Competitiveness of green hydrogen: a systematic literature review through the TCCM prism

Mounia Hda[1], *Jihane Ikhmim*[1*], and Youssef Ettoumi[2]

[1]LEFMI, Faculty of economics & management, Ibn Tofail University, 14000 Kenitra, Morocco
[2]National School of Architecture, 93002 Tetouan, Morocco

Abstract. This study presents a systematic literature review on the competitiveness of green hydrogen, with a particular focus on emerging economies. Faced with the urgent need to decarbonize sectors that are difficult to electrify, green hydrogen appears as a strategic option, but its widespread adoption remains hampered by issues of cost, technological maturity, and governance. Using the TCCM (Theory, Context, Characteristics, Methodology) approach, this research analyzes a corpus of 45 indexed articles to identify the major determinants of competitiveness. The results show that competitiveness does not depend solely on lower technological costs, but on a systemic combination of factors including stable regulation, suitable infrastructure, innovation, partnerships, and financing mechanisms. The comparative analysis also reveals different trajectories among importing, exporting, and emerging economies, confirming that competitiveness is contextualized rather than universal. The synthesis ultimately highlights a "triangle of competitiveness" based on regulatory stability, secure financing and the development of shared infrastructure, an essential condition for the transition of green hydrogen from the status of a promise to that of a deployed industrial sector.

Keyword: - *Green hydrogen, Competitiveness, Emerging economies, Energy transition, Policy and infrastructure*

1 Introduction

In response to climate urgency and rising energy demand, green hydrogen is increasingly viewed as a key energy carrier for decarbonizing hard-to-electrify sectors. Produced through renewable-powered water electrolysis, it offers a carbon-free alternative to fossil-based gray hydrogen. Many developed and emerging economies are integrating green hydrogen into their energy transition strategies. The International Energy Agency projects global hydrogen demand to reach about 130 million tons by 2030, a 45% increase compared to 2023, with hydrogen potentially supplying up to 10% of final energy demand by mid-century [1].

Despite these prospects, green hydrogen remains economically uncompetitive in the short term. Current production costs, typically USD 4–6/kg, are significantly higher than those of

[*]Corresponding author: jihane.ikhmim@uit.ac.ma

gray hydrogen (USD 1–2/kg) [2], limiting large-scale deployment. Closing this cost gap requires coordinated policy support, technological progress, and favorable investment conditions. This article therefore examines the economic, technological, and institutional conditions under which green hydrogen can evolve from a promising option into a genuine competitiveness lever for emerging economies.

To this end, the study conducts a systematic literature review on green hydrogen competitiveness, with a focus on emerging economies. It synthesizes recent findings on costs, policies, innovation, and value chains to identify key determinants of competitiveness, using the TCCM framework (Theory, Context, Characteristics, Methodology) to structure the analysis.

2 Literature Review

Recent studies have widely analyzed the economic viability of low-carbon hydrogen, its competitiveness against fossil-based alternatives, and strategies for developing a competitive hydrogen sector. Several works focus on the geographical dimension of hydrogen costs and trade. Perey and Mulder (2023) [3] examined whether Europe should produce hydrogen locally or import it and in which form. They showed that transport distance and mode are key cost drivers: pipelines are the cheapest option for distances below 10,000 km, while for longer distances conversion into carriers such as ammonia becomes more cost-effective despite efficiency losses.

Beyond cost analysis, other studies assess broader competitiveness in the hydrogen economy. Yin et al. (2024) [4] proposed an International Hydrogen Competitiveness Index to compare countries' ability to develop a hydrogen industry, highlighting that export leadership will favor countries combining strong resources, supportive policies, and innovation ecosystems. National strategies also reflect efforts to balance decarbonization and competitiveness. Quitzow and Lentschig (2024) [5] analyzed Germany's hydrogen strategy, which prioritizes green hydrogen to decarbonize industry and achieve carbon neutrality by 2045 through investments in R&D and pilot projects.

At the European level, Nuñez-Jimenez and De Blasio (2022) [6] identified three strategic pathways for securing a competitive hydrogen supply: domestic self-sufficiency, cost-optimized regional imports, and diversified global imports to enhance energy security.

Several studies project significant cost reductions for hydrogen, reinforcing expectations of improved competitiveness. Reuß et al. (2024) [7] reported a broad consensus on declining electrolytic hydrogen costs, while Algburi et al. (2025) [8] projected a 30–50% cost reduction by 2030, potentially making green hydrogen competitive with fossil-based alternatives. The 2021–2022 energy crisis further illustrated these dynamics: Münster et al. (2024) [9] showed that high gas prices made green hydrogen costs comparable to blue hydrogen. Finally, Duraković et al. (2023) [10] analyzed the interaction between green and blue hydrogen, concluding that in the short term they are competitors; strong early policy support for green hydrogen could significantly increase hydrogen prices by 2030 due to higher initial costs.

3 Methodology

To conduct this systematic literature review, we followed a rigorous approach in accordance with PRISMA standards. This framework aims to ensure the transparency and comprehensiveness of the review process by documenting each step, from source identification to study selection and inclusion, in a standardized manner.[11].

Specifically, we developed a research protocol detailing the research question, the literature search strategy, the inclusion/exclusion criteria, and the data extraction/synthesis methods.

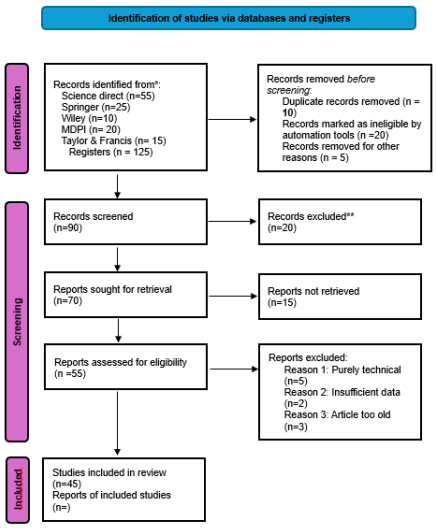

Fig. 1. Prisma diagram

The search for articles was conducted primarily using the Scopus database, targeting peer-reviewed academic publications available between 2019 and 2025. The keywords used are:
("Energy transition") AND ("Green hydrogen") AND ("Competitiveness")
("Energy transition") AND ("Green hydrogen value chain")
("Energy transition") AND ("Hydrogen policy")
("Energy transition") AND ("Industrial decarbonization") AND ("Hydrogen")
("Energy transition") AND ("Energy security") AND ("Hydrogen")
After eliminating duplicates, filtering by the relevance of the title/summary and applying the inclusion criteria (studies dealing with the competitiveness or economic factors of green hydrogen, with a possible emphasis on emerging countries), a final corpus of approximately 45 articles was selected for in-depth analysis.
Each selected article was coded according to the TCCM (Theory, Context, Characteristics, Methodology) approach.[12]This framework allows the review results to be structured clearly, while identifying potential gaps and future avenues at each level of analysis, and allows for the systematic examination of four complementary dimensions of the literature:
The theoretical foundations used (what concepts or theoretical frameworks underlie each study);
The empirical or geographical context (country, sector, period) of the work;
The characteristics and themes studied (main variables analyzed);
The research methodology used (quantitative/qualitative approach, data used, analysis techniques).
Finally, an analytical cross-section reveals an integrative reading demonstrating that the competitiveness of green hydrogen is never linked to a single isolated factor, but to an optimal combination.

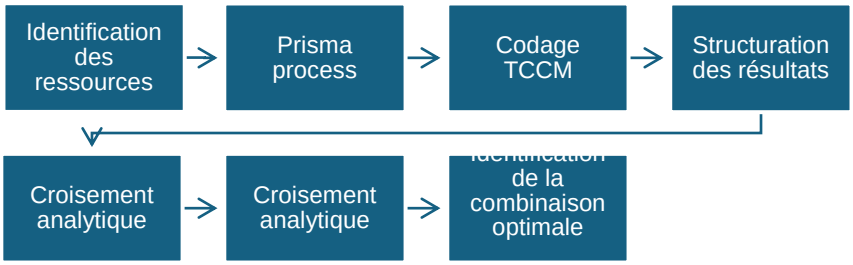

Fig. 2. Methodological approach

4 Results and discussion

4.1 Theoretical Dimension

From a theoretical standpoint, it appears that the majority of studies on the competitiveness of green hydrogen adopt a primarily techno-economic and empirical approach, without always relying on an established theoretical framework. This contrasts with other, more mature research fields. Most articles primarily aim to assess economic feasibility, model costs, or compare deployment scenarios, from a highly applied perspective. A few authors, however, situate their analysis within the broader context of the energy transition or industrial competitiveness: for example, some works link it to the concept of competitive advantage (traditionally derived from the theory of the firm) or to the frameworks of socio-technical transition (examining how new technologies integrate with and replace existing systems). But these explicit theoretical foundations remain the exception.
In the analysis of TCCM theories, it is possible to identify the theories used, but also the conceptual models, analytical frameworks and paradigms used to explain the relationships between variables.[13]

Table 1. Main theory/conceptual framework identified according to the TCCM framework

Theory	**Main idea**	**Keywords**
Energy transition[14]	Green hydrogen helps to replace fossil fuels and serves as a balancing solution for integrating renewable energies (solar, wind) into the energy system.	Substitution – Renewables – Flexibility – Energy security
Hydrogen Economy[15]	Competitiveness depends on the cost of production, the size of the global market, and coordination between public and private actors at several levels.	Cost – Market – Competitiveness – Governance
Sustainable development / SDGs[16]	The development of the hydrogen sector must create economic value, protect the environment and promote social inclusion to support the Sustainable Development Goals.	Sustainability – Inclusion – Environment – Equity
Carbon neutrality and governance[17]	Climate and energy policies must be coherent and coordinated between institutions to achieve carbon neutrality by 2050.	Zero carbon – Regulation – Policy coherence – Institutions

Source: Authors

In summary, the literature on green hydrogen is still at an emerging stage where the imperative is first to demonstrate competitiveness or identify key factors, rather than to test hypotheses derived from existing theories.

4.2 Context

The geographical context reveals an asymmetrical structure of the future global green hydrogen market, where countries are adopting differentiated positions according to their resources and strategic priorities. On one hand, some states like Germany or Japan are positioning themselves as importers-transformers, primarily seeking to secure their energy supply through the import and conversion of carriers such as ammonia.[18]Conversely, countries such as Australia, Saudi Arabia, and Chile are positioning themselves as major exporters, relying on very low production costs and key port hubs. Finally, emerging economies with significant growth potential (Morocco, India, Namibia) are adopting a strategy of industrial integration, seeking to capture more value by developing not only production but also local processing. This geographical diversity demonstrates that competitiveness is driven by a geo-economic and strategic logic rather than a uniform dynamic.[19].

At the sectoral level, the analysis reveals a multi-level organization linking national, regional, and global scales. At the national level, strategies are primarily based on public policies, resource availability, and industrial priorities, aiming to integrate green hydrogen with economic competitiveness and the creation of local value chains. At the regional level, the focus is on cooperation, infrastructure sharing, reducing logistics costs, and establishing export corridors. Finally, at the global level, competitiveness relies more heavily on the implementation of international standards, particularly regarding green certificates, carbon traceability, and guarantees of origin—essential conditions for ensuring the credibility of trade and investor confidence. Thus, sectoral competitiveness results from coherent governance across these three levels.[20].

Finally, the timeframe shows that the dynamics of green hydrogen follow a progressive trajectory structured in successive phases. Between 2023 and 2030, the priority is industrial demonstration, marked by the deployment of large-scale projects supported by public funding and logistics hubs. The period from 2030 to 2040 corresponds to a phase of acceleration and scaling up, characterized by a significant decrease in investment costs, further industrialization, and a broadening of uses, particularly in the chemical and steel industries. Finally, the 2040–2050 horizon aims for achieving carbon neutrality, requiring a stable regulatory framework, harmonized standards, and a sufficiently attractive carbon price. This progression confirms that the competitiveness of green hydrogen is neither immediate nor automatic, but depends heavily on the stability of temporal and political trajectories.[21].

Table 2. TCCM Context Analysis Dimensions

Dimensions of analysis	**Subcategories / Details**
Geographical dimension	-Importers-transformers: Germany, Japan: energy security through import and conversion. -Massive exporters: Australia, Saudi Arabia, Chile: low-cost production and port hubs. -Emerging structuring countries: Morocco, India: industrial integration and capture of the value chain.
Sectoral dimension	-National: internal strategies (Morocco, India, Chile) linking resources, industry, public incentives. -Regional: pooling of logistics, reduction of export costs by approximately 20%. -Global: need for international standards (green certificates, CO_2 traceability, guarantees of origin).
Time dimension	-2023–2030: industrial proof → transition to giga-projects, public funding and port hubs. -2030–2040: scaling up → 45% reduction in CAPEX for electrolysis and increased competitiveness in the chemical and steel industries. -2040–2050: carbon neutrality → importance of CO_2 pricing, stable regulation and harmonized standards.

Source: Authors

4.3 Characteristics and themes of the work

The characteristics identified in the literature show that the competitiveness of green hydrogen relies on an architecture of interdependent variables. Dependent variables directly reflect expected outcomes, including industrial adoption, economic feasibility, sector maturity, and cost competitiveness. These performance levels are closely linked to independent variables, primarily related to the policy and regulatory framework, the availability of renewable resources, technological advancements, and input costs, which constitute the main structural drivers. The analysis also reveals the key role of moderating variables such as social acceptability, organizational maturity, and regulatory stability, which influence the speed and success of the transition. Mediating variables, such as financial incentives and international or regional cooperation, play a transmission function by facilitating the transformation of structural conditions into concrete results. Finally, control variables, related to the initial energy context, geopolitical conditions, and governance, determine the overall feasibility framework and explain the differences in trajectories between countries. Together, these characteristics show that the competitiveness of green hydrogen results from a multi-factorial system, where public policies, technological innovation, institutional capabilities and contextual environment interact closely.

Table 3. Characteristics of the analyzed works

Variable category	Main variables
Dependent variables	- Industrial adoption - Economic feasibility - Societal and environmental performance
Independent variables	-Political and regulatory framework- Techno-economic factors- Institutional governance- Structural characteristics of the territory
Moderating variables	-Collective leadership- Social acceptability and organizational maturity- Technical and logistical dimension- Geopolitical and regulatory stability
Mediating variables	-Financial incentives- Local skills and institutional capacities- Regional cooperation and agile governance
Control variables	-Initial energy structure- Geographic, social and environmental factors- Political stability and capital attractiveness- Public governance and regional partnerships

Source: Authors

4.4 Methodologies used in the literature

The literature analyzed reveals a wide methodological diversity, illustrating the multidimensional complexity of green hydrogen competitiveness. The identified studies primarily rely on three types of approaches: quantitative, employing econometric models, techno-economic simulations, and cost analyses; qualitative, based on case studies, document analyses, or expert surveys; and mixed methods, combining numerical data and interpretive frameworks to better understand political, industrial, and technological interactions.[22]The nature of the data used is also diverse: some research relies on secondary sources (databases, institutional reports, international statistics), others on primary data collected through interviews, questionnaires, or consultations with stakeholders, while some studies construct their own datasets from aggregations or composite indicators. Finally, the methods and tools of analysis reflect this diversity, ranging from strictly quantitative analyses to qualitative approaches, and even hybrid

methods that link economic measures, political dynamics, and sociotechnical dimensions. Together, these methodological choices demonstrate a research field in development, employing a variety of tools to address an inherently complex issue.

Table 4. Methodological dimensions

Methodological dimension	Main categories
Typology of research	- Quantitative approaches - Qualitative approaches - Mixed approaches
Nature of the data used	- Secondary sources - Primary data - Constructed data
Analysis methods and tools	- Quantitative - Qualitative - Hybrids

4.5 Analytical Cross-Tabulation

The analytical cross-referencing of the dimensions of the TCCM framework highlights a clear convergence between theories, contexts, variables, and methodologies, revealing a systemic model of green hydrogen competitiveness. The results first show that the theoretical frameworks of energy transition and multi-level governance are applied differently depending on geographical trajectories (importing, exporting, or emerging countries). They then emphasize that the main determinants of competitiveness (political stability, technological innovation, public/private investment, and territorial embeddedness) are confirmed by quantitative approaches in the North and by more institutional and qualitative approaches in the South. Furthermore, the cross-referencing of variables and methodologies reveals a complementarity between quantitative analyses, which validate efficiency and performance, and qualitative approaches, which explain feasibility and acceptability.[23].

Table 5. Analytical cross-referencing of results

Cross axes	Relationships and convergences identified	Key Results/Lessons Learned
Theories × Contexts	The frameworks for energy transition and multi-level governance are applied differently according to three trajectories: importers (Europe, Japan), exporters (Australia, Saudi Arabia), emerging countries (Morocco, India).	→ Three strategic models emerge: securing local industry through a legal framework, exporting green energy through hubs, creating a regional industrial base.
Theories × Variables	Approaches from the hydrogen economy and sustainable development highlight the complementarity between public policies, technological innovation and socio-economic inclusion.	→ The major determinants of competitiveness are: political stability, public/private investments, territorial anchoring.
Contexts × Methodologies	Studies on Northern countries favour quantitative tools, while those on the South opt for qualitative and mixed approaches (interviews, SWOT).	→ Methodological differentiation: techno-economic modeling in the North, institutional and social analysis in the South.
Variables × Methodologies	Independent variables are measured via multi-criteria models, while moderating variables are based on qualitative surveys.	→ Combining approaches: quantitative for efficiency, qualitative for feasibility.
Methodologies ×	Quantitative approaches empirically validate	→ The TCCM reveals an

Theories	hypotheses from economic and technological theory; qualitative approaches shed light on the dimensions of governance and acceptability.	epistemological complementarity: numbers explain performance, stories explain success.
Contexts × Variables	The weight of the variables varies according to industrial maturity: in the North, priority is given to cost; in the South, priority is given to governance and regional cooperation.	→ The competitiveness of green H_2 depends on a balance between costs, institutions and infrastructure.
Cross-sectional synthesis (T×C×C×M)	The four axes of the TCCM converge towards a systemic model where public policies, infrastructure and financing interact.	→ Validated overall model: Competitiveness triangle = Stable regulation + Shared infrastructure + Secure financing

Finally, the cross-cutting synthesis confirms that the competitiveness of green H_2 is based on the interaction of three inseparable pillars: stable regulation, shared infrastructure and secure financing, thus constituting the "triangle of competitiveness" validated by the literature.

5 Conclusion

This systematic literature review highlights that green hydrogen is no longer just a technological promise, but a genuine strategic option to support the energy transition and strengthen industrial sovereignty. However, its competitiveness cannot be reduced to a simple cost equation. It results from a set of combined conditions: a clear and stable policy framework, sustained public and private investment, suitable infrastructure, and governance capable of coordinating all stakeholders. The TCCM approach has shown that these dimensions interact and reinforce each other, thus confirming a systemic rather than fragmented view of competitiveness.

The results also highlight that trajectories vary according to geographical contexts and national priorities: energy security for some importing countries, export strategies for states with abundant resources, and the pursuit of industrial integration for emerging economies. This observation underscores that the competitiveness of green hydrogen is neither automatic nor universal, but rather contextualized, gradual, and dependent on coherent strategic choices.

Ultimately, the literature converges on one certainty: green hydrogen can become a structuring pillar of low-carbon economies, provided that countries, especially emerging ones, establish this "competitiveness triangle" combining stable regulation, shared infrastructure, and secure financing. The challenge now is no longer solely technical, but profoundly political, economic, and institutional.

References

[1] Executive summary – Global Hydrogen Review 2025 – Analysis. IEA n/a https://www.iea.org/reports/global-hydrogen-review-2025/executive-summary (accessed December 19, 2025).

[2] Curcio E. Techno-economic analysis of hydrogen production: Costs, policies, and scalability in the transition to net-zero. Int JHydrog Energy 2025;128:473–87. https://doi.org/10.1016/j.ijhydene.2025.04.013.

[3] Perey P, Mulder M. International competitiveness of low-carbon hydrogen supply to the Northwest European market. Int JHydrog Energy 2023;48:1241–54. https://doi.org/10.1016/j.ijhydene.2022.10.011.

[4] Yin Y, Wang J, Li L. An Assessment Methodology for International Hydrogen Competitiveness: Seven Case Studies Compared. Sustainability2024;16:4981. https://doi.org/10.3390/su16124981.

[5] Quitzow R, Lentschig H, Friedrich-Ebert-Stiftung B de P. German hydrogen strategy. Preserving the competitiveness of industry as part of the global energy transition. Friedrich-Ebert-Stiftung, Paris Office, 41 bis, bd. de la Tour-Maubourg, 75007 Paris (France); 2024.
[6] Nuñez-Jimenez A, De Blasio N. The Future of Renewable Hydrogen in the European Union: Market and Geopolitical Implications | The Belfer Center for Science and International Affairs 2025. https://www.belfercenter.org/publication/future-renewable-hydrogen-european-union-market-and-geopolitical-implications-0 (accessed December 20, 2025).
[7] Frieden F, Leker J. Future costs of hydrogen: a quantitative review.Sustain Energy Fuels 2024;8:1806–22. https://doi.org/10.1039/D4SE00137K.
[8] Algburi et al. Renew. & Sust. Energy Transition: Global perspective on green hydrogen 2025. https://fr.scribd.com/document/890381377/1-s2-0-S2667095X25000170-main (accessed December 19, 2025).
[9] Münster M, Bramstoft R,Kountouris I, Langer L, Keles D, Schlautmann R, et al. Perspectives on green hydrogen in Europe—during an energy crisis and towards future climate neutrality. Oxf Open Energy 2024;3. https://doi.org/10.1093/ooenergy/oiae001.
[10] Duraković G, Crespo del Granado P,Tomasgard A. Are Green and Blue Hydrogen Competitive or Complementary? Insights from a Decarbonized European Power System Analysis 2023. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4400830 (accessed December 20, 2025).
[11] PRISMA 2020 flow diagram. PRISMA Statement nd https://www.prisma-statement.org/prisma-2020-flow-diagram (accessed October 28, 2024).
[12] Paul J, Rosado-Serrano A. Gradual Internationalization vs Born-Global/International new venture models: A review and research agenda. Int Mark Rev2019;36:830–58. https://doi.org/10.1108/IMR-10-2018-0280.
[13] Paul J, Khatri P, Kaur Duggal H. Frameworks for developing impactful systematic literature reviews and theory building: What, Why and How? JDecis Syst 2024;33:537–50. https://doi.org/10.1080/12460125.2023.2197700.
[14] Geels FW. A socio-technical analysis of low-carbon transitions: introducing the multi-level perspective into transport studies. JTransp Geogr 2012;24:471–82. https://doi.org/10.1016/j.jtrangeo.2012.01.021.
[15] Braga H, Gouvea R, Gutierrez M. The Green Hydrogen Economy and the Global Net Zero Agenda: A GreenPowershoring & Green Watershoring Perspective. Mod Econ 2024;15:23–48.
[16] Martins FP, De-León Almaraz S, Botelho Junior AB, Azzaro-Pantel C, Parikh P. Hydrogen and the sustainable development goals: Synergies and trade-offs. Renew Sustain Energy Rev2024;204:114796. https://doi.org/10.1016/j.rser.2024.114796.
[17] Evro S, Oni BA,Tomomewo OS. Carbon neutrality and hydrogen energy systems. Int J Hydrog Energy 2024;78:1449–67. https://doi.org/10.1016/j.ijhydene.2024.06.407.
[18] Quitzow R, Nunez A, Marian A. Positioning Germany in an international hydrogen economy: A policy review. Energy Strategy Rev 2024;53:101361. https://doi.org/10.1016/j.esr.2024.101361.
[19] Fasihi M, Bogdanov D, Breyer C. Techno-Economic Assessment of Power-to-Liquids (PtL) Fuels Production and Global Trading Based on Hybrid PV-Wind Power Plants. Energy Procedia 2016;99:243–68. https://doi.org/10.1016/j.egypro.2016.10.115.
[20] Lentschig H, Patonia A, Quitzow R. Multilateral governance in a global hydrogen economy: An overview of main actors and institutions, key challenges and future pathways. Int J Hydrog Energy 2025;97:76–87. https://doi.org/10.1016/j.ijhydene.2024.11.393.
[21] Leuthold A, Terrapon-Pfaff J, Viebahn P. Implementation factors for green hydrogen projects: A systematic literature review. Sustain Energy Technol Assess 2025;82:104555. https://doi.org/10.1016/j.seta.2025.104555.
[22] Roy D, Bhowmik M, Roskilly AP. Technoeconomic, environmental and multi criteria decision making investigations for optimisation of off-grid hybrid renewable energy system with green hydrogen production. J Clean Prod 2024;443:141033. https://doi.org/10.1016/j.jclepro.2024.141033.
[23] Pomerlyan E, Belitski M. Integration - Growth relationship: A literature review and future research agenda using a TCCM approach. Eur Manag J 2023;41:1106–18. https://doi.org/10.1016/j.emj.2023.10.003.