated timber) and exploring innovative building and engineering techniques suited to these materials (see also Giurca & Befort, 2023). Rather, the transition also precipitates substantial changes in the organization of the sector's value chain. Secondly, our study reveals that bio-based construction is highly localized in terms of market formation and legitimacy dynamics, which markedly differs from the widespread mass markets characteristic of conventional carbon-intensive building materials (Dewald & Achternbosch, 2016). Therefore, support measures for the bio-based construction sector must take the local context into account. If the bio-based construction sector is to evolve into a global (mass) market, substantial institutional support will be essential.

Despite the valuable insights provided by the study, there are few potential limitations that should be acknowledged. Firstly, the analysis mainly focuses on the upstream and the core segments of the value chain, while the downstream one has been left out. Even though we have good reasons not to focus on this segment, as explained in Section 2.2, its exclusion may still result in a partially incomplete picture of the innovation landscape of the bio-based construction sector. The second potential limitation is linked to the data used. As in any qualitative study, subjectivity and bias both from the interviewer and interviewee part might be present. However, we took various steps in order to ensure validity and robustness of our findings.

From a scholarly perspective, our paper enriches the literature on the geography of innovation and sustainability transitions by offering insights into how the multi-scalar configuration of innovation system resources can vary along a sector's value chain and demonstrating how the configuration of innovation systems can evolve during ongoing transition processes. In doing so, the paper aligns with recent dynamic perspectives on the formation of global innovation systems (Heiberg & Truffer, 2022). Moreover, our work adds to the emerging literature on innovation systems in the bioeconomy (Befort, 2023; Losacker et al., 2023) by elucidating the multi-scalar nature of resource formation, which, in the context of the construction sector, tends to be highly localized.

CRediT authorship contribution statement

Francesca Mazzoni: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sebastian Losacker:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests

Sebastian Losacker reports financial support was provided by German Federal Ministry of Education and Research (BMBF). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Tab. A1
Selected interview questions investigating innovation and valuation modes along the value chain

GIS dimension	Selected interview questions
Innovation mode	*In your company how do you develop new sustainable solutions and innovations?* *What is the role of cooperation, collaboration and partnerships for the innovation process of your company?* *Where are the most important partners that you need for the innovation process of your company geographically located? How important is their location to you?* *What is more important for the development of sustainable innovations in your company: collaboration with scientific partners or with industry partners?*
Valuation mode	*What role do local conditions play for the success of the project?* *Do you think that the project could have been realized elsewhere?* *How does the market for your sustainable solutions look like?* *Who are your customers and what are their demands?* *Where are your customers geographically located?* *How do your customers perceive/accept your sustainable solutions?* *What is important for the market expansion and scaling of your sustainable solution?*

Note: The questions were adjusted and modified based on the category of interviewed stakeholder and its position along the value chain

Tab. A2
Selected quotes demonstrating innovation and valuation modes along the value chain

Value chain segment	GIS dimension	Selected quotes
Upstream	Innovation mode	*"[name of the inventor] has already launched various patents on the basis of timber construction systems. And we simply recognized this potential, teamed up with him, took over his patent, his most promising patents, and further developed these systems in collaboration with [name of the inventor], who continues to act as an external consultant for us." (Germany_Startup_2)* *"Some of them [partners] are in China, but majority are all international based who drive the real changing of things. So we work with teams from US, Germany, Japan, Canada, Denmark, you name it. It's all around the world" (China_Startup_1)* *"If we're talking about some kind of data exchange, on the basis of which something is developed, then it doesn't matter where you're sitting. If it's really about concrete logistics processes that have no prospect of improving, of course, that's relevant. But I believe that solutions can always be found everywhere. Accordingly, I would not restrict myself in any way" (Germany_Startup_2)* *"We are in international and truly international societies in exchange with other universities. In the wood sector, for example, there is the organization "Inter" International Network of Timber Engineering and Research. We meet annually in this network and discuss research in the field of wood." (Germany_Researcher_2)*
Upstream	Valuation mode	*"I use mud, the local mud from the site, which I excavate to some extent from the foundation. And I use locally available timber within a few kilometers radius, and bamboo as another one and any other agri-based product that I can get my hands on." (India_Researcher_4)* *"I built a prefabricated house, which was for a client from Rome, and sent it in 2003. Now, the Rome climate is different from Bangalore climate in India. Now, how do we give that insulation there? For that we use foam insulation. But then again, I changed it from what we were doing to something which the climate would need there, with some kind of insulation or some kind of a panel from inside, and then putting a foam instead of plaster from inside." (India_Researcher_4)* *"We must have materials that are certified and therefore come from certain sources. In order to supply our products, we are trying to move around our area, even limiting the offer, saying we cannot offer all the colors in the world, we have these colors around and we use and supply these ones, otherwise it is not consistent [with their sustainability-related beliefs and mission]. Maybe we strive to improve the range of colors we can offer, but we would not go and buy it on the other side of the planet." (Italy_Supplier_5)* *"I would ideally see a scenario where we can continue to produce locally, but in other markets. So you could use local resources, you could implement the successes you've developed from this market and adapt them to the local species and different environments there, to have also local success there because the resource is there. I think it would also help and support the local economy." (China_ Startup_1)*
Core	Innovation mode	*"We have different collaborations in my business, I would say, first among architects. We like to do that for two reasons. On the one hand, to learn from each other, to exchange ideas. But to be honest, we're not usually a large group of architects, and it's quite common for us to do so in order to increase our economic clout. Collaboration with other disciplines is enormously important, as a generalist architect you need the expertise of specialist engineers, because you definitely need them to help you develop what you want." (Germany_Architect_2)* *"The companies I look for are in a close range, obviously not too far away because it has to be sustainable even from the economic point of view" (Italy_Architect_2)* *"I'm part of an association of architects. As part of this group we continually stimulate each other and we are stimulated by new materials and possibilities. It is an association that has as its goal, among other things, to provide training among the members, but also in schools, in companies and, if necessary, it provides support to members for their projects. It is also in this context that I learnt how to design sustainably." (Italy_Architect_3)*
Core	Valuation mode	*"A sustainable construction project is not standardizable. The project depends on the place, for example bioclimatic is fundamental for a project. So, knowledge of the place, knowledge of the inhabitant is fundamental, so every project has to start from scratch. And that is the fascination of architecture." (Italy_Architect_3)* *"When it comes to the building process, we try to be extremely local. So, using local resources and if we don't have the skills locally, we either skill workers ourselves if we know we have the skill or we have the competence. Otherwise, we call people in to skill the local labor." (India_Architect_3)* *"Timber construction makes a lot of sense if you do it where wood is available. If you now have a project in Saudi Arabia, that might not play a role. For example, we are building a nursing home entirely in wood. Of course, I would never build that in a country where there is simply no wood." (Germany_Engineer_1)*

Tab. A3
Characteristics of interviewees and companies considered in the study

Interview name	Interviewee role	Organization size	Organization details
China_Startup_1	CEO	Medium	Engineered bamboo supplier
China_Supplier_1	CEO	Large	Bamboo construction material supplier
China_Supplier_2	Sales Director	Large	Bamboo construction material supplier
China_Architect_1	CEO	Medium	Construction project management and consulting company
China_Architect_3	Managing Director	Medium	Architectural firm focused on sustainable building solutions
China_Architect_4	Co-Founder; Professor	Large	International architecture firm, research on sustainable architecture
China_Architect_8	Founder; CEO	Small	Architectural firm focused on bamboo architecture
China_Architect_10	Architect and Co-founder	Medium	Architectural firm focused on sustainable and bio-based architecture
China_Designer_2	Director	Small	Bamboo design center
China_Researcher_1	Professor	Medium	Research on bio-based construction materials
China_Researcher_2	Professor	Small	Research on bio-based construction materials
China_Researcher_3	Professor	Medium	Research on sustainable and bio-based architecture
China_Researcher_4	Professor	Big	Research on bamboo construction materials
Italy_Supplier_1	Technical sales manager; Architect	Small	Supplier of clay, wood and other natural materials
Italy_Supplier_2	Marketing & communication	Small	Supplier of cork products
Italy_Supplier_3	CEO	Medium	Supplier of wood and laminated timber
Italy_Supplier_4	CEO	Small	Supplier of hemp products
Italy_Supplier_5	CEO; Architect	Small	Supplier and construction company focused on clay
Italy_Supplier_6	Sales manager	Big	Supplier of wood
Italy_Supplier_7	CEO	Small	Supplier and construction company focused on different natural materials
Italy_Supplier_8	CEO	Small	Supplier and construction company focused on wood
Italy_Supplier_9	CEO	Small	Supplier and construction company focused on different natural materials
Italy_Startup_1	CEO; Architect	Small	Suppliers of materials derived from recycled natural waste
Italy_Planner_1	CEO; Engineer	Medium	Planning studio focused on wood constructions
Italy_Architect_1	Architect & Engineer; R&D specialist	Big	Architectural firm focused on sustainable constructions
Italy_Architect_2	Architect & Engineer	Small	Architectural firm focused on bio-based architecture (raw earth, bamboo, straws)
Italy_Architect_3	Architecture studio founder; Architect	Small	Architectural firm focused on bio-based architecture
Italy_Architect_4	Associate architect; Project leader	Big	Architectural firm focused on sustainable buildings
Italy_Architect_5	Architecture studio founder; Architect	Small	Architectural firm focused on bio-based architecture (wood)
Italy_Engineer_1	Associate engineer	Medium	Engineering firm focused on wood constructions
India_Supplier_3	CEO	Medium	Supplier and construction company focused on bamboo
India_Supplier_11	Managing Director	Medium	Supplier and construction company focused on bamboo, mud, recycled wood
India_Architect_3	CEO; Architect	Small	Architectural firm focused on stabilized earth architecture
India_Architect_2	CEO; Project manager	Medium	Non-profit organization for sustainable housing
India_Architect_4	Founder & Architect (2 interviewees)	Medium	Architectural firm focused on earth construction & intelligent water and sanitation designs
India_Architect_6	CEO	Medium	Architecture Consultancy focusing on bio-based resources such as waste or flyash.
India_Architect_8	Founder	Medium	Architectural firm focused on incorporating earth into conventional constructions
India_Startup_1	CEO	Small	Provider of a novel biobased technology for constructing walls
India_Startup_2	CEO	Small	Supplier of bio-based bricks
India_Researcher_2	Consultant; Researcher	Medium	Research institute for bamboo & international consulting firm
India_Researcher_3	Executive director; Architect	Medium	Research institute focused on raw earth construction and architecture
India_Researcher_4	CEO; Architect	Big	Bamboo advocate: R&D, architecture, education & training
Germany_Startup_1	Co-CEO	Small	Designer of circular masonry systems and bricks
Germany_Startup_2	Head of Public Relations	Small	Suppliers of timber and modular wooden building blocks
Germany_Architect_1	Project Manager	Medium	Architectural firm focused on wood constructions
Germany_Architect_2	Business Owner; Architect	Medium	Architectural firm focused on wood constructions
Germany_Architect_3	Business Owner; Architect	Small	Architectural firm focused on repurposing/upgrading existing buildings with sustainable materials
Germany_Architect_4	Business Owner; Architect	Medium	Architectural firm focused on wood constructions
Germany_Researcher_1	Head of Research	Big	Research institute focused on bio-based building materials
Germany_Researcher2	Professor	Big	Research institute focused on timber construction
Germany_Supplier_2	Key Account Management	Large	Supplier of cross-laminated timber
Germany_Planner_1	Business Owner	Medium	Planning firm focused on timber construction
Germany_Engineer_1	Founder	Medium	Engineering firm focused on sustainable projects
Germany_Engineer_2	Team Leader; Engineer	Medium	Planning firm focused on timber construction projects
Germany_ Engineer_3	Head of Sustainable Structures	Small	Engineering firm focused on wood constructions

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