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Scaling up of hydrogen supply chains: the role of supply chain governance

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ABSTRACT

The purpose of this study is to explore if and how interfirm governance can foster the scaling up of hydrogen supply chains. We applied an interview study approach conducting semi-structured interviews with 13 experts from hydrogen production, storage, transportation, and utilization. This research shows that the industry background and the engagement intentions of actors, as well as political funding programs, strongly influence the choice of governance mechanisms to coordinate the scaling up of hydrogen supply chains. While formal governance mechanisms are mainly used for economic safeguarding, informal mechanisms enable the tremendous level of collective learning necessary for the scaling up of hydrogen supply chains. Novel theoretical and managerial insights are provided regarding the influence of governance mechanisms on the scaling up process and showing the importance of collective learning when building hydrogen supply chains.

KEYWORDS: Scaling Up · Hydrogen · Supply chain · Governance · Mechanism · Collective Learning

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1 INTRODUCTION

Sustainably produced, *green* hydrogen has a low carbon footprint and is an important component of politically driven decarbonization projects [1, 2]. Green hydrogen is used as a climate-friendly energy carrier, specifically in climate-critical industrial sectors (e.g., steel industry or heavy duty mobility) [3, 4] and is thus considered to have high market potential, due to its energetic and material nature.

However, sustainable hydrogen does not exist as a naturally occurring resource [5], but must be produced, stored, and transported in multi-layered processes in hydrogen supply chains (HSC) before it can be used [6]. HSCs currently have very low capacity. However, high amounts of green hydrogen are required to implement green hydrogen as a component of the politically driven decarbonization process. Thus, HSCs have to increase their hydrogen production and delivery rates [7]. Such a process of scaling up involves several different actors and companies whose activities need to be coordinated when increasing the capacity. The decisions and actions of hydrogen producers, transporters, and end users must be aligned, for example, regarding delivery quantities and timing, to optimally determine, e.g., the means of transport (e.g., by pipeline or truck) [8].

The coordination and management of interfirm activities are done using interfirm governance (also called supply chain governance) [9]. Interfirm governance provides a decision making framework for transactions in which governance mechanisms (GM) are used to influence partners actively [10]. GMs are selected according to the given external factors influencing an interfirm relationship, but also according to the internal aspects of the business relationship [11]. In this study, we aim to show how GMs can be used to foster and coordinate the scaling up process of HSCs.

There is already a broad base of literature on HSCs [e.g., 12–14] and also on scaling up of supply chains in general [e.g., 15, 16]. Previous research on HSCs has focused, for example, on the different planning tasks and challenges of the individual stages of supply chains

[e.g., 17]. However, research on the governance of HSCs in general and also on the governance for scaling up of HSCs is scarce. Existing scaling up studies from other industries [18] are difficult to transfer to the unique settings of HSCs due to the high relevance of political actors, high investments, and technologies, which require extensive development to be adapted to the capacities of future HSCs. Knowledge from existing governance research [11] can also only hardly be transferred to HSCs as high investments and technologies (e.g., pipelines) enforce long-term partnerships, while political actors can foster and hamper the exchange between partners (e.g., political funding programs vs. anti-trust laws).

To enable a successful scaling up of HSCs, it is important to coordinate and align the decisions and activities of all partners. Thus, GMs should be identified that consider the challenging characteristics of the partners (e.g., different industry backgrounds, conflicting interests) and of the processes (e.g., application of novel technologies). Therefore, the contextual factors and intentions influencing the selection and functioning of GMs should be investigated to fully understand their mode of action in the unique environment of HSCs. Thus, the objective of this research is to analyze the role of interfirm governance in the scaling up of HSCs. We examine how GMs are used to coordinate the actors and safeguard their business activities in the process of scaling up. The following research question arises from this research objective:

RQ1: *Which contextual factors influence the choice and the functioning of governance mechanisms in the scaling up of hydrogen supply chains?*

RQ2: *How do governance mechanisms enable and foster the scaling up of hydrogen supply chains?*

The study offers various managerial implications and theoretically contributes to the operations and logistics literature. We show how formal and informal GMs help coordinate the scaling up of HSCs. Thereby, we highlight the unique contextual factors of HSCs influencing the choice of GMs, showing that external factors like political funding programs and regulations as well as internal factors like the relationship history between actors are decisive in the choice of GMs. Further, we highlight that informal GMs have a particularly positive impact on the scaling up process of HSCs, while formal GMs mainly have a safeguarding role. Next to the general outcomes of governance systems in HSCs, we emphasize the role of collective learning in the process of scaling up and explain how joint technical developments and structural network integration can contribute to scaling up of HSCs. To deepen the contribution of the study, we formulated propositions that point out the most remarkable findings of this study.

2. THEORETICAL BACKGROUND

2.1 Structure of Hydrogen Supply chains

Based on the structure of fossil raw material supply chains [19], we divided the examined HSCs into three sections: upstream, midstream, and downstream.

The upstream section covers the hydrogen production. There are various options to produce hydrogen. The largest quantities of hydrogen are produced conventionally, using fossil primary energy carriers such as crude oil or natural gas [20]. Next to this conventional, emission-intensive form of hydrogen production, there are options to produce hydrogen with lower levels of emissions [21]. Hydrogen can be produced using electrolysis with sustainably produced electricity, e.g., from photovoltaic or wind power plants [20, 22].

The upstream section is followed by the midstream section, which includes the transportation and storage of hydrogen. Hydrogen can be transported, e.g., by trucks, trains, or ships [6, 17] and pipelines [24]. Yang and Ogden [25] describe several factors influencing the choice of the means of transportation, e.g., the amount of hydrogen or the transport distance.

Additionally, to the decision regarding the means of transportation, choices regarding the hydrogen form while transporting and storing are also major tasks in the midstream section. Hydrogen has a low volumetric energy density and is processed before being transported over longer distances. One possibility to transport hydrogen more efficiently is to increase the pressure of the hydrogen, to change the aggregate state of the hydrogen, or to bind it to another chemical carrier [26]. Hydrogen, for example, can be temporarily liquefied with a high energy input [27], which allows a further increase in volumetric energy density and, thus, a more efficient transport [26].

Next to the efficiency- and safety-related hydrogen processing, hydrogen storage is another process step in the midstream section. Hydrogen storages are used to absorb disruptions in hydrogen production or to compensate for fluctuating demand volumes [6, 19, 20].

The midstream section is followed by the downstream section, which comprises the various hydrogen consumers. Industrial companies, such as refineries, or companies from the chemical industry, are important hydrogen consumers [28]. Next to the industrial sector, companies from the mobility sector are key actors in the downstream section. Especially actors in heavy-duty mobility are keen on using hydrogen as a fuel for trains, trucks, ships, or air crafts [3, 29].

2.2 Supply Chain Governance

Supply chain governance also referred to as interfirm governance, is an overarching framework for decision

making processes in business relationships [30, 31]. The goal of supply chain governance is to manage interfirm business relationships [32], coordinate the behavior of actors [33], and safeguard against opportunism [34]. GMs are used to actively influence the behavior of partners [10] and are generally categorized as formal and informal mechanisms [9]. Formal mechanisms are characterized by their controlling and structuring aspects. Specifically, contracts, but also other controlling mechanisms such as audits and monitoring, are classified as formal mechanisms [11, 35]. In contrast to formal mechanisms, informal mechanisms (also called social or relational mechanisms) influence the behavior of partners based on interpersonal and social aspects [36–38].

In the literature, research on supply chain governance is often theoretically supported by Williamson's [39] transaction cost theory [e.g., 40, 41]. Transaction cost theory explains how transactions between two or more parties are organized and processed and why certain actors behave in certain ways. The theory assumes that the transaction costs themselves should be minimized and that partners only act with bounded rationality and opportunistically. Bounded rationality refers to the fact that actors cannot know and process all relevant information about a transaction. Opportunism refers to actors' interest in maximizing their own benefits, even when doing so might harm the interfirm relationship.

The objectives of supply chain governance can be explained using the transaction cost theory. First of all, the behavior of partners is influenced with the help of GMs in order to minimize transaction costs. Additionally, GMs can be used, for example, to stimulate the timely exchange of information and data before a transaction and thus increase rationality [39, 42]. The tendency towards opportunism in interfirm relationships, which is assumed according to the transaction cost theory, can also be reduced by using supply chain governance [43]. Sheng et al. [44] show, for example, that the use of contracts, but also relational GM, such as flexibility or information sharing, reduces the likelihood of opportunistic behavior.

The governance of supply chains and networks plays an important role in the literature and is often addressed [45–49], whereby the distinction between formal and informal GMs is often used to explain the functioning of GMs [50] (see Table 1). In particular, the interplay between the two types of GMs is discussed extensively [51]. Especially in the beginning of business relationships, formal GMs are used to coordinate the partners. At the same time, coordination with informal GMs is challenging, as there is usually no mutual trust

Table 1: Formal and Informal Governance Mechanisms [11]

Governance Mechanisms	Examples of Mechanisms	Explanation and Effects
Formal Mechanisms: Influencing partners' behavior in a structured and partly bureaucratic way.	Contracts	- Definition of decisions rights, prices, purchasing conditions, quality levels, etc. - Sharing revenue and risks between partners [56]
	Formal information sharing	- Intended sharing of information and data, mostly via data exchange systems or reports [57] - Sharing of strategic and operational data (e.g., real-time demand data or material flow), which is used for decision making [58]
	Audits and Monitoring	- Constant and close observation of partners' behavior to enforce rules and contracts [59] - Announced and unannounced control dates to inspect, e.g., partners' production facilities [30]
	Shared Standards	- Common definition of certain characteristics of interfirm collaborations (e.g., data exchange standards) [60] - Common definition of certain characteristics of the product being exchanged (e.g., sustainability or quality standards) [61]
Informal Mechanisms: Influencing partners' behavior on the social relationship level.	Informal information sharing	- Interpersonal information exchanges in meetings, emails, or conversations [57] - Reliance on informal information sharing depends on the culture and size of the companies [62]
	Trust	- Confidence that partner will not behave opportunistically - Enables extensive information sharing - Fosters investments in interfirm relationships [63]
	Common Norms and Values	- Shared beliefs on how to structure a business relationship and how to behave in transactions [64] - Shared norms and values as the basis for informal governance [65]

between the partners yet [38]. However, formal GMs, like contracts, are inflexible and incomplete, leaving room for opportunistic behavior [52, 53]. Therefore, informal GMs coordinate the partners beyond the limitations of formal mechanisms. They foster the willingness to comprise in business relationships based on the striving for long-term success of the relationship rather than short-term individual profits [53, 54]. Thus, Poppo and Zenger [35] state that formal and informal GMs are used as complements to achieve efficient coordination and proper safeguarding in business relationships. While the complementary use of formal and informal GMs is recognized in the scientific community, some research articles also show opposing effects of formal and informal GMs. Malhotra and Murnighan [55] show an example that formal, binding contracts increase cooperation between partners but decrease trust between partners.

Next to the interplays between the GMs, the literature also highlights the importance of considering the different contextual factors influencing the effectiveness of GMs when aiming to fully understand the functioning of GMs [51]. Pilbeam et al. [11] summarize various factors affecting the choice, functioning, and effectiveness of GMs, e.g., the effects of globalization, uncertainties, or business relationship characteristics. A joint history of the partners (number of transactions, duration of the relationship, etc.) can foster, e.g., the usage of informal GMs. In contrast, the need for standardized rules in globalized import and export relationships urges the use of formal GMs.

The governance of HSCs has not been studied in the literature yet. However, regarding the complex processes and actions of the involved actors, the governance of HSCs is important to align the different activities and interests to foster the quantitative scaling up of the network capacity. Thereby, a special focus should be on the unique contextual factors of HSCs (e.g., application of new technologies, or different conflicting industry backgrounds), influencing the governance to fully understand the functioning of GMs in the novel setting of scaling up HSCs.

2.3 Collective Learning for the Scaling up of Supply Chains

Past literature shows that scaling up processes includes learning how to structure and manage the growing processes of supply chains and also how to apply new technologies [e.g., 15, 18]. Generally, learning in organizations and supply chains has been studied in the operations and logistics literature for some time. Learning in organizations refers to collecting and generating knowledge that allows actors to perform activities more efficiently or learn new activities [66]. During the learning process, organizations analyze former behavior and draw conclusions to improve future activities [67]. A general distinction is made between single loop, double loop, and deutero learning [68, 69]. Single loop learning refers to improvements within an existing, well-proven framework (e.g., a process), which will only be slightly adapted. Double loop learning extensively changes or shifts the complete framework and therefore requires multiple adaptation rounds [68]. Next to single and double loop learning, deutero learning is also discussed in the literature, referring to "the creation of norms, rules, and conditions by which these knowledge creation processes may be done best" [70].

Additionally to the distinction between single loop, double loop, and deuteron learning, literature additionally distinguishes between strategic and technology learning. Strategic learning refers to the strategic re-orientation of business relationships. Kuwada [71, p. 723] assigns two characteristics to strategic learning: "First, strategic learning tends to be learning without questioning of the validity of assumptions rather than learning through trial and error. Second, strategic learning includes the process of distilling corporate-level knowledge from business-level knowledge. It is learning from indirect experiences." Technology learning (also called technological learning) refers to all efforts to improve operational, duplicative, adaptive, and innovative capabilities regarding technologies [72, 73].

Learning within organizations can also be transferred to collective learning within supply chains. Collective learning in supply chains involves actors from several different organizations. The actors of the different organizations exchange information or analyze previous activities and derive new knowledge that allows them to improve their own or joint processes in the future [66]. Collective learning in supply chains is challenging because the different organizations may pursue different interests and behave opportunistically during the learning process [74]. To reconcile the different interests in supply chains and to coordinate the activities of organizations, interfirm governance must be designed accordingly [11], in our case, to enable collective learning. Soundarajan et al. [75], for example, explain that collective learning is specifically fostered through an agile governance design and that top-down governance tends to hinder the process of collective learning. Additionally, Ghosh and Fedorowicz [63] show which GMs should be used for coordination and performance improvements, which in turn enhance collective learning.

We argue that to fully understand how supply chain governance enables and promotes the scaling up of supply chains, we also need to analyze how supply chain governance enhances collective learning. Companies need to learn how to strategically structure and manage growing supply chains, and how to apply new technologies to successfully scale up supply chains. Despite conducting a comprehensive literature review in several databases (viz. Google Scholar, Academic Search Elite, Business Source Complete), we could not find any papers clarifying which GMs should be used to enhance collective learning in HSCs.

However, companies aiming to improve collective learning should know which GMs are used to enable, promote, and coordinate collective learning, despite, e.g., different interests in the business relationship. Therefore, we also aim to investigate which GMs should be used to not only coordinate the scaling up of HSCs but also to enable collective learning during the process of scaling up.

3. METHODOLOGY

Qualitative research approaches enable the analysis of multi-layered cause-and-effect relationships of current 'real-world' phenomena [e.g., 42]. The complex correlations of supply chain governance when scaling up HSCs are such a real-world phenomenon. In this study, we apply our knowledge of supply chain governance and the transaction cost theory to deductively explain the coordination of actors in the scaling up of HSCs. As a basis of our research, we conducted an expert interview study, whose exploratory design will help to achieve the research goal. Expert interviews have proven to be an efficient data collection method in the past [e.g., 75, 76]. To structure our interview study, we adapted the case study approach from Yin [76], which can be divided into four steps: planning, design, and preparation, data collection, data analysis, and sharing.

3.1 Planning, Design, and Preparation of the Expert Interview Study

The planning, design, and preparation phase includes the definition of the object of analysis and the expert selection for the interviews. To find the right interview partners, we first looked for suitable companies and then selected an expert within each chosen company for the interview. The companies were selected using lists from political funding programs, which include potentially fundable companies. Table 2 provides an overview of the companies and the interview partners. The choice of interview partners was based on their position in the company and their work experience in their current field of activity. The position in the company should involve contact with the various other actors in the network, thus giving the interviewee the opportunity to discuss the supply chain governance

Table 2: Analyzed companies and expert information

Company	Supply chain Stage	Activity	Company size*	Code Interviewee	Position Interviewee
CA	Upstream	Power grid operation	Very big	IPA	Project manager
CB	Upstream; overarching	Hydrogen production (electrolysis); overarching	Very big	IPB	Manager business development
CC	Upstream	Hydrogen production (electrolysis)	Big	IPC	Head of product management
CD	Midstream	Hydrogen storage	Medium	IPD	Head of business development
CE	Midstream	Hydrogen storage	Very big	IPE	Manager business development
CF	Upstream; Midstream	Hydrogen trade; overarching	Very big	IPF	Trade manager
CG	Midstream	Hydrogen transport (piped)	Big	IPG	Head of capacity management
CH	Midstream	Hydrogen transport (piped)	Very big	IPH	Manager project coordination
CI	Downstream	Hydrogen end use	Very big	IPI	Head of strategic procurement
CJ	Downstream	Hydrogen end use	Very big	IPJ	Manager project coordination
CK	Downstream	Hydrogen end use	Very big	IPK	Innovation manager
CL	Midstream; Downstream	Hydrogen transport; hydrogen end use	Very big	IPL	Project manager
CM	Overarching	Overarching	Very big	IPM	Innovation manager

*size categorization: very big (>1250 employees or >€250 Mio. turnover); big (<1250 employees + <€250 Mio. turnover); medium (<250 employees + <€50 Mio. turnover); small (<50 employees + <€10 Mio. turnover)

within the network. The interviewees have an average work experience of more than nine years in their current field of activity.

The data is collected with the help of semi-structured expert interviews using a guideline divided into different sections (e.g., cooperation in the network; scaling up process; governance).

3.2 Data Collection and Analysis

The interviews were conducted between November 2021 and January 2022 and had an average duration of 57:27 minutes. The interviews were transcribed and qualitatively analyzed using *MAXQDA 2020* [79]. The transcripts, totaling over 190 pages, were analyzed using a coding system, including codes, e.g., for formal and informal GMs, the contextual factors, the different governance outcomes. The codes were initially created deductively from the interview guideline and the literature review results. During the coding process, additional codes were added inductively.

Yin [76] describes four quality criteria to enhance the quality of case studies, which we apply to ensure high quality of our interview study approach: construct validity, internal validity, external validity, and reliability. Construct validity verifies that a piece of research actually uses the "correct operational measures for the concepts being studied" [74, p. 42]. In our research, construct validity is ensured by data triangulation. While the semi-structured interviews built the primary data source, further company-specific research was conducted in which publicly available documents from companies or cross-company projects were analyzed and compared with the results from the interviews.

Internal validity refers to the explanation of causal relationships between the individual study items [76, 80]. To increase the internal validity, we have placed a high value on explaining the causal relationships in the result and discussion section of this paper, also by using a framework. Additionally, the collected primary and secondary data are specifically examined for inconsistencies to ensure internal validity.

External validity refers to the transferability and generalizability of the results of a study. Results of qualitative studies generally have limited transferability and are rather intended to provide an accurate analysis of the cause-effect relationships between the studied items. Nevertheless, experts in this study are selected according to replication logic to ensure that our sample of interviewees reflects the reality in HSCs which enhances external validity. Therefore, we selected experts from upstream, midstream, and downstream companies in equal measure.

Reliability forms the fourth quality criterion and indicates whether the results of a study are reproducible [76]. To ensure reliability, the research procedure was archived using an interview study protocol, and a standardized interview guide was used during the interviews. Additionally, the transcripts were coded by two researchers to ensure consistent coding.

4. RESULTS

This research article explores which GMs are used in the process of scaling up HSCs and how these mechanisms coordinate the different actors during the process of scaling up. We first analyze the different contextual factors influencing the choice of GMs in HSCs to allow a better understanding of the functioning of the GMs, but also of the intentions to use these mechanisms. Afterward, we examine the different GMs and their outcomes, which are distinguished between collective learnings and general outcomes. We developed a framework summarizing the results of our data analysis and the connections between the examined aspects (Figure 1). The governance framework expands existing research [11], which generally highlighted the

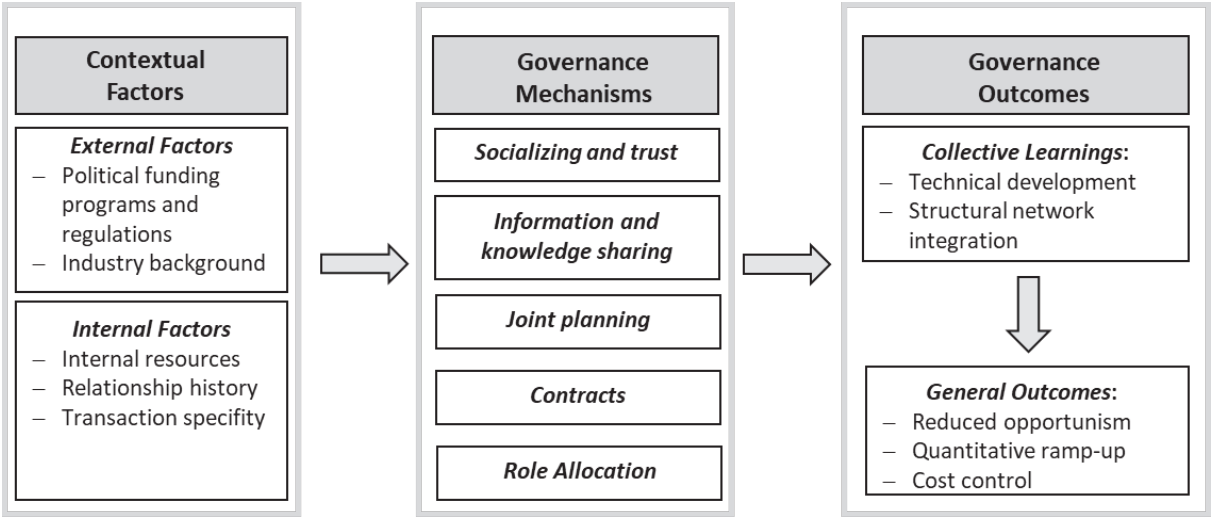

Figure 1: Governance Framework for the Scaling Up of Hydrogen Supply chains

influential relationships between contextual factors, supply chain governance, and the outcomes of business relationships but without considering the unique environment and aspects of HSCs.

4.1 Contextual Factors in Hydrogen Supply chains

Both external and relationship-internal factors influence the selection of GMs. External factors refer to aspects that cannot be influenced by the actors themselves (e.g., globalization, political regulations). In contrast, internal factors refer to aspects that can be influenced by the actors themselves (e.g., relationship history).

4.1.1 External Factors

During the interviews, two external factors were found, viz. *political funding programs and regulations*, as well as the *industry background*, which affect the design of the supply chain governance.

Political funding programs and regulations

Political funding programs but also political barriers and general legislation have a high impact on the design of interfirm governance for HSCs (e.g., IPA, IPC, IPE).

Political funding programs stimulate cooperation between companies in the scaling up of HSCs and initiate both information exchanges and joint planning activities between companies: "[... there are] large funding pots [provided by governments] [...] which then lead to projects being initiated [and] planned by the companies […]" (IPB). However, to receive funding, companies need to be in close contact and jointly draft the funding applications. Companies, therefore, get in touch at an early stage and try to informally develop a common basis for cooperation to submit funding applications jointly.

In contrast, restrictive political regulations, like anti-trust laws hinder the exchange of information between actors in the emerging hydrogen sector (IPG, IPH): "[...] Everyone in the hydrogen market has this problem at the moment: Who can actually talk to whom about what? It's extremely difficult [...]" (IPG). Uncertainties regarding the legality of information exchanges are described as a problem, especially regarding large infrastructure projects in the hydrogen market (IPH): "[...] This is somehow a bit absurd. [...]. Either we are supposed to cooperate with each other, or we are now competitors. But both at the same time somehow never really works." (IPH).

Industry Background

The diverse industry backgrounds of the actors in HSC have a great influence on the expectations of future business relationships, as well as on the behavior towards business partners, and often determines if partners have already worked together before (IPA, IPD, IPF, IPH, IPJ, IPM). IPA highlights difficulties during collaborations which may arise due to different industry backgrounds:

> "as a gas grid operator, you usually don't understand the electricity grid operator and the other way around as well. For example, in [...] which time intervals do you think [...]. In gas, you think in terms of days, and in electricity, you think in terms of milliseconds. And of course you first have to build up this cooperation, this mutual understanding" (IPA).

To create profitable collaborations, the expectations and understandings of HSCs should be aligned, of the hydrogen market in general, but also of the different technologies in the market, (IPA, IPD). The industry background and its peculiarities are therefore also seen as an influence that plays a role in shaping governance and the choice of mechanisms for coordinating business relationships in scaling up the HSCs.

4.1.2 Internal Factors

Next to external aspects that influence the governance design, also internal factors should be considered when selecting GMs for HSC, viz. internal resources, relationship history, and transaction specificity.

Internal Resources

The internal resources of companies in HSCs play a central role in developing the networks. Knowledge resources of the employees and their companies, as well as financial resources, are considerable aspects which influence the governance design.

Technical know-how enables actors to exchange information about technical issues and to learn new technical facts collectively with their partners (IPA, IPC, IPE). Technical know-how even has an effect on trust building in business relationships (IPE): "[...] you really get some trust […] from other partners because you just know a lot about these things [hydrogen technologies]." (IPE).

Next to knowledge resources, some actors prioritize financial resources, which are necessary to foster the development of HSCs. These financial resources give the companies a special power position in the network. Without their financial resources, the expansion of the networks would not be possible: "[...] These are very, very large investments that are needed. [...]" (IPI).

Relationship History

Another factor influencing the choice of GMs is the relationship history. During the design of new HSCs, companies use already existing business relationships and expand them to the HSCs (IPE, IPF, IPI, IPJ, IPM): "[...] the cooperation between [Company X] and us. It existed before [...] [Company X] has always been our direct cooperation partner, and it was quite natural that we immediately cooperate there [in the hydrogen market]." (IPM). IPI highlights that the transfer of

existing business relationships to the hydrogen market simplifies the cooperation since the competencies of the partners are already known.

When establishing new business relationships, the focus, in the beginning, is mainly on building a first trust base for cooperation. This trust-building process is not necessary for already existing business relationships, which is why they require different governance. The interview partners highlight that in existing business relationships, for example, information exchanges and collective learning are easier.

Transaction Specificity

Transaction specificity is another factor influencing the choice of GMs in HSCs (IPB, IPE, IPK, IPL). Cross-company projects in the hydrogen sector are specifically specified by very high and long-term investments in large facilities and plants: "But of course, if our pipelines […] are laid, then [… their location is fixed]. So that means there is already a high dependency for us that it [the pipeline] will be used in the long term. [...]" (IPG). To defuse the risk of investments not paying off, projects are planned and implemented in several stages (IPE, IPL).

IPK emphasizes that there is a high need for very detailed project plans due to the high investment sums in hydrogen projects. Therefore, intensive planning and detailed coordination of all activities is required to ensure synchronous development of interdependent project plans and project components (IPB, IPG, IPK).

4.2 Governance Mechanisms in Hydrogen Supply chains

Based on the identified external and internal contextual factors, companies use several GMs to coordinate all partners and their activities in the network. The interviewees describe that the focus in coordinating the business relationships to scale up HSCs is initially strongly based on informal mechanisms, viz. socializing and trust, information and know-how sharing, and joint planning. Over time the companies tend to use more formal mechanisms to safeguard their relationships, viz., contracts and written agreements, as well as role allocation.

4.2.1 Socializing and Trust

When building new HSCs, many partners do not know each other, partly distrust each other, and are not familiar with how the prospective partner behaves in business relationships: "[...] [there are] hurdles [...] that one does not know the company, does not know the business purpose or there is a certain distrust [...]." (IPM). To establish target-oriented and efficient business relationships, it is important that the companies involved know each other and create an initial basis of trust (IPE, IPK, IPL, IPM). IPM describes how personal contacts reduce initial hurdles: "[The hurdles ...] are reduced simply by being in contact with […] people [of the partner company]." (IPM). The interviewees emphasize that specifically also non-professional meetings during on-site visits strengthen the trust relationship between the partners: "Why do you go on on-site visits? Why do you usually have these meetings in person [...]? It's to make a relationship less formal because you have seen this person, you've talked to this person not only about collaborating on a project but also about […] their families and where they come from [...]." (IPE).

This initial trust building and socialization are considered very valuable for the coordination of the joint business activities: "[...] to build up a relationship with foreign companies, to build up a relationship of trust, that is already very valuable." (IPL).

4.2.2 Information and Know-How Sharing

Socializing and building trust are closely linked to the exchange of information and know-how, which is another GM frequently mentioned by the interviewees. Information and know-how sharing are about exchanging information, e.g., regarding processes or activities, but also about exchanging (e.g., technical) knowledge and developing it further together.

The exchange of information specifically helps to align the different interests and to understand what goals partners have when scaling up the network: "[...] before you go into a project like this, there are also corresponding exploratory talks with various partners, where we [...] especially look again: Do we have the same understanding of the market as the potential partner [...]." (IPD). The exchange of information is therefore used to align the different expectations on the business relationship: "[...] Then you usually first make an appointment and present the [… plan for the scaling up of the HSC] to each other […]. So we report on what our […plan] looks like, and the other side reports on what plans they have." (IPI).

After business relationships are established, the exchange of information and know-how continues. When scaling up HSCs, for example, partnership research projects are carried out that specifically foster the exchange of knowledge. This form of knowledge exchange and joint research sometimes also has a formal character: "[...] then we already define which part [of the technical development] we secure for patents and which part the partner secures for possible patents." (IPD). IPC emphasizes that the degree of knowledge sharing decreases with increasing technology maturity: "[...] in these early projects, where there is also much more collaboration with scientific institutes, there is, of course, significantly more know-how sharing involved. [...] Later on, that is less the case." (IPC).

4.2.3 Joint Planning

Joint planning of the scaling up of HSCs is another GM that was highlighted by the interviewees. Instead of all companies planning their activities in the network in isolation (e.g., transport of hydrogen), the companies already work together before the preparation

and implementation of the activities to find the best possible solution for all actors. Joint planning is strongly strengthened by political funding programs in the hydrogen sector, as these explicitly support the partnership-based design of funding applications that request cross-company projects (IPA, IPB, IPE, IPK, IPM).

Joint planning significantly helps to organize the complex structure of the process of scaling up of HSCs. Therefore, large project plans can also be broken down into individual components for structuring purposes: "[...] that is first broken down into subprojects. You have a subproject *production*, a subproject *transport*, [...], you have a subproject […] *customers* [...]" (IPA). Cross-company working groups can be used to manage the corresponding planning activities of the sub-projects (IPA, IPL): "[...] within these [sub-] projects you then have working groups that take care of an electricity grid connection or a gas grid connection or the technical feasibility concepts […]." (IPA). The different sub-projects always need to be aligned, e.g., regarding their technical or economic aspects, to fulfil the overarching project plan (IPA, IPC, IPD, IPM):

> "[...] And then there were always reuniting meetings, i.e. control meetings, where the results were then evaluated, presented, discussed, and then the next steps were discussed again and then [we] went back into the detailed groups." (IPD).

4.2.4 Contracts and Written Agreements

Next to informal GMs, formal structuring mechanisms, such as contracts and written agreements, are used to coordinate the scaling up of HSCs.

Contracts are used to gradually build and structure business relationships (IPD, IPF, IPI). IPD explains how a formalization of the business relationship follows the initial socialization and trust-building: "[...] it started with informal meetings [...]. But [...] because you also […] set the goal to tackle [apply for] a certain funding program [...] you then structure the collaboration [...]" (IPD). Some interviewees describe that a legally binding 'Final Investment Decision' is the most important component of the structuring process: "[...] everything must actually already be contractually wrapped up [safeguarded] at the time of the investment decision [...]" (IPG).

However, the structuring process includes not only legally binding elements but also written declarations of intent: "[...] the dialogue always starts informally, […] but the next thing is […] to draw up something, some letter of intent, memorandum of understanding, something, even if it is non-binding." (IPJ). IPF emphasizes that part of this structuring process are also mutual goals: "[...] it is important not to get lost in, let's say, generalities [...]. Instead, you really pursue goals, identify goals, and pursue them. You can actually see relatively quickly whether there is mutual interest. [...]" (IPF).

4.2.5 Role Allocation

Next to contracts and written agreements, role definitions and allocations are also an important formal GM.

The industry background holds the most significant influence on role allocation since most companies maintain the roles they already hold in supply chains in other industries (e.g., pipeline operator). However, some actors also take on new roles in the HSCs which they have not yet held. The emerging hydrogen market provides an opportunity for companies to expand their business activities (IPE, IPJ, IPL):

> "I mean, every company, I think, is also trying to evaluate where the boundaries are in a new market. Can we expand our business? Can we do more than we did before or should we do less? In the end, you always want to do more […] because they want to grow. So you always try to expand your boundaries." (IPE).

Because of these expansion ambitions, IPL explains that next to establishing trust via socialization, a "[...] clear role definition [...]" (IPL) becomes necessary in the governance of HSCs to prevent competitive constellations which may dampen the process of scaling up. IPM adds: "A good way is simply to have the conversation and clearly delineate areas of competence." (IPM).

4.3 Collective Learnings and general Outcomes in Hydrogen Supply chains

The application of GMs under the given external and internal context factors significantly influences the outcomes of business relationships, viz., reduced opportunism, the quantitative ramp-up and the cost control. Additionally, using GMs also enables and promotes collective learning, e.g., regarding strategy and technology, which foster the general outcomes themselves.

4.3.1 Collective Learnings

The interviewees mention that the general outcomes of reduced opportunism, quantitative ramp-up and cost control are specifically fostered by collective strategic and technology learning. The learnings described in the interviews are not achieved in one single workshop or project, but rather are developed in several steps. This gradual collective learning is caused and fostered through the stepwise expansion of the HSCs. After each expansion step of the network, the previous strategic and operational approach, as well as the technology used, are analyzed and evaluated.

Strategic learning

Strategic learning in HSCs refers to the structural network integration between the partners. The actors collectively learn in a step-by-step process which types of business relationships are particularly profitable and

should be further deepened and which structural links are particularly useful for expanding HSCs.

Initial business relationships in HSCs are established as "end-to-end" solutions. The actors, from the hydrogen producers to the consumers, are involved in creating an initial link between demand and supply carriers which are located closely to each other (IPD, IPK, IPL, IPM). Such initial project solutions are often described as cluster or island structures (IPH). In the next development step, pipelines are laid within the island structures to expand and intensify existing business relationships (IPI). In further network expansion steps, pipeline network operators may also act as connectors of several cluster structures (IPA, IPH). IPH explains such a cluster-connecting project: "[...] one would then try to connect these clusters bit by bit so that larger and larger clusters emerge [...]" (IPH).

The process of HSCs is analyzed and evaluated after each expansion step. Clusters and connections that function particularly well can be expanded further in the future. Clusters that have not yet been shown to be profitable can be examined in more detail, e.g., to analyze weaknesses and ameliorate them together in the future.

Technology learning

In HSCs, technology learning refers to collective developments of knowledge regarding the operation and improvement of hydrogen technologies and is fostered through the use of GMs in HSCs.

IPB explains that technology learning in HSCs is gradual, from small prototypes to large-scale hydrogen plants, with an increase in technology maturity:

> "[...] this scaling up, where I sort of technologically scale-up from a first industrial prototype [...] to a higher level of technology maturity [...] from the first proof-of-concept of the technology in the field to two to three times megawatt scale, or even to gigawatt scale, that's from my point of view this scaling up of the hydrogen supply chains. And that's not just about hydrogen production; it's also about storage, transportation, and utilization." (IPB).

To foster technology learning, collaborative partnership projects are being designed to collectively learn how hydrogen production, storage, and transportation technologies work and should ideally be used (IPA, IPB, IPC, IPD, IPE, IPL). These collaborative projects can be implemented in the early stages of network development, mainly as research or demonstration projects with high levels of information exchanges (IPA, IPB, IPC). This technology learning process takes place step by step (in loops). After each network expansion step, there is a joint evaluation of which technological applications and developments work particularly well and how certain (technical) barriers can be solved.

4.3.2 General Outcomes

Reduced Opportunism

One major outcome of applying governance mechanisms in the scaling up of HSCs is reduced opportunism. The interviewees differentiate between two main types of opportunism: theft of intellectual property and termination of the business relationships after unilaterally high investments.

Regarding the theft of intellectual property, companies fear that during the development of the business relationship, partners might behave opportunistically by misusing information that has been exchanged in confidence. In particular, opportunistic behavior is feared when information about technological innovations are shared, which is why NDAs and other contractual provisions are made to protect against opportunism (IPB, IPD): "one [...] tries to protect oneself" (IPD.)

Further, companies safeguard against partners leaving the business relationship after unilaterally high investments. Since certain actors in HSCs (e.g., pipeline operators) have to make high investments to enable the scaling up of HSCs, they want to share the risk of these high investments. They especially want their partners to stay in the business relationship for a long time so that the investment can pay off. Therefore, contracts are made to reduce the opportunism of partners leaving the business relationship early: "there is a leading partner who takes over the financing and […] supply contracts are then concluded between the respective supply chain steps, which are […] the basis for the FID [final investment decision]" (IPD).

Quantitative Ramp-up

The quantitative scaling up of the hydrogen supply capacity is one of the most important outcomes of the examined business relationships. Since the capacities of the current production and transport systems cannot cover future industrial hydrogen demands, a high priority is put on the quantitative expansion of the production and supply volume: "[...] These are really gigantic quantities that will be needed at some point in the future, and at the moment nowhere in the world is it planned that these hydrogen quantities can be produced and transported." (IPI).

The use of GMs to coordinate stakeholders, therefore, aims to establish the production, storage, and transportation of large quantities of hydrogen (e.g., IPB, IPF). The aim of supply chain governance in the studied business relationship is "that on a large scale, hydrogen is then available and can be used" (IPI). Therefore, governance coordinates all network activities aimed at a gradual increase in capacity (IPA, IPB, IPI, IPK, IPL). To enable the quantitative ramp-up, the interviewees mention that GMs especially allow collective learnings regarding strategy and technology, which in turn lead to the quantitative ramp-up (e.g. IPE, IPM). How GMs

enable collective learning is described in the discussion section.

Cost Control

Despite the quantitative ramp-up of the hydrogen supply volume, an important goal is to reduce hydrogen costs. Thereby, the interviewees mention not only the reduction of hydrogen costs, but also the control of transaction costs. During the quantitative ramp-up of the supply volume, the production costs for the hydrogen usually decrease: "So, purely from the plant inventory: 'the bigger, the cheaper' is a very simple rule." (IPK). The technological development process, which enables a gradual ramp-up of the production volume at moderate costs, helps to reduce hydrogen costs: "[...] through demonstration projects you get the costs into the range that […] you can use it economically [...]." (IPL).

While the hydrogen production costs per kilogram decrease when ramping up the volume, the transaction costs increase due to the extended hydrogen supply capacity (e.g., high ex-ante costs for transportation decisions). The interviewees highlight that it is important to control transaction costs so that they do not increase disproportionately. Joint projects and transactions should therefore be planned in detail before the project kick-off. While information sharing is used in the initiation phase of projects, formalizing mechanisms, such as contracts or the distribution of roles, should structure the plans to better keep the transaction costs in check.

The interview partners emphasize that, to reduce hydrogen and transaction costs, the gradual further development of the organization of the transactions should be fostered through collective learning, e.g., in the field of strategy and technology.

5. DISCUSSION

5.1 Proposition Development

The analysis of the interviews provides several new insights regarding how supply chain governance coordinates the scaling up of HSCs, also through collective learning. In the following, we show how this study contributes to the literature, e.g., by explaining why certain GMs are chosen and how they affect the scaling up of HSCs.

The first contribution shows how actors in the scaling up of HSCs can be coordinated despite their conflicting norms and values. The choice of GMs is significantly influenced by the given external and internal contextual factors [11]. When scaling up HSCs, the contextual factor of industry background is particularly salient. Actors from different sectors have different motivations to engage in hydrogen collaborations and projects: "[...] Everyone, of course, has their own incentives to do that. [...]" (IPK). For example, IPD explains the market-based motivation of actors who are transitioning from the fossil energy sector to the hydrogen sector: "[...] there are also companies, such as the oil and gas companies, whose business field is just declining at the moment and who are now thinking, what is a good, suitable business field that is just growing at the moment [...]" (IPD). In contrast, IPL describes the motivation of companies that are active in the hydrogen sector for ecological reasons: "[...] Well, to put it bluntly, there are green companies whose goal [...] is sustainability, and that is their primary focus. [...]" (IPL). While shared norms and values safeguard against opportunism [81], such conflicting values and norms could increase the likelihood of opportunism.

Past governance literature mainly focuses on shared but not conflicting norms and values among actors in supply networks [e.g., 62, 63]. Cannon et al. [82] explain, for example, that shared norms and values are essential to achieve certain behaviors of partners in supply chains, esp. since contracts are often incomplete. We contribute to the literature by analyzing the coordination of actors with conflicting norms and values. Our study shows, that despite conflicting values and norms, all partners are highly interested in expanding HSCs, whether for economic or environmental reasons. For a successful scaling up of HSCs, it is important that actors understand the different intentions to become active in the hydrogen market. Various GMs are used to develop mutual understandings of the individual engagement motivations: "[...informal] background discussions [are used] to even better understand motivations or […] pain points and to interpret them and to draw up solutions […]" (IPH). This matches with the results from Keller et al. [50], who show that through informal mechanisms, such as information sharing, socializing between partners, and trust building, actors can better understand the actual interests and behaviors of partners.

With a mutual understanding of the engagement intentions, scaling up processes are less likely to be disrupted by conflicts of interest since all actors can already adjust to the behavior and ideas of the partners. The following proposition can therefore be made.

P1: The industry background and the related engagement intentions strongly influence the need to use informal governance mechanisms for scaling up in supply chains.

The second contribution of this study shows that political funding programs increase the use of informal GMs.

Next to the industry background, political funding programs and regulations significantly influence the choice of GMs to coordinate the process of scaling up and promoting collective learning in HSCs. Political funding programs in the hydrogen market often explicitly require collective applications from several companies for the funding. The drafts of these joint applications are comprehensive cross-company projects (IPA, IPB, IPE, IPK, IPM). To receive funding,

companies must already collaborate intensively in the application phase and draft joint plans for the scaling up of the HSCs: "[...] you [...] ensure knowledge exchange with various other partners there to also receive the funding in the end." (IPA).

In the initial phase of funding applications, informal GMs are primarily used to establish initial personal relationships between the actors who want to apply for the funding jointly. It is emphasized that partners need to link closely and exchange a lot of information to understand the funding conditions and apply them in the best possible way: "[...] there are also partly unclear funding conditions [and regulations …], where you coordinate with each other how to interpret those [...]" (IPA). This initial informal contact between the partners lays the foundation for designing joint plans that are eligible for funding.

The design of joint funding applications needs to show how the actors aim to improve the strategic integration of their network and how they want to develop technically. The political decision-makers expect that these learnings do not only take place within the networks but are communicated to actors outside the network: "[...] [there is] usually a dissemination activity, so that the project results, the learnings are also shared. That's why you get the funding so that you can publish it with a larger audience." (IPC).

Political funding programs thus initiate new business relationships which need to be established with the help of informal GMs. The newly established business relationships offer opportunities for extensive collective learning in strategy and technology.

So far, literature focusing on politics influencing supply chain governance mainly referred to political regulation programs [e.g., 30, 83]. LeBaron and Rühmhorf analyze, for example, the influences of the UK Bribery Act and the Mordern Slavery Act on supply chain governance [84]. However, this study focuses on the impact of political funding programs on supply chain governance. The idea of funding programs to promote the scaling up of HSCs matches with transaction cost theory [39, 42], as relationships in HSCs are intensified specifically because of the decreased transaction costs due to funding programs. It is striking that so far literature showed that, political programs mainly fostered the use of formal GMs in supply chains, e.g., certificates (e.g., presupposed minimum standard in quality or sustainability) [85]. This study shows that political programs can also increase the use of informal GMs to enable the successful application of supply chain partners to political funding programs.

Further, informal mechanisms were previously seen as instruments to coordinate close and long existing business relationships, while formal mechanisms were used to shape new business relationships [9]. Our results show that informal mechanisms are also used to build new relationships, specifically to create a close relationship between previously unknown partners as a basis for collective learning. The following proposition can therefore be drawn.

P2: Political funding programs greatly impact the use of informal governance mechanisms to promote collective learning.

Political funding programs specifically encourage the application of informal GMs to foster collective learning. However, there are also political and societal barriers that should be addressed with the help of GMs, resulting in multi-stage learning processes to foster the scaling up of HSCs.

Several interviewees explain that the broad expansion of HSCs requires intensive communication and educational work to reduce concerns of political and societal actors (IPG, IPH, IPK): "[...] infrastructure projects [...] are not self-propelling, you also have to do a lot for them. Many fears have to be addressed and dispelled." (IPG). To reduce fears and reservations regarding new infrastructure projects (e.g., pipelines), a lively exchange between the network actors and political as well as societal decision-makers plays a central role in the gradual dissolution of external barriers. Additionally, to the implementation of direct exchange relationships with political and societal actors, public communication strategies should be developed for every joint project. Therefore, the players in the hydrogen market must exchange information extensively to pursue a joint communication strategy vis-à-vis political and societal players.

The reduction of political barriers through close communication channels with companies is extensively covered in the literature [e.g., 82]. Past literature also points to a few barriers when building HSCs, such as poor technology maturity or leakages [e.g., 17]. We contribute to the literature not only by highlighting more barriers but also by showing options to reduce these barriers. First, we introduce two new major barriers in the scaling up of HSCs, viz. social and political barriers and the industry background. Second, we explain possible approaches when facing the barriers. We highlight, for example, the importance of evaluating after each scaling up step which communication strategies reducing barriers were well received by the stakeholders and for which project types a particularly more intensive public relations work is necessary. This multi-stage learning process leads to an effective decrease of barriers and thus of the transaction costs in the scaling up of HSCs. Therefore, the following proposition can be established.

P3: Multi-stage learning processes are essential for decreasing political and societal barriers as well as transactions costs in the gradual scaling up of hydrogen supply chains.

While the internal and external contextual factors significantly influence the choice of GMs, the expected outcomes also influence the choice of governance. A key outcome for the efficient development of HSCs is the gradual strategic and technology learning in the

HSC. Successful but also unsuccessful scaling up activities are analyzed after their implementation to draw appropriate lessons for future activities: "[…] you try to take into account the learnings over the past few years. So you had a few successes, and you had a few things that didn't work out." (IPE). The gradual expansion of HSCs offers opportunities to apply the learnings in the next expansion step: "[...] it's always an iteration process." (IPJ).

To enable collective learning, informal GMs are used in the companies studied. An important informal GM is to create trust between the partners and to involve the partners in the expansion processes: "But the current solution is to talk a lot with each other […] to create trust." (IPD). If partners trust each other and have the feeling that they can benefit from joint processes, they become more involved in the processes and enable the sharing of knowledge and the complementary use of resources. Next to the trust-building mechanism, joint planning and informal information exchanges are specifically used to foster collective learning. IPL explains, for example, that the joint planning and implementation of demonstration projects allow for comprehensive technology learning: "we use demonstration projects to identify […] the right technologies for us. [...] that's what demonstration projects are good for, to gather experience, to test it, to understand it better." (IPL). While jointly planning the demonstration projects, the partners exchange a lot of information regarding the tested technologies, which allows them to collectively learn how to operate, adapt, and improve them.

Our findings support existing literature on collective learning. The direct positive influence of joint planning and informal information sharing on collective learning matches, for example, with Ghosh and Fedorowicz [63], who showed an indirect link between information sharing and collective learning. However, even though the literature on HSCs [e.g., 12–14] and on collective learning [e.g., 72, 73] is broad, the two research fields have not been combined yet. Thus, we contribute to the literature by showing that in HSCs, collective learning is mainly on a strategic and technological level. Further, we show, that also in HSCs, informal GMs support collective learning. The following proposition can be made.

P4: Informal governance enables strategic and technology collective learnings and a more efficient scaling up of hydrogen supply chains.

Informal GMs play an important role in coordinating the scaling up of HSCs and enabling collective learning. Formal GMs are also used to coordinate the actors in HSCs. Specifically, contracts financially secure investment projects and expansion steps: "[…] at the time of the investment decision, everything has to be actually already contractually signed and sealed, [...] because we need a very long time until we have earned our money again and we simply need the security for our investments." (IPG). Next to the duration of the cooperation, also the supply volume and the hydrogen prices can be contractually fixed: "The customer must know in the long term that he gets the price [... and …] we need – as an infrastructure operator – long-term contracts […], so that we know we also have something to transport and not [that] in the end, there is a pipeline that no one needs." (IPH). Next to the safeguarding of financial aspects, contracts are also used to avoid opportunism, for example, to secure intellectual property using NDAs or patents (IPA, IPB). These findings match with former findings in the literature, which show the safeguarding effects of contracts [e.g., 44].

While the interviewees assess the safeguarding with contracts positively, there are also mitigating effects of formal mechanisms: "[...] it becomes very formal, so there are an infinite number of contracts or contracts are in development, how the cooperation is to be structured. It's very, very cumbersome [...]" (IPL). This hampering character of formal mechanisms might negatively affect scaling up and collective learning processes. Informal mechanisms, on the other hand, are judged to be less complicated and more practicable in daily business operations: "that there is also then an informal level that just gets going." (IPL). These results support the existing literature proving the rather flexible coordination with informal GMs [e.g., 9]. Since the application of GMs in HSCs has not been studied before, we can extend the existing HSC literature [e.g., 12–14] and show the role that informal and formal GMs play in coordinating the scaling up processes. The following proposition regarding formal GMs can be formulated.

P5: Formal mechanisms safeguard economic interests and avoid opportunism to enable the quantitative ramp-up in the scaling up of hydrogen supply chains.

Based on the framework introduced at the beginning of the result section (Figure 1), the developed propositions from the discussion section allow the highlighting of the most remarkable connections between elements of the initial framework (Figure 2).

We show how several contextual factors influence the choice of GMs, whereby the industry background with its related engagement intentions as well as political funding programs and regulations have a remarkably strong impact on using informal GMs (P1; P2). These informal mechanisms not only directly lead to a scaling up of the hydrogen networks but also enable comprehensive collective learning (P4). Collective strategic and technology learning are the main contributors to the scaling up of HSCs but are also used to reduce political regulations (P3). On the other hand, formal GMs safeguard economic aspects in the scaling up of HSCs and thus directly foster the achievement of general outcomes, e.g., by controlling the costs (P5).

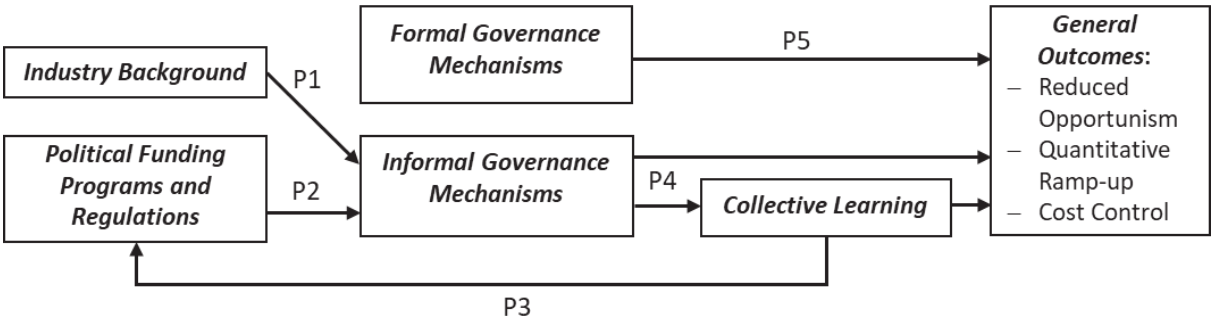

Figure 2: Propositions regarding the supply chain governance of hydrogen supply chains

5.2 Theoretical implications

Research on supply chain governance typically focuses on a particular contextual setting (e.g., an industry [87] or an emerging technology [88]), the use of certain mechanisms (e.g., trust [63]), or the achievement of certain governance outcomes (e.g., increased sustainability [89]) [11]. This article enriches the existing governance and collective learning literature from different perspectives. First, the comprehensive analysis of the contextual factors of supply networks from the hydrogen industry enables the development of appropriate governance strategies to scale up supply networks. Further, the paper focuses on governance mechanisms to enable collective learning to scale up networks, which provides new insights regarding the existing collective learning literature. In the following, the most important theoretical implications, which can be derived from the results of the paper, are presented.

The governance literature shows that past business relationships between companies significantly influence the choice of governance strategy [11]. The social exchange theory [90, 91] highlights that recurring transactions serve to build trust and commitment and thus enhances collaboration in business relationships. This matches the results of our research. The examined supply networks of this study not only show the lack of trust due to missing previous business relationships but even distrust between the actors due to different industry backgrounds. Because of the missing trust, the scaling up processes between companies only start on a small scale. After building trust and using other informal governance mechanisms in recurring transactions the scaling up processes can be enhanced. While this research provides novel insights on dealing with distrust in business relationships, future research should also investigate how trust can be built in the presence of absolute mistrust and conflicting interests.

Further theoretical implications can be derived from the insights on collective learning. Through strategy and technology learning, actors can jointly reduce transaction costs in supply networks in long-term. Research results concerning the enhancement of collective learning show that collective learning can be promoted with the help of informal governance. By demonstrating the direct influence of informal governance mechanisms on collective learning, it extends the literature on collective learning and governance, which has so far only shown an indirect link between governance and collective learning [63]. Future research should explore how also formal mechanisms can support collective learning additionally to informal governance mechanisms. Intensively examined mechanisms, such as contracts [e.g., 92], can be used, for example, to define the scope of collective learning. In addition, contracts can be used to protect against opportunism [93]. Since collective learning involves sharing a lot of information and data, it should be investigated whether contracts can also protect against opportunism or if other governance mechanisms are needed.

Previous literature in the field of collective learning focuses on innovation enhancement [94] or quality enhancements [95] generated due to collective learning. Our article expands the focus of the collective learning literature by showing how collective learning helps companies to deal with political and social barriers in large infrastructure projects and how the corresponding learning cycles contribute to scaling up processes. The important insights laid by this article on collective learning, e.g., concerning negotiation and communication strategies targeting the population and politics in large-scale infrastructural projects, should be further developed in the future. For example, a framework for systematic, collective negotiation and communication strategies for large-scale infrastructural projects could be developed.

5.3 Managerial implications

Several managerial implications can be derived from the results of the interview study and the propositions developed from it. The implications refer to the governance of scaling up processes and collective learning.

We first show that companies should build a trusting relationship with their partners to enable the scaling up of their supply network. In the supply networks investigated in this study, there was a high level of mutual distrust among the actors at the beginning of the business relationships due to different industry origins (e.g., oil vs. sustainability industry). However,

trust is essential for successful collaborations in supply networks [63]. In order to enable and finance the scaling up process, the different actors have to write funding applications together, despite their mutual mistrust. In some cases, corporate strategies and other sensitive data must be disclosed in the funding applications. In addition, the successful writing of funding applications requires close cooperation and commitment to the business relationship. Sharing sensitive data and close cooperation between the partners require a certain level of trust in the business relationship [96]. Companies should, therefore, intensively exchange ideas, organize formal and informal meetings, and introduce the individual employees to each other, especially before the start of the business relationship, in order to build trust between the companies and thus lay the foundation for the scaling up process.

The results of our study show that companies should also actively promote collective learning if they aim to scale up their supply networks. Collective learning enables, e.g., developing and applying new technologies and strategies in supply networks [66]. Companies can apply these new technologies and strategies to drive the scaling up process successfully. In fact, our study shows that collective learning is one of the most important governance outcomes for enabling the scaling up process.

To enable collective learning, informal governance mechanisms, specifically trust, are necessary so that partners in the supply network are willing to engage in collective learning. Using informal mechanisms creates a basis of trust that enables the lively exchange of information and knowledge, which are essential for collective learning [97]. To promote and simplify information and knowledge sharing in the further course of the business relationship, companies should also use information and communication technology which significantly simplifies information sharing [98].

For collective learning in the supply networks studied, a lot of sensitive information and knowledge, e.g., from technology development, is shared with partners. This shared information and knowledge can be misused in opportunistic activities [99]. While using informal governance mechanisms reduces the misuse of shared knowledge [35], companies should also consider, for example, contractual safeguards to protect their own data and intellectual property in collective learning.

6. CONCLUSION AND LIMITATIONS

This research analyzed how GMs coordinate actors in the scaling up of HSCs and shows why formal and informal GMs are chosen to improve the process of scaling up. First, this study identifies several new contextual factors influencing the choice and functioning of GMs. Further, our results highlight that informal GMs are used to create new business relationships and foster an efficient scaling up of HSCs, also by enabling collective learnings. Formal GMs are mainly used to safeguard economic interests in the scaling up process of HSCs, despite their mitigating effects on trustful collaborations. Additionally, the study shows that collective strategic and technology learning are the main drivers for an efficient scaling up of HSCs.

Although the study was conducted with high scientific care, some limitations restrict the generalizability of the work. First, further quantitative research will be required to strengthen the validity of qualitatively generated findings in this work and make them generalizable. Another limitation is the early stage of the development of HSCs. As soon as highly developed, large HSCs exist, they should be studied to investigate the success of the proposed GMs in the long term.

Additionally, the evolution of the actors' business relationships in highly developed HSCs should be studied. While GMs are currently used specifically to build trusting, close collaborations, these trusting relationships between different actors could turn into competitive relationships. At the moment, the actors cooperate during the process of scaling up to implement hydrogen as a common commodity. In the future, competition for low prices or scarce hydrogen resources may arise, which could damage the trusting relationships and could mitigate the effects of informal GMs. In this context, the role of formal mechanisms to coordinate the network and ensure collective learning despite the competition could be examined.

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APPENDIX

Coding scheme showing the first two levels of coding

Coding categories	First Subcode Category	Frequency
Contextual Factors		
External Factors		
	Political funding programs and regulations	188
	Industry background	93
Internal Factors		
	Internal resources	72
	Relationship history	87
	Transaction specifity	25
Governance Mechanisms		
	Socializing and trust	29
	Information and knowledge sharing	115
	Joint planning	112
	Contracts	77
	Role Allocation	118
Governance Outcomes		
Reduced Opportunism		40
Collective Learnings		
	Technical development	14
	Structural network integration	116
General Outcomes		
	Quantitative ramp-up	19
	Cost control	21